TABLE OF CONTENTS

1. INTRODUCTION

The development of all branches of nuclear science, and consequently the developing knowledge of nuclear reactions and their applications, have been very rapid. As the result of development of new methods and technologies, integral cross section data on large number of reaction types are of interest as the function of energy of the incident particles up to about 100 MeV for charged particle induced reactions. Several new area had been developed in which nuclear reactions are used to gain information on the structure, composition of the investigated material or to modify them. The knowledge of the reaction cross section data is essential in order to be able to optimise the experimental circumstances, hence, reduce the uncertainties/impurities in the final results/products in such applications as: direct charged particle activation analysis (CPAA) to determine the minor and major components of the investigated samples [1, **B22**], thin layer activation (TLA) technique [2] to measure the wear, corrosion and/or erosion of the irradiated surface, monitoring the performances of charged particle beams [3], production of isotope mainly for diagnostic use in nuclear medicine where one should keep the influence of the side reactions on the final product as low as possible to produce the desired isotope without radioactive impurities [4]. An other important area where integral cross section data are needed is the high energy applications [5], (such as proton therapy or the suggested transmutation of the activity of the used fuel elements of reactors to transform the long lived fission product into a shorter lived one), in which the high energy particles slow down and stop in the target and/or collimator producing high amount of activity. To estimate the produced activity not only the high energy cross section data but middle and low energy data are also required. An other field were nuclear reaction data are needed is the nuclear astro-physics [6, 7], to model the different processes take place in the stars and in the other objects of the universe.

The situation with regard to charged particle cross section data is less satisfactory when compared with neutron cross section data. In the latter case, a large number of data has been collected for almost all stable isotopes. The charged particle induced reactions had been of less importance in technological applications in the past with the result that the charged particle reaction data is less advanced. Beside these facts there is an other important drawback, namely one part of the measured experimental data are old, measurements were done using an experimental technique with limited resolution and precision or using old nuclear data, hence, the gained information not reliable enough. In some cases no experimental cross section data are available at all.

A survey of the reactions investigated and published in **A1 - A18** using low and medium energy light charged particle beams showed that the status of the data is usually do not fulfil the requirements for most of the applications. The excitation functions used in the applications have to be well defined and their numerical values accurately known. The nominal errors of the measured cross sections ascribed by authors usually vary between 10 and 15 percent [8], but the data presented by different authors at the same energy points differ more significantly. Therefore, it is essential to set up recommended data base for standard reactions with low uncertainty using critically compiled and evaluated experimental data. Certainly, the discrepancies found in experimental data from various authors for the same reaction often exceed the quoted error figures, but this reflects the difficulties encountered in the measurement of excitation functions.

In the lack of the experimental data there are several theoretical approaches for calculating low and middle energy charged particle cross sections data, but in general the

applicability of the codes developed on the theory is limited by several factors. The results indicate that calculated excitation functions, at least for proton induced reactions obtained with standard set of input parameters, could be used as estimates with adequate accuracy. For reactions involving "complex" particles (like deuteron, ^{3}He or alpha particles) in the entrance and/or exit channels [9] the results are less satisfactory. Individual selection of input parameters according to nuclear data available for specific mass region or by experience could perhaps give better agreement with the experimental data. At this present status, unfortunately, the theoretical calculation do not give reliable result for all the charged particle nuclear reactions, but they can be used to fit the experimental data and interpolate in-between the measured data points or extrapolate the available cross section data beyond the energy region of the measured experimental data points. Although the study of integral cross section data and excitation functions does not lead to detailed analysis of reaction mechanism, they do contribute to the investigation of the validity of theoretical reaction models.

Systematic investigations of charged particle induced nuclear reactions on different materials are in progress in many laboratories for evaluating their potential use in different applications and basic science. The Nuclear Data Section of the International Atomic Energy Agency had started a Co-ordinated Research Project for development of a reference charged particle cross section data base for monitor reactions and reactions for producing medically important radioisotopes with the co-operation of seven laboratories from all over the world, in which program our institute also participates [10].

In this thesis experimental integral cross section data are presented on the reactions important for monitoring the intensity and/or energy of charged particle beams, for isotope productions, for direct charged particle activation analysis and for applications of thin layer activation technique. The used experimental techniques of the measurement are also described and some example are given for the applications of the measured cross section data.

With a view to enhancing our knowledge of the necessary excitation functions we have performed detailed and systematic measurements on selected target materials bombarded by light charged particle beams. A comprehensive survey, compilation, measurement and critical evaluation of the absolute cross section data of the reactions investigated were done [**A1 - A18**]. For the reactions induced by light charged particles important for several applications in which our department is engaged recommended data sets were prepared [**A5, B12,** 11] based on all the available experimental data including our result.

2. NUCLEAR REACTIONS

2.1. Mechanism of reactions

Each time when an energetic particle encounters with a nucleus a nuclear reactions can take place in which a new nucleus and out going particle(s) can form. Up to a few MeV particle energy elastic and/or inelastic scattering can occur and both the target nucleus and the bombarding particle can change their energy state. At higher bombarding energy the incoming particle a can penetrate into the nucleus A and can stay there for a relatively long time (10^{-15} s) and a compound nucleus C^*, usually in a highly excited state, is formed, while the energy of the bombarding particle are distributed among the nucleons of C^* evenly. Then the decomposition of C^* into $B + b$ occurs. This compound model was proposed first by Bohr in 1936 [12].

$$a + A \rightarrow C^* \rightarrow B + b$$

With increasing energy the density of excited states increases rapidly in C^* forming a continuum from where b can be emitted before the whole energy can distribute evenly among the nucleons involved and permitting the nucleus to be treated by statistical methods. This type of the reactions called the precompound reaction mechanism. In this energy region (10 MeV - 30 MeV) the cross section has no strong dependence on the energy.

Increasing further the bombarding energy the projectile "stays" much less time in the vicinity of the target nucleus (10^{-22} s) and can interact only with one or a few nucleons of the target nucleus. The intensity of this direct reaction is slowly dependent on energy.

2.2. Reaction energy

The energy conservation low in any nuclear reaction type $A(a,b)B$ is valid, that means the total energy sum of the rest and kinetic energy of the system before and after the reaction is equal. The reaction energy is defined by:

$$Q = (m_A + m_a - m_B - m_b)c^2$$

$$Q = (M_A + M_a - M_B - M_b)931.5 \quad MeV$$

The minimal projectile energy in he laboratory system required to initiate an endothermic reaction ($Q < 0$) is the threshold energy E_{thr}. In the nonrelativistic case E_{thr} is obtained by:

$$E_{thr} = -Q\left(1 + \frac{M_a}{M_A}\right)$$

The height of the Coulomb barrier is in the laboratory system is calculated in MeV by:

$$E_c = \frac{Z_A\, Z_a\, e^2}{4\pi\varepsilon R} \approx \frac{Z_A\, Z_a}{A_A^{1/3}\, A_a^{1/3}}$$

where Z_A and Z_a are the proton number of the target and projectile, respectively, e is the elementary charge, $R=r(A_A^{1/3}+A_a^{1/3})$ is the distance between the centre of the target and projectile, r = 1.4 10^{-15} m, ε is the permeability of vacuum and A_A and A_a are the nucleon number of the target and the projectile, respectively.

2.3. Cross section

When energetic charged particle beam interacts with a target material the bombarding particles can overcome the Coulomb-barrier of the target nuclei and nuclear reactions can take place. The probability of the occurrence of a nuclear reaction is called cross section. The number of nuclei formed in a nuclear reaction along the path of charged particle during bombardment as the function of time is given by the expression:

$$n^*(t) = \frac{I(t)}{ze}\frac{N_A f}{M}\int_{x=0}^{\infty}\int_{E=0}^{\infty}\int_{E_1=0}^{\infty} c(x)\; g(E_0,E)\; h(E,E_1,x)\; \sigma(E_1)\; dE\; dE_1\; dx \qquad (1)$$

where $n^*(t)$ is the reaction rate, the number of isotopes formed per second,
- $I(t)$ describes the beam intensity as the function of time,
- ze the charge of the bombarding particle,
- N_A is the Avogadro's number
- M is the molar mass of the target material
- f is the isotopic abundance of the target isotope involved in the reaction
- $c(x)$ is the concentration of the target isotope
- $g(E_0,E)$ is the energy distribution of the beam around the E_0 average value, which is approximately Gaussian type
- $h(E,E_1,x)$ describes the straggling effects, represents the probability density for a particle of primary energy E at the target surface to have an energy E_1 at a depth x where the reaction takes place.
- $\sigma(E_1)$ is the reaction cross section

In general practice a simplified version of the above formula is used. When the cross section σ(E) has low variation with energy, then the energy spreading effects have negligible consequences and the formula (1) can be simplified.

$$n^*(t) = \frac{I(t)}{ze}\frac{N_A f}{M}\int_{E=0}^{E_b}\frac{c(x)\ \sigma(E)}{S(E)}dE \qquad (2)$$

Where S(E) describes the stopping power. In additions using a stacked target composed of thin foils with a thickness of Δx, corresponding to an energy loss of ΔE of the bombarding particles, and the $c(x) = c$ concentration is constant over the target foil the following expression is valid for the production rate $n^*(t)$:

$$n^*(t) = \frac{I(t)}{ze}\frac{N_A f\, c}{M}\overline{\sigma}\Delta x \qquad (3)$$

where $\overline{\sigma}$ is the average cross section over the ΔE energy interval.

Radioactive isotopes can decay as soon as they are formed. Taking into account the decay during irradiation the total number of radioactive atoms N^* present in the sample at the end of bombardment (EOB) is given by:

$$N^* = \int_0^{t_b} n*(t)\, e^{-\lambda t} dt \qquad (4)$$

where λ is the decay constant of the produced isotope and t_b is the irradiation time.
When the beam intensity is constant all along the irradiation then the production rate is constant, $n*(t) = n$, and the above expression easy to integrate. After integration and rearrangement of the equation (4) and expressing N^* with the measured peak area $T\gamma$ one can have the formula which is used to calculate the mean cross section corresponds to a certain thin foil in the stacked target.

$$\overline{\sigma} = \frac{M\, z\, e\lambda\ T_\gamma}{\Delta x\, N_A\ f\, c\, Q\left(1-e^{-\lambda\, t_b}\right) e^{-\lambda t_c}(1-e^{-\lambda t_m})\varepsilon_1\varepsilon_2\varepsilon_3\varepsilon_4} \qquad (6)$$

Where T_γ is the measured net peak area, t_c is the cooling time, t_m is the measuring time ε_1 is the detector efficiency including the geometry factor, ε_2 is the relative ratio of the measured gamma-line, ε_3 is the correction factor for possible recoil loss and dead time and ε_4 is the correction for finite target thickness [13].

2.4. Reaction yields

The yield of a nuclear reaction is defined as the production rate of the newly formed nuclei per unit bombarding particle current:

$$Y(E_b) = \frac{n*(t)}{\frac{I(t)}{ze}} = \frac{N_A f c}{M} \int_{E=0}^{E_b} \frac{\sigma(E)}{S(\mathrm{E})} dE \qquad (7)$$

.

M. Bonardi gave an overview in his work [14] of the different yield definitions used in practical applications. The three main definitions with absolute physical content are: the thin target yield [$BqC^{-1}MeV^{-1}$], thick target yield [BqC^{-1}] and saturation yield [BqA^{-1}]. In the everyday practice some authors also prefer to use the expression of the yield at the end of bombardment. The yield measured after one hour one microampere irradiation ($Bq\ \mu A^{-1}\ h^{-1}$) also can be found in the literature which can give different value from those calculated using the above physical definition of the yields. The difference is more significant for radioisotope having short half life compared to the one-hour irradiation time.

3. EXPERIMENTAL TECHNIQUES AND METHODS

3.1. Methods of cross section measurements

The cross section of a charged particle induced reactions can be determined by detecting the reaction products directly (gamma photons, out going particles formed in the investigated process) or measuring the produced activity.

In the direct measurements the reaction products are detected by a sophisticated experimental techniques (special detectors, fast electronics, coincidence system, dedicated data handling and storage units, etc.) which are more complex than those applied in the frequently used activation method. The advantage of the direct method is the possibility of the determination of differential cross section and the high sensitivity (coincidence technique, particle counting). Using the activation method the reaction cross section is determined trough the measurements of the activity of the radioisotopes produced in the investigated nuclear reactions. The main advantage of the activation method is that the irradiation and the measurement are separated in time. Cross section measurements using activation method can be done on a single or stacked target. When performing such experiments several experimental parameter are needed to be optimised in order to obtain valuable data and minimise the uncertainty of the final result. These are: the type of particle, incident energy of the beam, irradiation time, beam intensity. While measuring the induced activity one should choose carefully the cooling time, measuring time and measuring geometry.

3.2. Stacked target method

In applied nuclear physics the cross section measurement of a nuclear reaction is in most cases done by stacked foil irradiation followed by accurate γ-spectrometry. This way not only a single but simultaneous bombardment of several thin targets can be done or special combination of target materials resulting a series of data points in one irradiation. In addition one can investigate several nuclear reactions parallel occurring in the target at the applied bombarding energy. From the measured primary experimental data (peak area) and the irradiation and target parameters the cross section is calculated. Due to energy loss of the bombarding beam, each foil is irradiated at different beam energy, resulting several experimental points of the $\sigma(E)$ curve for only one irradiation. The stacked target technique can be applied for targets consist of thin foils and/or gas cells. A stacked target beside the target foils contains one or more monitor foils to determine the energy and/or the flux of the bombarding particle beam. In special cases energy degrader foils are placed in the stack. Their purpose is only to enhance the energy degradation in the stack, where otherwise a large number of target foils would have been necessary to cover the whole energy region. During nuclear reactions, the newly formed nucleus will be recoiled by transfer of kinetic energy from the incident particle. As a result the nuclei formed near to the surface will be able to escape from the sample. These recoiled and escaped nuclei can be implanted into the next foil in the stack modifying the activity of the foils. To overcome this problem catcher foils are applied to stop the escaping reaction products.

3.2.1. Target preparation

For cross section measurement one parameter regarding the target is important: the thickness of the target material. The primary energy of the beam gradually decreases while travelling trough the target material due to the energy loss. Therefore it is necessary to keep the target as thin as possible to assure negligible energy loss. One can prepare thin targets on several ways. The most frequently used thin target preparation methods are: use of thin films or foils, electrodeposition, evaporation or sedimentation of the target material on thin backing, use of target material in gas form. We have applied all these techniques during our experimental works. Typically target foils are cut out of a larger foil of the appropriate material with known purity and certified thickness. (In most cases we used Goodfellow materials.) The thickens of the foils (in mg/cm^2) is checked by calculating the surface and determining the weight of the foils. Using electrodeposition, evaporation or sedimentation the target thickens determined by measuring the geometrical size and the weight of the deposited spot of target material. An other possibility to measure the thickness of thin layers is the Rutherford backscattering (RBS).

Using a stack of thin foils one can determine several points of the excitation function with one irradiation. To cover a larger energy range with only a limited number of target foils, one can include several extra degrader foils in the stack. The degrader foils do not need to be of the same material as the target, but their purity and thickness should be known with the same accuracy. They can also be used as monitor foils or catcher foils too. Before assembling a stack the number of foils needed in one irradiation has to be determined. One should find the optimal number of foils. Too few foils in a stack will lead to more irradiations to cover the required energy region, while too many foils in a single stack will induce cumulative energy uncertainties due to inaccurate knowledge of the primary bombarding energy and of the foil thickness which influence the result of the stopping and straggling [15] calculations. The number of foils is hence determined by the energy range of interest, the stopping power of the target material, the acceptance level of energy uncertainty and the available irradiation time.

3.2.2. The irradiation circumstances

The irradiation parameters of importance are the type of particle, the energy and intensity of the beam and the irradiation time. The first two parameter are determined by the type of reaction and the energy interval of interest. According to the selected particle type and the required beam energy the irradiations were done at the MGC-20E cyclotron, Debrecen, Hungary, at the CV-28 compact cyclotron, Jülich, Germany, at the MGC-20 cyclotron, Turku, Finland and at the CGR-560 cyclotron Brussels, Belgium. Cross section measurements should hence only be performed after an energy calibration of the accelerated beams. The energy calibration method were different for the accelerators used. In Debrecen and Turku calibrated analysing magnet (stabilised calibrated magnetic field and pairs of slits) are used to determine the proper value of the primary beam energy which is in first order is estimated on the extracting radius and the cyclotron frequency. In Jülich [16] and Brussels [17] special Time of Flight technique are applied to determine the exact distance between the successive beam bunches. This distance is related to the energy of the cyclotron beam.

The beam intensity and the irradiation time are coupled parameters, since the total number of incident particles determines the produced activity. Target were irradiated in a special insulated vacuum chamber served as Faraday-cup and equipped with electron supressor to reduce the influence of the secondary electrons generated by the bombarding particles in the target and in the collimator. The applied voltage on the electron suppressor varied from -70 V to -100 V depending on the actual geometry and construction of the irradiation chamber. The beam intensity were always kept low, typically between 50 and 500 nA, to avoid the target loss due to the high dissipated energy. If it was necessary extra cooling was applied to keep the temperature of the target low [**A16**]. In all the experiments the total number of the incident particles were determined trough the charged collected in Faraday-cup and in most cases the flux of the bombarding particles was monitored via monitor reactions. Usually we found an agreement between the values measured by the two methods of 8% to 20%.

3.2.3. Determination of particle energy in a stacked target

Cross section measurements using activation method can be done on a single or stacked target, but in all cases the bombarding energy for each layers of the target need to be determined accurately. For calculating the energy loss of the bombarding particles the formulae of Andersen and Ziegler [18, 19] have proven to be easily applicable in every situation we encountered. On the basis of theory, experimental data and systematics they gave a 12- and 9-parameter formula for the hydrogen and helium projectiles, respectively, for all target materials.

The use of stacked gas targets requires special attention for determination of the energy and the flux of the beam in different sections of the target. Therefore, we have studied the penetration of energetic charged particle beams into highly pressurised gas targets. Several experimental methods have been developed to study the interaction of charged particle with pressurised gas targets (measurement of the activity of the produced radioisotopes, the yield of the secondary neutrons, the heat, the charge , the emitted light the change of gas density, temperature, refractory indexes and so on). The photographic view reflects the shape of the beam in the target and gives the maximum penetration of the beam. The asymmetric beam shape observed is due to the upward thermal gas stream in the target. The interferometric studies showed that there is strong upward thermal transport of the gas heated by the particle beam in the target chamber [20]. An overview of the applied methods and results can be found in the thesis of O. Solin [21] and in [22]. When a parallel beam of charged particles passes through a medium, the particles are scattered and the beam diameter gradually expands with increasing depth. Multiple scattering of the beam by the target chamber entrance window and by the target gas as well as reduction of the target gas density seriously affect the location of the energy deposition in the target causing a loss in the production capability of the particle beam. An intense particle beam may reduce the gas density to such an extent that the target is no longer sufficiently thick to stop the beam or to degrade the incident energy to the practical threshold energy of a certain nuclear reaction.

We have studied the interaction of charged particle beams with gas targets at horizontal and vertical beam-lines using video and photographic technique [**A12**] and plexi-glass windowed study chambers. Beside the optical study we have measured for the first time the charge distribution inside the target chamber on a remote positioned isolated electrode. Our optical study and charged distribution measurements confirm the asymmetric beam shape

observed by optical study at horizontal irradiation [**A12**]. According to the expectation we found that the shape of the beam is symmetrical at vertical irradiation which can be concluded from the heat transfer in presence of vertical gravitational field model. Studying the beam build-up in time in the target chamber after the beam stop opening we found and reported for the first time a dynamic effect, an oscillation of the maximal range of the impinging particle beam. The period of the oscillation was around one second. The amplitude of the oscillation depends on the beam density and the geometry of the irradiation chamber. At the first impact the beam is symmetric then gradually reaches its maximal size in length while becoming more an more wide. Then the volume of the beam strike oscillates around the length of the equilibrium state and meanwhile becoming asymmetric in shape at horizontal irradiation set-up. At vertical irradiation no asymmetry was observed. A simple phenomenological model is proposed for the observed phenomena [**A12**].

The density variation of the target gas under nonuniform heat production and mass transport as a function of time in- and outside of the beam volume gives a possible explanation of the observed effects. The model has to be confirmed by further experiments and with computer simulation. As far as the applications are concerned, the observed beam shapes at vertical and horizontal irradiation are important and have already been taken into account in the construction of high yield gas targets for isotope production and for proper choice of beam current, gas pressure and irradiation geometry in nuclear data measurements.

For measuring excitation function on gaseous material we used single and/or stacked gas targets. The gas cells were placed in a metal tube which served as a Faraday-cup and the irradiation were performed in air. The relatively large cells prevent us to carry out the irradiation under vacuum. The beam current measured on the Faraday-cup was used only for orientation because of the possible alteration effect caused by the ionised air between the targets and the closing window of the beam extraction unit. The windows of the target cells or extra monitor foils were used to determine the beam intensity and energy in the irradiated cells trough monitor reactions. Detailed description of the technique is given in [23, 24].

3.2.4. Activity measurements

After irradiation the activity of the target foils need to be determined. Standard high resolution gamma-spectrometry was applied to measure the activity in most cases without any prior chemical treatment. The spectroscopic analysis is best done on a detector with high energy resolution (Ge(Li) or HpGe type detectors) using a classical set-up (detector, amplifiers, ADC, multichannel analyser- one or more of these units can be computer controlled). This way optimal separation between the different gamma-lines can be guaranteed. The detector set-up is calibrated carefully both in energy scale and counting efficiency using standard gamma-sources. One should use the calibrated geometry and sample holder to perform activity measurement, since the detector efficiency includes the geometry and attenuation factors too. Always special care was taken while determining the detector efficiency in the energy region around maximal value of the efficiency curve.

The activity of the target foil can be determined trough the measurements of the intensity of a single gamma-photon emitted after each decaying isotopes, or in the case of pure β^+ decaying isotopes through the measurement of the 511 keV annihilation gamma-line. In this later case one should use an absorber to stop the β^+ particles in the vicinity of the irradiated target to ensure the proper measuring geometry. Gamma-measurement was always carried out with the “live time“ correction on (internal algorithm or external pulser and

correction) to correct for the dead time of the set-up. The dead time has to be kept under 5% for representative data collections. General practice was to measure each target several times to check the decay for the different nuclides. Also in cases of mixed gamma-lines, allowing some of the nuclides to decay completely, can be the way to separate the contribution of the different nuclides to the investigated gamma-line.

During nuclear reactions, the newly formed nucleus will recoiled by transfer of kinetic energy from the incident particle. As a result the nuclei formed near to the surfaces of the foils will be able to escape from the foil and will be stopped by the next or previous foil. Recoil fractions are only important when working with very thin foils, which typically done for reactions induced by particles with high stopping power. In cases where recoil might be an important parameter, extra foils, catcher foils, have to be included in the stack for every target foil. These foils will catch the escaping recoil nuclei which foils afterwards can be measured together with or separate from the target foils and correction can be made for the recoiled nuclei. If the foils are thin, but the stack was only made up of target foils, recoil is again of no importance. The loss in one foil is almost balanced by the gain from the previous one, except for the first foil in the stack.

Using stacked target technique to determine a reaction cross section one has to measure many samples having different activity and has to optimise the sequence of the foils in order no to loose information due to the too high or too low count rate. We have developed a computer controlled sample changer system which can be programmed to change the sequence of the foils by checking the dead time. This unit consist of a standard high resolution gamma-spectrometer, (HpGe Canberra detector and power supply, a Tc244 Tennelec amplifier and signal processor, a PC-II 8000 Nucleus 8k plug-in analyser card and a PC386 personal computer) and an automatic sample changer an positioner system driven by stepping motors controlled by the PC. The irradiated foils stored in a shielded rotating sample changer with 32 coded sample positions placed at about four meter distance from the shielded detector. The sample to be measured selected, transported and positioned automatically in front of the detector. This unit was built with the help of the National Committee for Technical Development.

4. RESULTS AND DISCUSSION

4.1. Monitor reactions

4.1.1. Motivation and status of monitor reactions

In an experiment with charged particle irradiation one should know the beam energy and intensity preferably as a continuous function of time and more importantly as the penetration depth, which in fact can not be realised hundred percent. Instead they are determined in steps, in a few points only, and most cases only integral data can be obtained. Generally one can have information on the primary energy and/or intensity and the time dependence (if any) and spatial distribution of the beam energy and intensity is calculated (energy loss, energy spread, straggling, scattering, particle range).

Several methods had been developed for measuring intensity of charged particle beams such as: beam current transformers, calorimetric methods, collecting charge in a Faraday-cup, applications of monitor reactions. The procedures used for determining the energy of the bombarding beam such as: Rutherford back-scattering, magnetic spectrometers, range-energy functions, calibrated analysing magnets, measurement of spatial separation between neighbouring bunches of the particles in the beam, TOF, etc. are technically more sophisticated, and need more expertise in applications [25].

The use of monitor reaction is a simple method to determine the flux and can also provide a check of the calculated particle energy incident at a thin foil and yet it assures the necessary precision needed in different applications. From the activity induced by charged particle beam and from the known cross section-energy relation of the reaction takes place in the monitor foil, the energy or the intensity of the bombarding beam can be calculated. If the beam parameters were established using monitor reactions, one can actually obtain only relative values for the measured cross section. The measured values can only be as good as the values for the cross section of the used monitor reactions.

Regarding the available experimental cross section data for monitor reactions, a survey showed [26], that the status of the monitor reaction data is not satisfactory. As in [27] it was pointed out, even in the case of $^{63}Cu(p,n)^{63}Zn$ and $^{65}Cu(p,n)^{65}Zn$ reactions, for which many independent studies have been performed, there exist some discrepancies which may not be solved clearly on the basis of available experimental data. And also, for the different kinds of incident beam than protons, it seems that the experimental precision is not sufficient in all interested energy regions, or in some cases there is no experimental data at all. Therefore, our aim - in agreement with the recommendation of the Nuclear Data Section of the IAEA [28] - was:

- To continue the cross section measurements on selected target material to collect more precise experimental data to solve the discrepancies exist among the available data.
-To search for new reactions and measure their excitation functions using all the four light charged particle beam (proton, deuteron helium-3 and alpha) on the same type of target materials.

-To suggest new monitor reactions to utilise the principles of parallel determination of the flux and energy developed by us (see later).
-To provide reliable data base after compilation and critical evaluation of the available data for the reactions used for monitoring charged particle beams.

4.1.2. Requirements for a monitor reaction and use of monitor reactions

There are several criteria regarding the monitor targets and monitor reactions. These include the availability of the material, the physical and chemical characteristics of the target, the decay parameters of the produced nucleus, the slope of the excitation function in the energy region in question, and the undesired interfering reactions. Among them the cross section is the most important signature of a material used for monitoring of charged particle beams. The use of monitor reactions demands as a prerequisite well known and reliable excitation functions of the monitor reactions. The main requirements are:

Nuclear properties

- Suitable half-life of the isotope used for monitoring purposes. There is only practical consideration to give the range of the half-life and it is: The half-life of the isotope used for monitoring purposes can not be too short or very long comparing to the irradiation time.
- The reaction must have high cross section in the investigated energy region.
- For flux determination a reaction having flat plateau of the cross section in the investigated energy region is the most suitable one. This way the derived flux value do not suffer much from the error of the energy determination.
- The reactions suitable for energy determination must have a cross section with high slope, that provides good energy resolution in the investigated energy region.
- The gamma-photons emitted by the nuclei produced in the monitor reaction should have a proper energy and high relative intensity.
-. The reaction product must remain in the monitor foil (do not volatile, evaporate or escape).
We have added to the broadly accepted principles the next two points to improve the performances of the method and reduce the overall cost.
- Multiple reactions with overlapping energy regions for simultaneous flux and energy determination.
-Possibility to use the same material for monitoring different type of charged particle beams (p, d, ^{3}He, α) is an advantage.

Other necessary physical and chemical properties

- Chemical stability, chemical resistance.
- Good mechanical properties regarding thin foil production.
- Availability, low price.
- Good heat and electrical conduction.
- Stabile physical and chemical structure against the energy dissipation of the bombarding beam.
- Strengths against mechanical deformations.

The above mentioned requirements give a serious limitation for the number of materials having the right properties to be used for monitoring beam performances. Taking into account all these requirements, the following metallic materials could be considered as appropriate candidates for monitor target: aluminium, titanium, iron, nickel and copper[28].

At medium energy irradiation one can place several foils in a stack to cover the whole energy region from the primary particle energy down to the threshold of the investigated reactions. Many foils in one stack then results large uncertainty in the lower section of the energy scale due to the commulative errors in the foil thickness uniformity. Solving this problem we have adopted a simple method to increase the precision of the energy scale in the low energy part by using more than one monitor reactions [**B18**] in the same monitor foil. In our method beside the knowledge of the cross sections of the applied monitor reactions, use of infinite thin monitor foil and monoenergetic bombarding beam we have postulated two basic principles on which this method is based:

1. The intensity (energy) calculated from the same monitor reaction takes place in the monitor foils placed at different position in the stack should result the same values only if the beam energy (intensity) in each monitor foil is determined correctly and no beam loss occurred along the stack.
2. The intensity (energy) calculated from one monitor foil in the stack using different monitor reactions should result the same values only if the beam energy (intensity) in that monitor foil is determined correctly.

Using these two assumptions the energy and the flux can be determined more accurately applying successive approximation in the calculation of flux and energy. In the same time one can avoid the large uncertainty of the calculated flux or energy using a rapidly changing part of the excitation function of a single monitor reactions.

4.1.3. Measurements of monitor reactions

The chemical and physical properties of the materials suitable for monitoring charged particle beams are known and available. Among the nuclear data required the cross section is the most important signature that one should determine carefully to be able to use the appropriate reaction for monitoring. In a series of systematic experiments our group have investigated the excitation functions of the ^{nat}Ti(p,x) [29], ^{nat}Ti(d,x) [**A4**], ^{nat}Ti(^{3}He,x) [30], ^{nat}Ti(α,x) [30], ^{nat}Fe(p,x) [**A5**], ^{nat}Fe(d,x) [**A6**], ^{nat}Ni(p,x) [31], ^{nat}Ni(d,x) [**A1**], ^{nat}Ni(^{3}He,x) [**A2**], ^{nat}Ni(α,x) [**A3**], ^{nat}Cu(p,x) [30], ^{nat}Cu(d,x) [**A6**], ^{nat}Cu(^{3}He,x) [30], ^{nat}Cu(α,x) [30] ^{nat}Mo(d,x) [**B4**] nuclear reactions. The table 1. summarises only the reactions presented in papers **A1 - A6**, sorted by according to the type of the bombarding particles and the target materials. Reactions recommended for monitoring purposes are denoted by an asterisk. In papers **A1 - A6** compilation of data available in literature on the investigated reactions in most cases are also given. Evaluating the experimental data including our results showed that in some cases additional experiments are still required to be able to solve the discrepancies found.

Table 1. Charged particle induced nuclear reactions measured on natural titanium, iron, nickel and copper for monitoring purposes.

Reaction		investigated energy range MeV	No. of data points	References and monitor reaction
$^{nat}Ni(d,x)^{55}Co$	*	10.6 - 20.15	32	A1
$^{nat}Ni(d,x)^{56}Co$	*	2.3 - 20.15	54	$^{27}Al(d,x)^{24}Na$
$^{nat}Ni(d,x)^{57}Co$		10.6 - 20.15	32	
$^{nat}Ni(d,x)^{58}Co$	*	2.3 - 20.15	54	
$^{nat}Ni(d,x)^{57}Ni$		10.6 - 20.15	32	
$^{nat}Ni(d,x)^{60}Cu$		10.6 - 20.15	32	
$^{nat}Ni(d,x)^{61}Cu$	*	2.3 - 20.15	54	
$^{nat}Ni(^{3}He,x)^{52}Mn$		27.6 - 35.0	10	A2
$^{nat}Ni(^{3}He,x)^{52}Fe$		29.8 - 35.0	6	$^{nat}Ti(^{3}He,x)^{48}V$
$^{nat}Ni(^{3}He,x)^{53}Fe$		23.8 - 35.0	10	
$^{nat}Ni(^{3}He,x)^{55}Co$	*	19.8 - 35.	17	
$^{nat}Ni(^{3}He,x)^{56}Co$	*	2.1 - 35.0	28	
$^{nat}Ni(^{3}He,x)^{57}Co$	*	5.8 - 35.0	28	
$^{nat}Ni(^{3}He,x)^{58}Co$	*	8.6 - 35.0	26	
$^{nat}Ni(^{3}He,x)^{56}Ni$	*	13.2 - 35.0	23	
$^{nat}Ni(^{3}He,x)^{57}Ni$	*	8.6 - 35.0	32	
$^{nat}Ni(^{3}He,x)^{60}Cu$	*	5.8 - 35.0	23	
$^{nat}Ni(^{3}He,x)^{61}Cu$	*	5.8 - 35.0	28	
$^{nat}Ni(^{3}He,x)^{62}Zn$		5.8 - 35.0	15	
$^{nat}Ni(^{3}He,x)^{65}Zn$	*	8.6 - 25.9	12	
$^{nat}Ni(\alpha,x)^{62}Zn$		17.15 - 24.5	8	A3
$^{nat}Ni(\alpha,x)^{63}Zn$	*	5.9 - 24.5	21	$^{nat}Cu(\alpha,x)^{66}Ga$
$^{nat}Ni(\alpha,x)^{65}Zn$	*	7.8 - 24.5	19	$^{nat}Ti(\alpha,x)^{51}Cr$
$^{nat}Ni(\alpha,x)^{60}Cu$		17.15 - 24.5	5	
$^{nat}Ni(\alpha,x)^{61}Cu$	*	2.34 - 24.5	26	
$^{nat}Ni(\alpha,x)^{57}Co$		13.5 - 24.5	8	
$^{nat}Ni(\alpha,x)^{57}Ni$		17.15 - 24.5	7	
$^{nat}Ti(d,x)^{43}Sc$		11.8 - 21.3	15	A4
$^{nat}Ti(d,x)^{44m}Sc$		2.95 - 21.3	65	$^{27}Al(d,x)^{24}Na$
$^{nat}Ti(d,x)^{44g}Sc$		2.95 - 21.2	53	
$^{nat}Ti(d,x)^{46}Sc$		2.95 - 21.3	65	
$^{nat}Ti(d,x)^{47}Sc$		2.95 - 21.3	65	
$^{nat}Ti(d,x)^{48}Sc$		2.95 - 21.3	65	
$^{nat}Ti(d,x)^{48}V$	*	2.95 - 21.3	65	
$^{nat}Fe(p,x)^{56}Co$	*	5.8 - 17.5	17	A5 $^{65}Cu(p,n)^{65}Zn$
$^{nat}Fe(d,x)^{56}Co$	*	6.93 - 21.3	31	A6
$^{nat}Fe(d,x)^{57}Co$	*	0.94 - 21.3	36	$^{27}Al(d,x)^{24}Na$
$^{nat}Cu(d,x)^{65}Zn$	*	5.16 - 20.2	46	

* Proposed monitor reaction

4.1.4. Results and conclusions

We have investigated 38 nuclear reactions induced by protons, deuterons, helium-3 and alpha particles on target materials titanium, iron, nickel and copper metallic foils. Among them we found 20 reactions having suitable properties for monitoring the four above mentioned particle beams.

The $^{nat}Fe(p,x)^{56}Co$ reactions is one of the most frequently used reactions in the applied nuclear physics, therefore, we gave detailed, comprehensive literature survey, critical compilation and recommended data set based on experimental evaluation method for the reaction $^{nat}Fe(p,n)^{56}Co$ in [**A5**]. The method for evaluating the critically selected experimental data sets was described in [**B8**]. It consist of successive weighted averaging of the weighted spline fitted individual experimental data sets to determine a recommended data base for the reaction investigated.

For deuteron bombardment the $^{27}Al(d,x)^{24}Na$ is a well established reaction to monitor the beam parameters [26]. Beside the excellent parameter of the target material (Al) and the produced isotope (^{24}Na) unfortunately, the reaction has relatively high Q value (-12.3 MeV). Therefore, the reaction can not be used for monitoring purposes below 15 MeV in practice. For monitoring low energy deuteron beams we have investigated the $^{nat}Ti(d,x)$ [**A4**], $^{nat}Fe(d,x)$ [**A6**], $^{nat}Ni(d,x)$ [**A1**] and $^{nat}Cu(d,x)$ [**A6**] processes and measured the excitation functions of the reactions from the threshold up to 21.3 MeV energy (see also table 1.). The beam currents were measured by Faraday-cup in all cases and were found to be lower by 10 % than the value obtained by using the $^{27}Al(d,x)^{24}Na$ monitor reaction (E_d = 21.0 MeV, σ = 54 mb). The experimental cross section data measured were compared to the data available in the literature for the reactions investigated and several disagreements were solved. With the new monitor reaction we proposed ($^{nat}Ti(d,x)^{48}V$, $^{nat}Fe(d,x)^{56,57}Co$, $^{nat}Ni(d,x)^{56,58}Co$, $^{nat}Ni(d,x)^{61}Cu$ and $^{nat}Cu(d,x)^{65}Zn$) the energy region was extended below 15 MeV where the deuteron beams can not be monitorised with the $^{27}Al(d,x)^{24}Na$ reaction.

We have investigated for the first time the $^{nat}Ni(^3He,x)$ processes from threshold up to 35.0 MeV ^{3}He-particle energies [**A2**]. Thirteen reaction products were studied and the excitation functions for the production of ^{62}Zn, ^{60}Cu, ^{56}Ni and ^{57}Ni appear to be interesting from the viewpoint of potential application as monitor reactions. These excitation functions exhibit plateau over a broad energy range, a fact which could help to avoid errors in the flux determination originating from the improper estimation of the mean energy of the bombarding particle in the monitor foil. The same applies to some extent to the product ^{56}Co over the ^{3}He particle energy range of 18-28 MeV. The use of the excitation function of ^{55}Co, ^{56}Co, ^{57}Co, ^{58}Co, ^{65}Zn, ^{61}Cu, ^{52}Fe, ^{53}Fe and ^{52}Mn may allow a simultaneous determination of flux and energy [**B18**] of the bombarding ^{3}He particle energy.

The alpha particle induced reactions on natural nickel, $^{nat}Ni(\alpha,x)$ were investigated up to 24.5 MeV [**A3**]. All together eight reactions were studied. The reactions leading to the formation of ^{61}Cu, ^{63}Zn and ^{65}Zn on chemically resistant and mechanically stable nickel are very promising for monitoring alpha-particle beams because of the relatively high cross section values and low threshold energies. The excitation function of the reaction products ^{57}Co, ^{57}Ni, ^{60}Cu, ^{67}Cu and ^{62}Zn were measured only in a few points above their respective threshold energy and the cross sections are relatively small in that energy region, hence they can be used for monitoring purposes only in limited cases.

Our systematic investigation resulted a significant contribution to the field of measurements and applications of the cross sections of charged particle monitor reactions.
We proposed to use the same type of target material for all the four light bombarding particle beams and investigated the properties of the reactions on Ti, Fe, Ni and Cu.
We have completed the available data sets by expanding the investigated energy region and eliminated the existing disagreements among the available cross section data.
We proposed new reactions to monitor low energy deuteron beams and new reactions for complex monitoring of charged particle beams (independent flux and energy determination in the same time).
The collected and critically evaluated experimental data including our results were supplied to the theoretical evaluators to calculate a recommended data sets for the selected reactions.
Further investigations are in progress:
- to complete the investigations of reactions of light charged particle on ^{nat}Ti, ^{nat}Fe and ^{nat}Cu,
- to extend the measurements at higher energies in order to be able to monitor medium energy charged particle beams and to exploit the capabilities of the multi-reaction monitoring method.

The work already has been started, in the frame of an international project, co-ordinated by the International Atomic Energy Agency, to establish a reliable charged particle cross section data base for the reactions used in production of medically important radioisotopes, among them for the reactions applied for monitoring the production processes.

4.2. Isotope productions

4.2.1. Medical isotopes

Radioisotopes can be grouped according to their use in nuclear medicine: isotopes for diagnostic and isotopes for therapeutical purposes. Regarding the production facilities of the isotopes two main groups exist, isotopes produced by reactors and isotopes produced by accelerators, mainly by cyclotrons.

Regarding the development of a new radiopharmaceutical one of the most important step is the selection of the radionuclide for labelling and its production route. This process starts from nuclear data. Their use is mandatory for achieving optimal production yield and radionuclidic purity. The important nuclear data for a radioisotope are: the half life, decay mode, type and energy of the radiation, cross section or yield of the reaction in which the isotope can be produced, the intensity of the possible side reactions.

The aim of our cross section measurements in connection with the isotopes produced routinely for medical use were:
-To complete the data base from reaction threshold up to the available particle energy.
-To solve the disagreements among the data sets measured in different laboratories.
-To set up recommended data base for all the main and side nuclear reactions take place on the investigated target material during bombardment.
- To search for new isotopes that can be used in nuclear medicine.
The results are presented in the publications [A1, A9, A10, A11] and summarised below. The investigated reactions are listed in table 3.

Table 3. Reactions investigated producing medically important radioisotopes

Reaction	Investigated energy range MeV	No. of data points	Reference number
$^{122}Te(d,n)^{123}I$	4.7 - 21.1	20	A10
$^{123}Te(d,2n)^{123}I$	6.1 - 12.5	13	A9
$^{123}Te(d,n)^{124}I$	4.4. - 12.5	14	A9
$^{60}Ni(d,n)^{61}Cu$	2.3 - 20.1	54	A1
$^{22}Ne(p,x)^{22}Na$	5.5 - 17.3	15	A11

^{123}I : We have investigated the $^{122}Te(d,n)^{123}I$ reaction in details and found a 2 MeV energy shift of the data of Zaidi et al. [32]. Regarding the $^{123}Te(d,2n)^{123}I$ reaction we have measured the cross section of the reaction on enriched ^{123}Te for the first time and pointed out that the reaction can not be used for producing clean ^{123}I in disagreement with the conclusion of Pimental et al. [33] who investigated the $^{nat}Te(d,x)$ processes.
^{124}I : The $^{123}Te(d,n)^{124}I$ reaction was measured on enriched ^{123}Te isotope for the first time and was pointed out that the process has low yield therefore not optimal for production purposes but can be used for small quantity production.
^{61}Cu : The cross section of the $^{60}Ni(d,n)^{61}Cu$ reaction was measured in details and on the basis of the calculated yield we have proposed for the first time the most economical production route for ^{61}Cu on enriched ^{60}Ni at small cyclotron.
^{22}Na : The cross section of the $^{22}Ne(p,x)^{22}Na$ reaction was measured in details giving significant contribution to the three experimental data point of Saam et al. [34]. We have pointed out that the above process has the highest yield in the energy range available at small cyclotrons.

4.2.2. Radioisotopes of Iodine

The iodine isotopes are among the radioisotopes most widely used in nuclear medicine. A large number of radiopharmaceuticals labelled with radioiodine $^{123, 125, 131}I$ are known and used in Single Photon Emission Computed Tomography (SPECT). For more quantitative studies involving Positron Emission Tomography (PET) the longer lived ^{124}I ($T_{1/2}$ = 4.15 d) has found some applications and the ^{120g}I ($T_{1/2}$ = 1.35 h) also appears to be very promising.

Both the direct and indirect production routes for production of iodine isotopes were studied at small and medium energy cyclotron. The most important processes are the proton and deuteron induced processes on the isotopes of tellurium. The tellurium has 8 stable isotopes on which several reactions can take place resulting also undesirable impurities at different levels depending on the enrichment of the Te target. To avoid radioisotopic impurities in the final product highly enriched (therefore, very expensive) tellurium target should be used. Knowing the excitation function of all the reactions of proton and deuteron bombardment on tellurium isotopes one can estimate the yield of the main and the side processes and can choose the best production routes, energy window for the available tellurium target material.

In the papers [**A9, A10**] we have investigated the present status of the production data of ^{123}I and ^{124}I isotopes on enriched Te isotopes using deuteron bombardment. We also

studied the production of ^{120g}I and ^{124}I using proton bombardment in [**B2, B9**]. Despite of the several comprehensive paper published on the production of these important iodine isotopes there are still unresolved discrepancies among the presented experimental data [35].

Surveying the model calculations it was found that Shubin and co-workers made comparison of the experimental data with the results generated by different computer codes for deuteron and proton induced reactions on different isotopes of tellurium, antimony and xenon and pointed out the problem of some experimental data sets [36, 37].

4.2.2.1.Production of ^{123}I

The ^{123}I ($T_{1/2}$ = 13.2 h,) radioisotope is of considerable interest for diagnostic nuclear medical studies, therefore, widely used in Single Photon Emission Computed Tomography (SPECT). For production of ^{123}I a large number of production route have been suggested and most of them where investigated in detail [38].

In a survey of experimental data we found no experimental cross section data for the reaction ^{123}Te(d,2n)^{123}I.. Two works were available for the ^{122}Te(d,n)^{123}I reaction measured enriched ^{122}Te and ^{nat}Te targets, which were not in agreement with each other.

We have measured the cross section of the above two reactions using stacked target technique and enriched ^{122}Te and ^{123}Te targets. Thin targets were prepared by electrolytic deposition onto Ti backing and irradiated with deuteron beams up to 21 MeV bombarding energy. The titanium foils served also for monitoring the bombarding beam. The cross section of the ^{122}Te(d,n)^{123}I reaction was measured in 20 points from 4.7 up to 21 MeV to complete the available data. On the basis of the result of our measurement we could conclude that the data given by Zaidi et al. [32] on the reaction of ^{122}Te(d,n)^{123}I, has an energy shift upward of about 2 MeV. It is a significant shift which influences considerably the optimal energy range. We have measured the cross section of the ^{123}Te(d,2n)^{123}I reaction for the first time in 13 point from 6.1 up to 12.5 MeV. The experimental data were spline fitted and the integral thick target yields were calculated and compared with the yields of the other production routes. Due to the proximity of the thresholds of the ^{123}Te(d,2n)^{123}I and ^{123}Te(d,n)^{124}I reactions a simultaneous production of ^{123}I and ^{124}I cannot be avoided. The impurity level of ^{124}I in the ^{123}I is about 2% at EOB and increases with decay time. This would be a serious drawback as far as the use of ^{123}I in humans is concerned. We therefore disagree with the conclusion of Pimental et al. [33] that the ^{123}Te(d,2n)^{123}I process is suitable for “in-house” production of ^{123}I. Since the yield of the ^{122}Te(d,n)^{123}I process is lower than the yield of the ^{123}Te(d,2n)^{123}I reaction production of ^{123}I by deuteron bombardment without the impurity of ^{124}I is possible only via the ^{122}Te(d,n) reaction at a lower production level. Considering the ^{123}Te(p,n) and ^{122}Te(d,n) processes both required highly enriched targets because of the formation of the ^{124}I via ^{124}Te(p,n)^{124}I and ^{123}Te(d,n)^{124}I reactions respectively. The ^{123}Te(p,n) process has higher yield than the yield of the ^{122}Te(d,n) reaction, but the cost of the highly enriched ^{123}Te target significantly higher than the price of the ^{122}Te target [**A10**].

***4.2.2.2.**Production of ^{124}I*

The production of ^{124}I ($T_{1/2}$ = 4.18 d, β^+ = 25 %) has received enhanced attention only in recent years using the relatively high yield proton and deuteron induced reactions on

tellurium isotopes. The ^{124}I has appropriate characteristics for its novel use in certain radiopharmaceuticals that can be utilised at low dose for PET diagnostic evaluation of physiologic functions, and at high dose for radiotherapy [39]. The most common routes for production of ^{124}I are the ^{124}Te(d,2n)^{124}I and ^{124}Te(p,n)^{124}I reactions [35, 40, 41, 42,]. We investigated for the first time the ^{123}Te(d,xn)^{124}I processes from their respective threshold to 12.5 MeV. Thin samples of 85.4 % and 91.0 % enriched ^{123}Te were prepared by electrolytic deposition on Ti and the radioactivity of the produced isotopes was determined via high-resolution HpGe detector gamma-ray spectrometry. The measured data showed that the energy range E_d = 11→6 MeV would be useful for the production of ^{124}I. A yield of 2.8 MBq/μAh can be expected. Due to the proximity of the thresholds of the ^{123}Te(d,n)^{124}I and ^{123}Te(d,2n)^{123}I reactions a simultaneous production of ^{123}I and ^{124}I cannot be avoided. The level of ^{123}I impurity in ^{124}I is therefore high but this is not a serious problem since it decreases rapidly with time. The cross section of the ^{123}Te(d,n)^{124}I reaction was measured in 14 energy points and the thick target yield was calculated from the curve fitted over the experimental points. The yield of the ^{124}I via the ^{123}Te(d,n) reaction is rather low, so that the commonly used ^{124}Te(p,n) and ^{124}Te(d,2n) processes are still to be preferred to use for production of ^{124}I. More detailed discussion of the production of ^{124}I can be found in paper [**A9**].

4.2.3. Production of ^{61}Cu

Copper isotopes are used to produced labelled pharmaceuticals for brain and heart investigations [43]. The production of medically important ^{61}Cu ($T_{1/2}$ = 3.4 h) was investigated via the ^{nat}Ni(d,x) process [**A1**]. In the investigated energy region the main contributing reaction is the ^{60}Ni(d,n)^{61}Cu. The low isotopic abundance of ^{61}Ni (1.13%) and ^{62}Ni (3.59%) in natural nickel explain the negligible low contributions of the ^{61}Ni(d,2n) and ^{62}Ni(d,3n) reactions even far above their thresholds. On the basis of our result the proposed energy range for the production of ^{61}Cu is E_d = 11 → 4 MeV. The expected yield for this energy range amounts to 100 MBq(2.7 mCi)/μAh. The short lived radioactive copper impurities at EOB, produced in a 95 % enriched ^{60}Ni target, are negligible at E_d<11 MeV. The production of ^{60}Cu ($T_{1/2}$ = 23.2 min) starts above 11 MeV through the ^{60}Ni(d,2n)^{60}Cu reaction. The ^{62}Cu ($T_{1/2}$ = 9.74 min) can be formed via the ^{61}Ni(d,n) (Q = 3.6 MeV) and the ^{62}Ni(d,2n) (Q = -6.5 MeV) processes. As longer lived radioactive copper contaminant the ^{64}Cu ($T_{1/2}$ = 12.7 hours) nuclide can only be induced via the ^{64}Ni(d,2n) reaction (Q = -4.7 MeV). Taking into account the low abundance of the isotopes ^{61}Ni, ^{62}Ni and ^{64}Ni in a nickel target with natural isotopic composition, the contamination ratios would be even lower in a highly enriched ^{60}Ni target. Furthermore, as the ^{60}Cu and the ^{62}Cu have short half-lives compared to the half-life of ^{61}Cu, these impurities would not cause any problem. The Ni and Co radioisotopes produced in the target can be removed from the final product by chemical separation.

For comparison of the different production routes of ^{61}Cu we reproduced the expected thick target yield for proton, Helium-3 and alpha particle bombardment on Ni and Co targets in Fig. 10 in [**A1**]. The integral yields as a function of energy were calculated for the ^{61}Ni(p,n)^{61}Cu, ^{58}Ni(α,x)^{61}Cu, ^{58}Ni(^{3}He,x)^{61}Cu, ^{59}Co(α,2n)^{61}Cu and ^{59}Co(^{3}He,n)^{61}Cu reactions. The cross section data of alpha- and ^{3}He-particle induced reactions on Ni were normalised to 100 % enrichment. The presented yield curves show that the ^{62}Ni(p,2n) and ^{61}Ni(p,n) processes lead to the highest production yields. The alpha- and ^{3}He-particle induced

processes on Ni and Co respectively, require higher energy and multi-particle machines and give yields lower than the proton induced reactions. The yield of the $^{60}Ni(d,n)^{61}Cu$ process at 20 MeV is about one tenth of the yield of the (p,n) process and about 8 times lower than the yield of the (p,2n) process, but below 15 MeV it is higher than the yields of all the other except the (p,n) process. During a three-hour irradiation with a 30 μA deuteron beam at 11 MeV, about 9 GBq of ^{61}Cu can be produced.

4.2.4. Production of ^{22}Na

The radioisotope ^{22}Na ($T_{1/2}$ = 2.6 year) find application in many fields. It is widely used for calibration of dose meters, detectors and other nuclear instruments. It is a convenient source for production of "slow" β^+ beams and also seems to be promising for calibration PET cameras. The $^{22}Ne(p,n)^{22}Na$ reaction also important for nuclear astrophysics. It has been applied some biological studies too.
Several routes have been suggested to produce ^{22}Na. These are discussed in more detail in the paper [**A11**] and [**B1**,**B6**] For production of ^{22}Na at a small cyclotron the $^{22}Ne(p,n)^{22}Na$ reaction seems to be very promising. In the literature we found only one single report which described cross sections at three energy points [34], which data were obtained using a long gas target. We decided to perform more detailed measurements using thin gas targets with a view to obtain the excitation function of this reaction from the threshold up to about 17 MeV. Stacked gas cells were irradiated with low intensity (100 - 200 nA) proton beams to minimise the well-known gas density reduction. Five cells were irradiated at three different energies to cover evenly the whole energy region interested. The beam current as well as the energy throughout the target were monitored using 8 μm Cu foils. After a proper cooling time the activity was measured without any prior chemical treatment through the $E\gamma$ = 1275 keV , $I\gamma$ = 100 % gamma-line. The cross section was measured in 15 energy points and a curve was fit to the experimental point using spline method. The integral yield was calculated from the fitted curve which amounts 304 kBq/μAh (8.2 μCi/μAh) over the optimal energy range Ep = 15→6 MeV at EOB assuming 100% enrichment. Comparison of the yields of the different production routes results that the $^{22}Ne(p,n)^{22}Na$ process is very promising and has the highest yield in the energy range available at small cyclotrons using enriched neon target.

4.3. Analytical and industrial applications of charged particle nuclear reactions

In this chapter a short summary is given of the applications of charged particle induced nuclear reactions. We will discuss how the activation technique were applied for measuring very low typically ppm concentrations of trace elements in high purity materials, and to measure low material losses due to wear, corrosion and/or erosion of an irradiated surface, and their relevance to cross section data of charged particle induced reaction.

4.3.1. Charged Particle Activation Analysis (CPAA)

The rapid development of all branches of nuclear science invokes a wide variety of applications of nuclear reactions. The neutron and charged particle activation analysis has become one of the most important methods for elemental analysis. Its extreme sensitivity makes it indispensable in many technical fields requiring material of high purity. It has also been used to analyse many different kind of materials occurring in nature or created by human. The introduction of activation analysis to medical and biological fields has led to the solution of numerous, previously unapproachable problems. The activation analysis has found applications in history, geology, archaeology, criminology and forensic science. Apart from its great sensitivity in determination of trace elements, activation analysis also makes it possible to carry out determinations non-destructively. For this reason, activation analysis is also a routine method in determination of the bulk elements.

Due to the rapid energy loss of a charged particle beam penetrating in a solid target material the volume which can be activated is very small comparing the investigated volume of the neutron activation analysis (NAA). There are two main groups of the analytical techniques: the relative method which requires a series of standards and the absolute or direct method in which the investigated quantity is determined trough the measurement of a basic physical quantity. The advantage of using direct method is laying in the fact that no standards are necessary, therefore, no standard preparation and irradiation is required which are time consuming and expensive process. For charged particle activation there is no possibility for parallel irradiation - as it is for neutron activation - and the uncertainty of the beam current measurement of the standard can introduce systematic error in the final result.

The sensitivity of the method generally depends on the type of matrix material and the type of element is to be determined, therefore, the parameter of a CPAA measurement always need to be optimised. We studied the direct CPAA method in which the concentrations are determined trough known excitation function of the nuclear reactions involved and gave an experimental method [**A14**, **B22, B23**] for the optimisation process of the parameters of a CPAA experiment (selection the type of bombarding particles, the primary bombarding energy, irradiation time, cooling time, measurement time).

Using proton induced nuclear reactions we investigated the trace elements of high purity aluminium [**A14**, **A15, B22**] and determined several trace elements in high purity aluminium from ppb to ppm level.

An important parameter of the high purity substances is the total bulk oxygen content. By tritium and ^{3}He particle irradiations the bulk oxygen content of high purity aluminium and

gallium was determined via the $^{16}O(t,n)^{18}F$ and $^{16}O(^{3}He,p)^{18}F$ reactions [**A15, A16, B22**]. The collected information were used to modify the purification process developed for the production of high purity aluminium and gallium. This technique also suitable to determine the average thickness of oxide layer of the internal granules of a sample made by powder metallurgy from high purity aluminium powdered material [**A15**, **B21**].

The activation method was used to determine the distribution of trace and major elements in glass samples, in the vicinity of certain type of anomalies, such as different inclusions, surface contamination and enrichment or loss of certain components of the glass [**A17**]. The elemental composition of the normal-quality and the different type of anomalies were determined, using charged particle and neutron activation. Two main groups of the anomalies were found: coloured spots on/near the surface caused by enrichment of the elements of the iron group , and stone-like inclusions caused by Zr coming from the furnace wall.

In an other application we demonstrated the capability of the method for testing the anti-wear properties of motor oils trough the change of the concentration of trace elements in the oil as function of running time of the engine [**A18].** The trace element concentration of the investigated oil samples were measured by CPAA method using 12 and 18 MeV proton irradiation.

4.3.2. Thin Layer Activation (TLA) techniques

The Thin Layer Activation (TLA) technique is an excellent tool for studying of very low levels of wear, corrosion or erosion. One can investigate and measure quantitatively the wear of different machine parts, quantify the efficiency of different surface treatment methods applied to modify the surface properties of materials, etc.. When a beam of accelerated charged particles enter into a material, the particles rapidly loose their energy and penetrate to a well defined depth and produce radioactive isotopes. The depth distribution of the activity called calibration curve is used to convert the change of the activity measured into linear or mass loss. There are two techniques in TLA application, namely the thin layer *difference technique* and the *concentration measurement* technique. In the first method, the remaining activity of the irradiated machine part is measured by gamma-spectrometry system. The loss of activity is converted to wear rate using the calibration curves. The sensitivity of this technique depends on the type of applications and typical value of wear rate can be measured is around 1 μm/h.

In the second method, the activity of the removed layer (the wear products) is collected and measured by gamma spectrometry. The activity of the wear products can be collected either in a special oil filter or can be measured in the oil flow itself. This technique allows to monitor more than one wearing areas connected by the oil flow simultaneously. The sensitivity of this technique for the typical cases is around 1nm/h. A comprehensive overview of the TLA technique is given in IAEA-TECDOC-924 [44].

The main advantages of the method are the high sensitivity and the possibility to follow the wear process of any mechanism without dismantling. To get optimal performances the thickness of the produced radioactive layer must be comparable with the expected wear. To plan an experiment and to determine the optimal irradiation conditions the knowledge of the nuclear data (excitation function of the reaction, stopping power of the matrix, etc.) are indispensable.

To produce a calibration curve a special sample (with the same physical and chemical properties as the real sample to be investigated) is needed to be activated. The calibration curve can be produced by subsequent removal of controlled thin layers of the activated surface while measuring the removed and/or remaining activity as well as thickness of the sample. Preparing a detailed calibration curve is very time consuming process and requires special, sometimes sophisticated equipments.

In principle the depth distribution of the produced activity can be determined by calculation. For homogeneous matrix materials with known stopping power regarding the bombarding particles the only limitation to determine the depth distribution of the produced isotope is the knowledge of the excitation function of the reaction involved. The activity profile depends on the shape of the cross section curve and the shape of the energy loss curve of the bombarding particles in the matrix. The later one has linear dependence with the density of the matrix. We have studied and proved, that to calculate the calibration curve for an element having homogeneous distribution in the matrix is possible knowing the excitation function of the reaction in question and the rough composition of the matrix material. In that case a few points of the activity distribution are enough to be measured and then the calculated calibration curve can be fitted over the measured points using the density as the fitting parameter. Knowing the excitation function one can do this fitting because the shape of the energy loss curve is not sensitive for a small change of the composition of the matrix material. This method was tested using the $^{nat}Fe(p,x)^{56}Co$ reaction and we found good agreement between the calibration curves determined by the step-by-step technique and the above described calculation method [**A5**].

We have measured the excitation function of several processes on the widely used construction materials, such as Ti, Fe, Ni and Cu [**A1 - A6**] (see chapter 4.1) improving the available data sets and presenting new reactions which can be used for TLA applications. On the basis of our result the application area of the double activation method (two different type of radioisotope with different gamma radiation having significantly different activity depth distribution) can be extended.

When a very low rate of wear, typically wear in submicron range, is to be investigated a very sallow activation of the surface is required and the implantation technique can be applied to create this suitable thin layer containing radioactive tracers. During nuclear reactions, the newly formed nucleus will be recoiled by transfer of kinetic energy from the incident particle. As a result the nuclei formed near to the surface will be able to escape from the sample. These recoiled and escaped nuclei can be implanted into a surface to be investigated. The maximum implantation depth depends on the reaction in which the nuclei formed, on the bombarding energy and also on the properties of the matrix material and can be between a few micrometer, for light recoiled nuclei like ^{7}Be and low stopping power matrix, and tens to hundreds of nanometers for heavier nuclei and matrices. We have investigated the possibility of recoil implantation of ^{7}Be.

The ^{7}Be radioisotope ($T_{1/2}$ = 53.29 d, $E\gamma$= 477.56 keV, $I\gamma$= 10.3 %) can be produced in several nuclear reactions among them the $^{9}Be(^{3}He,\alpha n)^{7}Be$, $^{nat}B(p,x)^{7}Be$, $^{nat}B(d,x)^{7}Be$ and $^{12}C(^{3}He,2\alpha)^{7}Be$ reactions. Materials containing beryllium boron or carbon as a matrix-component or at least in percentage quantities can be used for wear study by using the above reactions to produce ^{7}Be [**A7,A8**]. The cross section was measured and the yield calculated of the above reactions. Our results were compared with the data available in literature. We gave integral activity values of the ^{7}Be isotopes recoiled into Al samples from the $^{9}Be(^{3}He,\alpha n)^{7}Be$ and $^{12}C(^{3}He,2\alpha)^{7}Be$ reactions.

In table 3 the reactions investigated and tested for TLA applications are summarised. In addition to the list of the reactions in table 3. the charged particle induced reactions on ^{nat}Ti,

^{nat}Fe, ^{nat}Ni and ^{nat}Cu proposed for monitoring purposes also suitable for use in TLA applications as well as for direct charged particle activation, which broadens the groups of the matrix materials and trace elements can be investigated by using the TLA technique and CPAA method.

Table 3. Reactions for which cross section was measured and used in TLA technique.

Reaction	Investigated energy range MeV	No. of data points	Reference number
^{nat}C(^{3}He,x)^{7}Be	10.2 - 27.5	13	A7
^{nat}Be(^{3}He,αn)^{7}Be	4.5 - 27.5	14	A7
^{nat}B(p,x)^{7}Be	2.8 - 16.8	32	A8
^{nat}B(d,x)^{7}Be	1.3 - 9.5	12	A8
^{nat}Fe(p,x)^{56}Co	5.8 - 17.5	17	A5

4.3.3. Other applications

Most of the cosmic particles are protons and deuterons, therefore the cross sections of proton induced reactions on boron, neon and iron can be interesting for theoretical model calculations of the evaluations of stars. Also the ^{3}He induced reactions on light elements are important for the understanding of the energy productions cycles of the stars.

The proton induced reactions on ^{nat}Fe are important for the transmutation experiments since these reactions contribute significantly to the final activity.

5. SUMMARY

The development of all branches of nuclear science, and consequently the developing knowledge of nuclear reactions and their applications, have been very rapid. As the result of this development integral cross section data on large number of charged particle induced reaction are of interest as the function of energy of the incident particles up to about 100 MeV. Several new area had been developed in which charged particle nuclear data are used to gain information on the structure, composition of the investigated material or to modify them. Most of the applied nuclear methods based on the activation technique and require the knowledge of integral cross section data.

A survey of the available nuclear data of the reactions investigated and published using low and medium energy light charged particle beams showed that the status of the data is not satisfactory. Therefore, systematic investigations of charged particle induced nuclear reactions on different materials are in progress in many laboratories for evaluating their potential use in different applications and in basic science.

In this thesis with a view to enhancing our knowledge of the necessary excitation functions we have measured, compiled, critically evaluated the absolute integral cross sections of selected reactions induced by light charged particles important for applications in which our department is engaged. Some application of the cross sections are also discussed.
The thesis contains:

a., description of the experimental technique and the applied methods
b., results of cross section measurements of charged particle induced nuclear reactions
c., method for application of monitor reactions
d., method for calculation of TLA calibration curve,
e., method for optimising the CPAA experiment,
f., investigation of the interaction of high intensity charged particle beams and high pressure gas targets,
g., application of the cross section data for:
monitoring of charged particle beams
production of radioisotopes
analytical applications
thin layer activation.

For measuring the excitation functions of charged particle induced nuclear reactions the activation method and the stacked target technique was used. Solid and gas targets were irradiated made of natural and enriched material. For energy determination of the bombarding particle different methods were used depending on the laboratory where the irradiation was done. Faraday-cup technique was applied to measure the intensity of the bombarding beam and the obtained value was checked via monitor reactions. The activity of the produced radioisotopes was determined by using standard high resolution gamma-spectrometry without any prior chemical treatment. Mean cross section was calculated for each thin layer of the stacked target. Most cases production yield was determined using the measured excitation function. The results were compared with the data available in the literature.

In the frame of this thesis 46 individual excitation functions were measured and numerical data presented for the available energies for proton, deuteron, ^{3}He and alpha particle beams on ^{nat}Be, ^{nat}B, ^{nat}C, ^{nat}Ne, ^{nat}Ti, ^{nat}Fe, ^{nat}Ni, ^{nat}Cu, ^{122}Te and ^{123}Te target materials. In 16 cases we have investigated the reactions for the first time (^{nat}Be+^{3}He, ^{nat}Ni+^{3}He and ^{123}Te+d). We made an important contribution to the experimental cross section

data resolving many considerably high disagreements among the data presented by different authors. We have extended the borders of the investigated energy region and presented more detailed experimental data sets. We revealed systematic errors of the data published by different authors (energy shift of the data, data presented as cumulative data but neglecting the contribution of the isomer state, large differences in the intensity of the reactions, etc.).

In all the investigated processes a comprehensive literature survey was made to compile the available experimental data. In most cases critical evaluation of the data was presented. One of the most frequently used reactions is the $^{nat}Fe(p,x)^{56}Co$, therefore, after compilation and critical evaluation of the available experimental data we presented a recommended data set for the excitation function.

In some cases theoretical calculation was made to check the experimentally established excitation functions. In the calculation the statistical model theory taking into account preequilibrium effect was applied and the STAPRE computer code was used.

We have proposed an improved method for using monitor reactions. A monitor target material having more than one nuclear reaction for a specific bombarding particle with overlapping excitation functions can be used for parallel and independent energy and intensity determination of the bombarding beam. We have proposed the Ti, Fe, Ni and Cu for monitoring purposes, furthermore, these target materials can be used to monitor not only one type but all the four types (p, d, ^{3}He, α) of the light charged particle beams.

We have investigated the method of charged particle activation analysis CPAA and suggested the use of the absolute or direct method to determine concentrations. This direct method can be used provided the excitation functions of the nuclear reactions involved are known. The main advantage of the proposed method is laying in the fact that it requires no preparation and irradiation of special standards. We applied the direct method for determining the concentration of trace elements in high purity aluminium (11 trace elements in ppb and ppm concentration range were determined) The bulk oxygen content of aluminium and gallium was also measured. We have also investigated the elemental distribution of glass samples and gave explanation for the found anomalies in the elemental concentrations. We demonstrated the capability of the method for testing the anti-wear properties of motor oils trough the change of the concentration of trace elements in the oil as function of running time of the engine**.**

We gave an experimental procedure to determine the optimal experimental parameters of the method of charged particle activation analysis to be able to exploit the maximal sensitivity of the method.

Studying the thin layer activation (TLA) technique we proposed a method to calculate the calibration curves on the basis of the excitation function of the reaction in question, the stopping properties of the target material and only a few experimentally determined points of the calibration curve using the target density as fitting parameter. We have measured ultra fine wear of super hard turning tools as an application of the proposed method and the cross section of the $^{nat}B(p,x)^7Be$ and $^{nat}Fe(p,x)^{56}Co$ reactions.

We have studied the interaction of intense charged particle beams with high pressure gas targets, and confirmed the low speed mass transport of the target gas under vertical gravitational field and nonuniform heat production which can explain the observed shape of the beam. We have pointed out that there is a low amplitude oscillation of the beam shape and size during the first few seconds of the interactions. The density variation of the target gas under nonuniform heat production and mass transport as function of time in- and outside of the beam volume gives a possible explanation of the observed effects.

6. ÖSSZEFOGLALÓ

A nukleáris kutatások gyors fejlõdése maga után vonta nukleáris technikán alapuló különbözõ technológiák kialakulását és elterjedését. A legtöbb módszer az aktivációs technikát használja, amely a minta besugárzásán, aktiválásán és a keletkezett aktivitás mérésén alapszik. Az ilyen módszerek alkalmazásához integrális nukleáris adatokra, (hatáskeresztmetszet, reakció hozam) van szükség. Az irodalomban fellelhetõ egyes szerzõk által mért töltött részecske hatáskeresztmetszet adatok sok esetben jelentõsen eltérnek egymástól és számos ellentmondást tartalmaznak vagy hiányosak. Bizonyos reakciókra egyáltalán nincs publikált adat.

Csoportunk a nemzetközi együttmûködésben végzett szisztematikus mérésekkel, a rendelkezésre álló adatok összegyûjtésével és kritikai értékelésével a töltött részecske keltette magreakciók hatáskeresztmeszetének, gerjesztési függvényeinek fenti hiányosságait próbálta pótolni.

A dolgozat egyik motiváló tényezõje az alkalmazásokhoz szükséges új hatáskeresztmetszet adatok meghatározása volt. A másik fõ motiváló tényezõ törekvés a fellelhetõ adatok ellentmondásosságának feloldására és a kísérleti adatok pontosságának és részletességének javítására. Ennek megfelelõen a dolgozat összefoglalja :

a., a töltött részecske keltette magreakciók hatáskeresztmeszet mérésének leggyakrabban hasznát szendvics céltárgy besugárzásán alapuló módszerét,

b., a kiválasztott folyamatok hatáskeresztmetszetének meghatározását,

c., egy módosított eljárást ad a monitor reakciók használatára,

d., egy új módszert javasol a vékonyréteg aktivációs technika kalibrációs görbéjének meghatározására.,

e., kísérleti eljárást ad az aktivációs analitikai mérések paramétereinek optimális megválasztására,

f., vizsgálja a nagy intenzitású töltött részecske nyalábok és nagynyomású gáz céltárgyak kölcsönhatását,

g., példákat ad a mért hatáskeresztmetszet adatok alkalmazására a következõ témakörökben:

- töltött részecske nyaláb monitorizálása
- izotóptermelés
- analitikai alkalmazások
- vékony réteg aktivációs alkalmazások.

Kísérleti berendezések és alkalmazott módszerek

A vizsgált 46 magreakció hatáskeresztmetszetének meghatározását az alkalmazott magfizika területén leggyakrabban aktivációs módszert használtuk szendvics céltárgyakon. A szendvics céltárgy technika lényege, hogy vékony maximum néhány száz keV vastagságú céltárgyakat, általában vékony fóliákat helyezünk egymás után és sugárzunk be, aktiválunk egyszerre. A bombázó nyaláb részecskéi a szendvics céltárgyban fékezõdnek, energiájukat folyamatosan elveszítik ezért a szendvics céltárgy egyes rétegeibe különbözõ energiával lépnek be. Az összetett céltárgy tartalmazhat a céltárgy fóliákon kívül egyéb fóliákat is. Leggyakrabban egy vagy több monitor fóliát, energia elnyelõ fóliákat és a visszalökött magok

megfogására szolgáló fóliákat. A monitor fóliákat a bombázó nyaláb intenzitásának és/vagy energiájának meghatározására, ellenõrzésére használjuk. A monitor fóliában egy adott magreakcióban keltett aktivitás mértékébõl és a reakció ismert hatáskeresztmetszetébõl a bombázó nyaláb intenzitása és/vagy energiája meghatározható. Energia elnyelõ fóliák használatára szükség lehet, ha nagy kezdeti bombázó energiához képest kevés és/vagy vékony céltárgy fóliával rendelkezünk. Ekkor megfelelõ vastagságú energia elnyelõ fóliák elhelyezésével választjuk meg a mérendõ pontok eloszlását a vizsgált energia tartományban. A magreakciókban a keletkezõ új mag jelentõs kinetikus energiára is szert tehet. Így a felület közelében lejátszódó reakciókban keletkezõ magok elhagyhatják a céltárgy fóliát és a szomszédos fóliákba implantálódhatnak, ezzel mindkét fóliában megváltoztatva a mérhetõ aktivitás nagyságát. Ezen folyamat figyelembevételére elfogó fóliákat helyezünk a céltárgy fóliák mögé, Így az aktivitás meghatározásánál korrigálni tudunk a kilökõdött magok aktivitásával.

A besugárzásokat nemzetközi együttmûködések keretében MGC-20E (Debrecen), MGC-20 (Turku), CV-28 (Jülich) és CGR-560 (Brüsszel) típusú ciklotronok segítségével végeztük. A fém fóliákat vákuumban míg a gáz cellákat kihozott nyalábokkal bombáztuk. Az árammérés érdekében a besugárzó kamrák Faraday típusúak voltak, amelyeket elektronszupresszorral láttunk el a másodlagos elektronok hatásának csökkentésére. A gázcellák besugárzása kapcsán vizsgáltuk az intenzív nyalábok és nagynyomású gázok kölcsönhatásait. A besugárzott minták aktivitását standard nagy feloldású HpGe detektoros gammaspektrométerrel mértük. A maximális információ nyerés szempontját figyelembe véve a minták mérési sorrendjét és a detektor-minta távolságot optimalizáltuk. A minták cseréjét és pozicionálását a detektor elõtt egy PC vezérelt léptetõmotoros berendezés kifejlesztésével valósítottuk meg.

A töltött részecske nyalábok és gázcéltárgyak kölcsönhatásának vizsgálatához a szokásos árammérési technikát valamint fotó, film és videó technikákat használtunk.

Eredmények

Monitor reakciók

A töltött részecske nyalábok monitorizálására alkalmas magreakciók rendelkezésre álló adatairól az elmúlt években készült tanulmányok mind azt a következtetést vonták le, hogy pontosságuk általában nem kielégítõ, az adatok ellentmondóak, esetenként jelentõs hibákkal terheltek. A magreakciók gerjesztési függvényeinek valamint a besugárzások monitorizálására alkalmas folyamatok hatáskeresztmetszet adatainak összegyûjtésére, kritikai értékelésére, szükség szerint új mérésekkel való kiegészítésére, amely munkában csoportunk is részt vállal. Ezen szisztematikus mérés sorozat keretében több könnyû töltött részecske nyaláb monitorizálására alkalmas folyamatot vizsgáltuk. A dolgozat keretein belül a következõ folyamatokat vizsgáltuk: ^{nat}Ni(d,x) [**A1**], ^{nat}Ni(^{3}He,x) [**A2**], ^{nat}Ni(α,x) [**A3**], ^{nat}Ti(d,x) [**A4**], ^{nat}Fe(p,n)^{56}Co [**A5**], ^{nat}Cu(d,x) [**A6**], és ^{nat}Fe(d,x) [**A6**]. A fenti folyamatokban összesen 38 egyedi reakciót vizsgáltunk. A vizsgált reakciók többségénél a mérési eredmények alapján az összegyûjtött és értékelt irodalmi adatok közötti ellentmondások egy részét sikerült feloldani. A kísérleti pontokra spline módszerrel görbét illesztettünk és az illesztett hatáskeresztmetszet görbe alapján a reakciók hozamát kiszámoltuk. Összesen 20 reakciót javasoltunk a megvizsgáltak közül proton, deuteron, ^{3}He és alfa töltött részecske nyalábok monitorizálására.

Izotóptermelés

Radioizotópokat és radioizotópokkal jelzett vegyületeket elsõsorban diagnosztikai célból juttatnak be emberi szervezetbe. A szervek, szövetek bedúsítják ezeket az anyagokat amelyeket bomlásukat követõ sugárzásuk alapján képalkotó berendezésekkel (gamma kamera, pozitron emissziós tomográf, stb.) lehet megjeleníteni. A ^{123}I és ^{124}I izotópok orvosi diagnosztikában az egyik leggyakrabban használt ciklotronnal elõállított izotópok közé tartoznak. Leggyakrabban a legegyszerûbb direkt reakciókkal történik az elõállításuk, amelyek közvetlenül a ^{123}I és ^{124}I végmagokra vezetnek. Ugyanakkor a célanyag összetételétõl függõen jelentõs mennyiségû szennyezõ jód izotópok is termelõdhetnek, amelyeket kémiailag nem lehet szétválasztani a termelni kívánt izotóptól. A termelés optimalizálásához ismerni kell a fõ és mellék reakciók hatáskeresztmetszet függvényét, amely alapján a hozamok kiszámolhatók illetve az optimális céltárgy anyag összetétel, bombázó energia illetve céltárgy vastagság meghatározható. Szisztematikusan vizsgáltuk a fenti két izotóp elõállításának módját könnyû töltött részecske magreakciókon keresztül kis és közepes energiájú ciklotronok segítségével. Ezen munka részeként a ^{122}Te(d,n)^{123}I, ^{123}Te(d,2n)^{123}I és a ^{123}Te(d,n)^{124}I reakciók hatáskeresztmetszetét mértük [**A9, A10**]. Méréseink alapján megállapíthattuk, hogy a ^{122}Te(d,n)^{123}I reakcióra közölt két munka közül az egyik jelentõs, 2 MeV energia csúszással rendelkezik, amely a számolt hozam értékeket alapvetõen befolyásolja. A dúsított ^{123}Te céltárgyon pedig elsõként közöltünk kísérleti hatáskeresztmetszet adatokat.

Az orvosi diagnosztikában gyakran használják a réz izotópjait agy és szív vizsgálatokra [43] célokra. Az egyik ilyen izotópja a réznek a $T_{1/2}$ =3.4 óra felezési idejû 61-es tömegszámú. Az irodalomban összesen négy egymásnak ellentmondó munkát találtunk. Méréseink során meghatároztuk a ^{nat}Ni(d,x)^{61}Cu folyamat hatáskeresztmetszetét és megadtuk az optimális termelés bombázó energia tartományát. Vizsgálva a különbözõ elõállítási lehetõségeket megállapítható volt, hogy a ^{61}Cu elõállítása deuteron bombázással 15 MeV alatti energiákon igen kedvezõ. Rámutattunk, hogy csak a ^{61}Ni(p,n) folyamat rendelkezik nagyobb hozammal ebben az energia tartományban, Így a ^{nat}Ni(d,x)^{61}Cu folyamat jelentõs alternatív termelési eljárás lehet a ^{61}Cu elõállítására.

A ^{22}Na izotóp széles körben használt detektorok, dózismérõk hitelesítésére. Biológiai alkalmazások mellett javasolták PET kamerák hitelesítésére is. A ^{22}Ne(p,x)^{22}Na a nukleáris asztrofizikában is egy fontos reakció. A reakció hatáskeresztmetszetére összesen három mérési pont volt található amit hosszú gázcéltárgyon mértek. Méréseinkben 17 MeV proton energiáig vizsgáltuk a reakció hatáskeresztmetszetét szendvics gázcéltárgyat használva [**A11**]. A mért hatáskeresztmetszet pontokra illesztett görbe alapján számolt hozamról megállapítottuk, hogy a ^{22}Na elõállítására szolgáló különbözõ termelési módok közül a ^{22}Ne(p,x)^{22}Na folyamatnak van a legnagyobb hozama a vizsgált energia tartományban.

Aktivációs alkalmazások

A könnyû töltött részecske magreakciók egyik gyakorlati alkalmazása az töltött részecske aktivációs analízis. A módszer lényege abban áll, hogy a vizsgálni kívánt mintát töltött részecske nyalábbal besugározzuk, abban a mintát alkotó különbözõ elemeken lejátszódó magreakciókban radioaktív izotópok jönnek létre, amelyek a sugárzásukon keresztül azonosíthatok, a sugárzás intenzitásának mérésével pedig mennyiségük

meghatározható. A minta összetétele a kapott információ alapján két fõ módon határozható meg. Relatív vagy abszolút módszerrel. A relatív módszer alkalmazása során a mintához hasonló összetételû standard használata szükséges. Az abszolút vagy direkt módszer alkalmazásakor a mintában lejátszódó egyes magreakciók hatáskeresztmetszetét ismerve a mért aktivitások alapján a minta összetétele számolható. Ez utóbbi módszer alkalmazásához pontosan meghatározott töltött részecske magreakció hatáskeresztmetszet adatok szükségesek. Javasoltuk a direkt módszer alkalmazását és egyben vizsgáltuk és kísérleti módszert adtuk a besugárzási és mérési paraméterek optimális meghatározására amely paraméterek alkalmazása esetén maximális érzékenység érhetõ el.

A direkt módszer alkalmazásával vizsgáltuk nagy tisztaságú alumínium nyomszennyezõit [**A14, A15, A16, B22**]. Zónás olvasztással tisztított 6N (99.9999%) tisztaságú alumínium mintákban 11 különbözõ szennyezõt határoztunk meg 3.0 ppb és 4.4 ppm koncentráció tartományban. Külön foglalkoztunk a tisztított alumínium és gallium minták térfogati oxigén tartalmának meghatározásával [**A15, A16, B22**]. Az aktivációs módszer segítségével üveg minták térfogati és felületi hibahelyeit vizsgáltuk [**A17**] és megállapítottuk a hibák keletkezésének valószínû okait. Egy másik munkánkban bemutattuk az aktivációs módszer alkalmazhatóságát motorolajok kenõképességének vizsgálatára [**A18**], mérve az olajok az olajszûrõk által el nem távolított fém szennyezõinek koncentrációját.

A vékonyréteg aktivációs technika felületek kopásának, korróziójának vagy eróziójának mérésére alkalmas módszer. Lényege a következõ: A vizsgálni kívánt felületet töltött részecske besugárzással aktiváljuk. Ismerve a keltett aktivitás mélység eloszlását a mintában az aktivitás változás méréséből a felület anyagvesztesége, kopása korróziója vagy eróziója meghatározható. Ismerve a minta összetételét megfelelõ bombázó részecske, besugárzási energia és geometria választása esetén a kívánt aktivitáseloszlás elõállítható a mintában. A felületek jelzésére alkalmas radioaktív izotópok közül vizsgáltuk a ^{7}Be és ^{56}Co izotópok elõállítására szolgáló néhány reakciót. A ^{7}Be ($T_{1/2}$ = 53.29 nap) izotóp elõállítását a ^{9}Be(^{3}He,αn), ^{10}B(p.α), ^{11}B(p,αn) és a ^{12}C(^{3}He,2α) reakciókban vizsgáltuk [**A7, A8**] és meghatároztuk a folyamatok hatáskersztmetszetét és hozamát. A kapott eredmények alapján a vékonyréteg aktivációs módszer érzékenységét vizsgáltuk bór tartalmú, nagy keménységû forgácsolószerszámok élkopásán keresztül a besugárzási geometria függvényében [**A13**]. A leggyakrabban használt szerkezeti anyag az acél aminek a fõ komponense a vas, ezért vizsgáltuk a ^{nat}Fe(p,x)^{56}Co folyamat gerjesztési függvényét. Az összegyûjtött irodalmi adatok kritikai analízise után a mérési pontok hibáival súlyozott a kísérleti hatáskeresztmetszet pontokra függvényt illesztettük. Az így kapott ajánlott adat sort összehasonlítottuk kísérleti úton meghatározott a vékonyréteg aktivációs módszer során használt hitelesítõ görbékkel. Kidolgoztunk egy egyszerûsített eljárást a hitelesítõ görbék meghatározására, melynek lényege, hogy pontosan ismert gerjesztési függvény esetén a hitelesítõ görbe néhány kísérletileg meghatározott pontra történõ illesztéssel számolható, ahol a sûrûség az illesztési paraméter [**A5**].

A dolgozat témájához kapcsolódóan 46 egyedi töltött részecske indukált magreakció hatáskeresztmetszetét mértük meg a rendelkezésre álló energia tartományban proton, deuteron, helium-3 és alfa részecske nyalábokat használva ^{nat}Be, ^{nat}B, ^{nat}C, ^{nat}Ne, ^{nat}Ti, ^{nat}Fe,^{nat}Ni, ^{nat}Cu, ^{122}Te és ^{123}Te céltárgyakon nyaláb monitorizálás, izotóptermelés és aktivációs alkalmazások céljára. Közülük 16 esetben elsõként publikálva a reakciók gerjesztési függvényét (^{nat}Be+^{3}He, ^{nat}Ni+^{3}He és ^{123}Te+d). Az eredményeink jelentõsen hozzájárultak az egyes reakciókra mért adatok ellentmondásosságának feloldásához,

pontosításához. Számos esetben kiterjesztettük a gerjesztési függvények mérési tartományát és részletes kísérleti adatokat adtunk a vizsgált energia tartományban.

Minden vizsgált folyamat esetében összegyûjtöttük a más szerzõk által publikált adatokat azokat elemeztük és kiszûrtük a szisztematikus hibával terhelt adatsorokat (energia skála eltolódása a helytelen kezdeti energia meghatározása miatt, total hatáskeresztmetszet adatok amelyek nem tartalmazták az izomer állapot bomlásából származó járulékot, többszörösen eltérõ nagyságú hatáskeresztmetszet adatok, stb.).

Külön vizsgáltuk az egyik leggyakrabban használt szerkezeti anyag az acél fõ komponensén, a vason lejátszódó $^{nat}Fe(p,x)^{56}Co$ reakciót. Az adatok teljeskörû összegyûjtése és elemzése után egy ajánlott átlagolt adatsort számoltuk a kiválasztott kísérleti adatok alapján. Az egyes mérések adataira a kísérletipontok hibáival súlyozva spline módszerrel folytonos görbét illesztettünk, majd az illesztett görbéket súlyozottan átlagoltuk.

Néhány esetben a kísérletileg meghatározott adatsort elméleti számolással is ellenõriztük. A számolásban a STAPRE programcsomagot és a statisztikus modell elméletet használtuk figyelembe véve a közbensõmag egyensúlyi állapota elõtti részecske emissziót.

Javasoltunk egy eljárást több monitorreakció egyidejû használatára. Olyan monitor céltárgy alkalmazása esetén amelyen több reakciócsatorna is nyitva, és a reakciók küszöbenergiája eléggé különböznek egymástól, - ezért a gerjesztési függvényeik átfednek - lehetõség van a bombázó nyaláb intenzitásának és energiájának egyidejû de egymástól független meghatározására kettõ vagy több monitor reakció használatával. Méréseink alapján megállapíthattuk, hogy a Ti, Fe, Ni és Cu anyagok rendelkeznek a fenti feltételekkel és alkalmasak monitorizálási célokra mind a négy könnyû bombázó részecske nyaláb esetében (p, d, ^{3}He és α).

A töltött részecske hatáskeresztmetszet adatok alkalmazásai között vizsgáltuk a töltött részecske aktivációs analízis (CPAA) módszerét és javasoltuk a direkt módszer alkalmazását. A direkt módszer alkalmazása során a vizsgált elem mennyiségét a reakció gerjesztési függvényének ismeretében a mért aktivitás alapján határozzuk meg. Elkerülve ezzel hitelesítõ standard minták készítését besugárzását és aktivitásának mérését. Vizsgáltuk a módszer érzékenységi határának és a besugárzási valamint a mérési paraméterek összefüggését és kísérleti eljárást adtunk a töltött részecske aktivációs analízis optimális paramétereinek meghatározására. Alkalmazva a módszert nagy tisztaságú alumínium nyomszennyezõinek koncentrációját határoztuk meg (11 elem ppb és ppm koncentráció tartományban). Alumínium és gallium minták térfogati oxigéntartalmát mértük trícium és hélium-3 nyalábokkal végzett aktiválással. Vizsgáltuk üveg minták hibahelyeit és megállapítottuk a tapasztalt koncentráció anomáliák eredetét. Demonstráltuk az aktivációs módszer alkalmazhatóságát motor olajok kenõképességének vizsgálatára meghatározva a szerkezet kopásával kapcsolatos elemek az olajban felhalmozódó, vagy az adalék anyagok csökkenõ mennyiségét.

A vékonyréteg aktivációs technika alkalmazásához kapcsolódóan egy új módszert javasoltunk a kalibrációs görbe meghatározására. A módszer lényege, hogy néhány kísérletileg meghatározott pontra az alkalmazott töltött részecske folyamat gerjesztési függvényének ismeretében a kalibrációs görbe illeszthetõ még abban az esetben is ha a mátrix pontos összetétele nem ismert. Az illesztési paraméter a mátrix süsüsége. Szuperkemény forgácsoló szerszámok élkopásának vizsgálatán keresztül igazoltuk a fenti módszer használhatóságát $^{nat}B(p,x)^7Be$ és $^{nat}Fe(p,x)^{56}Co$ reakciók hatáskeresztmetszet adatait használva.

Vizsgáltuk intenzív töltött részecske nyalábok és nagynyomású gáz céltárgyak kölcsönhatását. Megerõsítettük a korábban tapasztalt gázkiritkulás jelenséget és elsõként vizsgáltuk a töltött részecske nyalábok és gázcéltárgyak kölcsönhatásának kezdeti idõszakában tapasztalható tranziens jelenséget. A jelenségre kvalitatív leírást adtunk.

7. ACKNOWLEDGEMENT

It is my pleasure to express my gratitude to all the people who helped me during my studies of charged particle induced nuclear reactions.

I wish to express my sincere gratitude to my promotor Dr. Ferenc Tárkányi, head of the Cyclotron Application Department, Institute of Nuclear Research of the Hungarian Academy of Sciences, (ATOMKI) to guide me to this field. His active support has been of the utmost importance for the progress of my work. I also thank him for the constructive criticism during the preparation of this manuscript.

I direct my thanks to my co-authors who's collaboration in various parts of the study has been necessary for the progress of the work. I also thank the help I received from my colleagues and friends.

I am very grateful to Dr. S. M. Qaim and Dr. A. Hermanne for their valuable help and comments .

I am much indebted to the technical staff of the Cyclotron Laboratories at ATOMKI, Debrecen, Åbo Akademi, Turku, KFA, Jülich and VUB, Brussels for their help I received throughout the years of the experimental part of this work.

This work was done partly in the co-operations Finnish-Hungarian, German-Hungarian and Belgian-Hungarian, supported by the Hungarian Academy of Sciences and National Committee for Technical Development and also partly was financially supported by the International Atomic Energy Agency, which possibilities and supports are gratefully acknowledged.

8. LIST OF PUBLICATIONS

8.1. Main publications A1-A18

Papers on which this thesis is based and are referred to in the text by **A1** to **A18**.

A1. **S. Takács**, M. Sonck, A. Azzam, A. Hermanne, F. Tárkányi
Activation cross section measurements of deuteron induced reactions of ^{nat}Ni with special reference to beam monitoring and production of ^{61}Cu for medical purpose
Radiochimica Acta **76** (1997) 15

A2. **S. Takács,** F. Tárkányi, A. Fessler, Z.B. Alfassi, S.M. Qaim
Excitation functions of ^{3}He-particle induced nuclear reactions on natural Ni with special reference to the monitoring of beam energy and intensity
Applied Radiation and Isotopes **46** (1995) 249

A3. **S. Takács,** F. Tárkányi, Z. Kovács
Excitation function of alpha-particle induced nuclear reactions on natural nickel
Nuclear Instruments and Methods **B113** (1996) 424

A4. **S. Takács**, M. Sonck, B. Scholten, A. Hermanne, F. Tárkányi
Excitation function of deuteron induced nuclear reactions on ^{nat}Ti up to 20 MeV for monitoring deuteron beams
Applied Radiation and Isotopes **48** (1997) 657

A5. **S. Takács,** L. Vasváry, F. Tárkányi
Remeasurement and compilation of excitation functions of proton induced reactions on iron for activation techniques
Nuclear Instruments and Methods in Physics Research **B89** (1994) 88

A6. **S. Takács,** F. Tárkányi, M. Sonck, A. Hermanne, S. Sudár
Study of deuteron induced reactions on natural iron and copper and their use for monitoring beam parameters and for thin layer activation technique
Proc. of 14th Int. Conf. on Applications of Accelerators in Research and Industry, Denton, Texas, 1996, p. 659.

A7. F. Ditrói, **S. Takács,** F. Tárkányi, I. Mahunka
Study of the ^{nat}C(^{3}He,2α)^{7}Be and ^{9}Be(^{3}He,αn)^{7}Be nuclear reactions and their applications for wear measurements
Nuclear Instruments and Methods **B103** (1995) 412

A8. F. Ditrói, **S. Takács,** F. Tárkányi, A. Fenyvesi, J. Bergman, S.-J. Heselius, O. Solin
Investigation of the charged particle nuclear reactions on natural boron for the purposes of the thin layer activation (TLA)
Nuclear Instruments and Methods **B103** (1995) 389

A9. B. Scholten, **S. Takács,** Z. Kovács, F. Tárkányi, S.M. Qaim
Excitation functions of deuteron induced reactions on ^{123}Te: relevance to the production of ^{123}I and ^{124}I at low and medium sized cyclotrons
Applied Radiation and Isotopes **48** (1997) 267

A10. **S. Takács**, A. Azzam, M. Sonck, F. Szelecsényi, A. Hermanne, F. Tárkányi
Excitation function of ^{122}Te(d,n)^{123}I nuclear reaction: Production of ^{123}I at low energy cyclotron
Accepted for publication in Applied Radiation and Isotopes

A11. **S. Takács,** F. Tárkányi, S.M. Qaim
Excitation function of ^{22}Ne(p,n)^{22}Na reaction: possibility of production of ^{22}Na at a small cyclotron
Applied Radiation and Isotopes **47** (1996) 303

A12. F. Tárkányi, **S. Takács,** S.-J. Heselius, O. Solin, J. Bergman
Static and dynamic effects in gas targets used for medical isotope production.
Nuclear Instruments and Methods A. (in print)

A13. L. Vasváry, F. Ditrói, **S. Takács,** Z. Szabó, J. Szûcs, J. Kundrák, I. Mahunka
Wear measurement of the cutting edge of superhard turning tools using TLA technique
Nuclear Instruments and Methods in Physics Research **B85** (1994) 255

A14. **S. Takács,** F. Ditrói, I. Mahunka
Trace element analysis by using the direct CPAA method
Nuclear Instruments and Methods in Physics Research **B10** (1985) 1051

A15. **S. Takács,** F. Ditrói, I. Mahunka
Investigation of aluminium made by powder metallurgy by using CPAA method
Nuclear Instruments and Methods in Physics Research **B43** (1989) 99

A16. F. Ditrói, **S. Takács,** I. Mahunka, P. Mikecz, Gy. Tóth
Determination of oxygen in high purity gallium by using charged particle activation analysis
Nuclear Instruments and Methods in Physics Research **B68** (1992) 166

A17. F. Ditrói, **S. Takács,** I. Mahunka, Z. Gémesi
Trace element study of glass samples by using activation methods
Nuclear Instruments and Methods in Physics Research **B50** (1990) 62

A18. F. Ditrói, I. Mahunka, **S. Takács,** S.A.H. Seif El-Nasr,
Trace element analysis of motor oil by CPAA method on external proton beam
Journal of Radioanalytical and Nuclear Chemistry, Articles **130** (1989) 263

8.2. Related publications B1 - B23

Papers published in referred international journals and/or conference proceedings are referred to in the text by **B1** to **B23**.

B1. A. Fenyvesi, S. Merchel, S. Takács, F. Szelecsényi, F. Tárkányi and S. M. Qaim
Excitation Functions of $^{nat}Ne(\ ^{3}He,x)^{22,24}Na$ and $^{nat}Ne(\alpha,x)^{22,24}Na$ Processes: Investigation of Production of ^{22}Na and ^{24}Na at a Medium-Sized Cyclotron
Accepted for publication in Radiochimica Acta (1997)

B2. B. Scholten, A. Hohn, **S. Takács**, Z. Kovács, F. Tárkányi, S.M. Qaim
Cross section measurements relevant to the production of medically interesting positron emitting radioisotopes ^{120g}I and ^{124}I
(Book of Abst.ENEA-ICTP, 1997, p.288) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B3. A. Hermanne, M. Sonck, **S. Takács**, F. Szelecsényi, J. Van hoyweghen, F. Tárkányi
Influence of secondary neutrons on cross section determination of proton and deuteron induced reactions on ^{nat}Ni targets
(Book of Abst.ENEA-ICTP, 1997, p.199) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B4. M. Sonck, **S. Takács,** F. Szelecsényi, A. Hermanne, F. Tárkányi
Excitation functions of deuteron induced nuclear reactions on ^{nat}Mo from threshold to 21 MeV: an alternative route for the production of $^{94m,\ 99m}Tc$ and ^{99}Mo
(Book of Abst.ENEA-ICTP, 1997, p.279) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B5. F. Szelecsényi, **S. Takács**, A. Fenyvesi, Z. Szûcs, F. Tárkányi, S.-J. Heselius, J. Bergman, T.E. Boothe
Study of the $^{197}Au(p,pn)\ ^{196m1,m2}Au$ and $^{197}Au(p,pn)^{197m}Hg$ reactions and their application for proton beam monitoring in radioisotope production
(Book of Abst.ENEA-ICTP, 1997, p.250) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B6. A. Fenyvesi, **S. Takács**, G. Petõ, F. Tárkányi, T. Molnár, S. Merchel, S.M. Qaim
Excitation functions of charged particle induced reactions on neon: relevance to the production of $^{22,24}Na$ and ^{18}F
(Book of Abst.ENEA-ICTP, 1997, p.285) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B7. M. Sonck, A. Hermanne, F, Szelecsényi, **S. Takács**, F. Tárkányi

Study of the $^{nat}Ni(p,x)^{57}Ni$ process up to 44 MeV for monitor purposes
Accepted for publication in Appl. Radiat. Isot. 1997

B8. F. Szelecsényi, T.E. Boote, S. Takács, E. Tavano, F. Tárkányi,
Evaluated cross section and thick target yield data bases of Zn+p precesses for practical applications,
Appl. Radiat. Isot. 48 (1977) accepted for publication

B9. F. Tárkányi, S. Takács, Z. Kovács, L. Andó
Production of ^{124}I for positron emission tomograph
Turun Yliopiston Julkaisuja - Annales Universitatis Turkuensis,
Sarja - Ser.D., Osa - Tom.185, Medica - Odontologica (1995) 31

B10. F. Szelecsényi, T.E. Boothe, E. Tavano, A. Fenyvesi, **S. Takács,** F. Tárkányi
(p,xn) and (p,pn) processes on ^{197}Au: new proton monitor reactions up to 30MeV
Proceedings of Sixth Workshop on Targetry and Target Chemistry. Vancouver B.C. Canada, August 17-19,1995. Eds:J.M.Link, T.J.Ruth. Vancouver, Triumf, Publ. Office, (1996) 125

B11. A. Fenyvesi, F. Tárkányi, F. Szelecsényi, **S. Takács,** Z. Szûcs, T. Molnár, S. Sudár
Excitation function and thick target yield of the $^{40}Ar(\alpha, p)^{43}K$ reaction: Production of ^{43}K
Applied Radiation and Isotopes **46** (1995) 1413

B12. F. Szelecsényi, T.E. Boothe, **S. Takács,** F. Tárkányi, E. Tavano, M. Plitnikas,
Nuclear data relevant to the production of ^{67}Ga: A critical comparison of excitation functions/thick target yield data $^{67}Zn(p,2n)$ nuclear reactions
Proceedings of the Fifth International Workshop on Targetry and Target Chemistry. Upton, September 19 to 23, 1993. Eds:J.Robert Dahl et al. Upten, BNL (1994) 234

B13. F. Tárkányi, **S. Takács,** S.-J. Heselius, O. Solin, J. Bergman
Study of static and dynamic effects in gas targets
Proceedings of the Fifth International Workshop on Targetry and Target Chemistry. Upton, September 19 to 23, 1993. Eds:J.Robert Dahl et al. Upten, BNL (1994) 48

B14. F. Szelecsényi, T.E. Boothe, E. Tavano, M. Plitnikas, Y. Feijoo,
S. Takács, F. Tárkányi, Z. Szûcs
New cross section data for $^{66,67,68}Zn+p$ reactions up to 26 MeV
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 393

B15. F. Ditrói, A. Fenyvesi, **S. Takács,** F. Tárkányi, J. Bergman, S-J. Heselius, O. Solin
Measurement of excitation function of $^{nat}B(p,x)^{7}Be$ nuclear reaction
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 383

B16. F. Szelecsényi, T.E. Boothe, E. Tavano, M. Plitnikas, Y. Feijoo,

S. Takács, T. Molnár, F. Tárkányi
Compilation and evaluation of cross sections thick target yields for ^{111}In production
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 1042

B17. A. Fenyvesi, F. Tárkányi, F. Szelecsényi, **S. Takács,** Z. Szûcs, T. Molnár, S. Sudár
Measurement of excitation function and thick target yield of the $^{40}Ar(\alpha,p)^{43}K$ reaction
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 406

B18. F. Tárkányi, F. Szelecsényi, **S. Takács**
Determination of effective bombarding energies and fluxes using improved stacked foil technique
Acta Radiologica. Supplementum **376** (1991) 72

B19. I. Gál, **S. Takács,** F. Tárkányi, L. Andó.
Beam splitting for parallel isotope production
Acta Radiologica. Supplementum **376** (1991) 73

B20. **S. Takács,** F. Ditrói, M. Pankotai, P. Fodor
Microelemental measurement of tomato plants by using PIXE and ICP methods
Nuclear Instruments and Methods in Physics Research **B49** (1990) 195

B21. **S. Takács,** F. Ditrói, I. Mahunka
Measurement of oxide-layer thickness of internal granules in high-purity aluminium
Acta Physica Hungarica **65** (1989) 355

B22. **S. Takács,**
Trace element analysis of high purity aluminium by charged particle activation analysis
University doctorate thesis, KLTE, Debrecen, 1985

B23. I. Mahunka, **S. Takács,** J. Dahlbacka,
Search for optimum parameters of CPAA measurements.
Proc. of 3rd Meeting on Nucl. Anal. Methods, Dresden, GDR, 11-15 April, 1983 (1983) 337

9. REFERENCES

1 P. Kruger
Principles of activation analysis,
John Wiley and Sons, New York, 1971

2 T.W. Conlon,
Thin layer activation for materials analysis
Atom, **287** (1980) 233

3 O. Schwerer, K. Okomoto,
Status report on cross-section of monitor reactions for radioisotope production,
INDC(NDS)-218/GZ+, IAEA, Vienna, 1989

4 K. Okomoto,
Data requirements for medical radioisotope production
Proc. of the IAEA consultant's meeting, Tokyo, Japan, 20 - 24 April 1987.

5 H.H.K. Tang, J.L. Romero
Hadron-induced reactions: From basic research to new technological applications
Proc. of 14th Int. Conf. on Applications of Accelerators in Research and Industry, Denton, Texas, 1996, p. 325.

6 H-T. Janka, E.Müller :
The first second of a Type II. Supernova: convection, accretion and shock propagation.
Astrophysical Journal **448**:L109-L113 (1995)

7 I. Iben Jr.:
Planetary nebulae and their central stars - origin and evolution.
Physics Reports **250**, pp. 1-94 (1995).

8 S.M. Qaim
Nuclear data relevant to cyclotron produced short-lived medical radioisotopes
Radiochimica Acta **30** (1982) 147

9 R.Nowotny, M. Uhl, *Calculation of excitation functions for charged particle induced reactions In the Handbook on nuclear data,*
Technical reports series No 273, IAEA,Vienna,1987, pp 441-477.

10 F. Tárkányi, P. Oblozinsky,
Development of reference charged particle cross section data base for medical radioisotope production,
Proc. of Int. Conf. on Nuclear Data for Science and Technology, May 19-24, 1997, Trieste, Italy (vill be published)

11 F. Szelecsényi, T.E. Boothe, E. Tavano, M. Plitnikas, Y. Feijoo, S. Takács, T. Molnár, F. Tárkányi,
Compilation and evaluation of cross sections thick target yields for ^{111}In production
Proc. of Int. Conf. on Nuclear Data for Science and Technology,
Gatlinburg, TN, USA, 9-13 May 1994, p. 1042

12 N. Bhor:
Neutron capture and nuclear constitution.
Nature **137** (1936) 344

13 H. Vonach, R.C. Haight, G. Winkler,
(α,n) and total α-reaction cross sections for ^{48}Ti and ^{51}V
Phys. Rev. **C28** (1983) 2278

14 M. Bonardi,
The contribution of nuclear data for biomedical radioisotope production from the Milan Cyclotron Laboratory
15 G. Deconninck :
Introduction to radioanalytical physics. Nuclear Method Monographs 1,
Akadémiai Kiadó, Budapest, 1978.
16 Z. Kormány, *A new method and apparatus for measuring the mean energy of cyclotron beams,* Nucl. Instr. Methods, **A337**, (1994) 258
17 M. Sonck, J.Van hoyweghen and a. Hermanne, *Determination of the external beam energy of a variable energy multiparticle cyclotron,*
J. Appl. Radiat. Isot., **47** (1996) 445.
18 H.H. Andersen and J.F. Ziegler, *The Stopping and Ranges of Ions in Matter, Vol. 3: Hydrogen Stopping Power and Ranges in All Elements,*
Pergamon Press, 1977.
19 J.F. Ziegler, *The Stopping and Ranges of Ions in Matter, Vol. 4: Helium Stopping Power and Ranges in All Elements,* Pergamon Press, 1977.
20 S-J. Heselius, P. Lindblom, O. Solin,
Optical studies of the influence of an intense ion beam on high-pressure gas target
Appl. Radiat. Isot. **33** (1982) 653
In Proc. of the IAEA consultant's meeting on Data requirements for medical Radioisotope Production, Tokyo, Japan, 20-24 April 1987,
INDC(NDS)-195/GZ, edited by K. Okomoto, IAEA, Vienna, 1988, p.98
21 O. Solin,
Interaction of high energy charged particles with gases,
Academic dissertation, Åbo Akademi, Turku, Finland, 1988
22 S-j. Heselius, P. Lindblom, O. Solin,
Optical studies of the Influence of an intense ion beam on high-pressure gas targets
Appl. Radiat. Isot., **33** (1982) 653
23 F. Tárkányi, S.M. Qaim, G. Stöcklin
Excitation functions of ^{3}He-and α-particle induced nuclear reactions on natural krypton: production of ^{82}Sr at a compact cyclotron
Appl. Radiat. Isot., **39** (1988) 135
24 F. Tárkányi, Z. Kovács, I. Mahunka, O. Solin, J. Bergman
Measurement of the $^{35}(\alpha,n)^{38}$K excitation function using chlorine gas target.
Radiochim. Acta, **54** (1991) 165
25 P.Strehl
Ion Beam Diagnosis, GSI-94-27,preprint April 1994, Darmstadt, Germany
26 O. Schwerer, K. Okomoto
Status report on cross sections of monitor reactions for radioisotope production,
In: IAEA-Report INDC(NDS)-218/GZ, Vienna, Austria, 1989
27 A. Hashizume,
Monitor reactions for the production of radioisotopes for medical use,
Proc. of IAEA Consultant's Meeting on Data Requirements for Medical Radioisotope Production, Tokyo, Japan 20-24 April, 1987, Ed. K. Okomoto, IAEA, Vienna, 1988, p.44
28 *Summary Report of the First Research Co-ordination Meeting on " Development of Reference Charged Particle Cross Section Data base for Medical Radioisotope Production*" Vienna, 15-17 Nov. 1995. ed. by P. Oblozinsky.

29 P. Kopecky, F. Szelecsényi, T. Molnár, P. Mikecz, F. Tárkányi
Excitation function of proton induced reactions on ^{nat}Ti used for monitoring bombarding beams,
Proc. of 6th Symp. on Medical Appl. of Cyclotrons, June 1 - 4, 1992, Turku, Finland, Ed. L.M. Voipio-Pulkki, U. Wegelius, (1992) p.23.

30 F. Tárkányi, F. Szelecsényi, P. Kopecky,
Cross section data for proton, ^{3}He- and α-particle induced reactions on ^{nat}Ni, ^{nat}Cu and ^{nat}Ti for monitoring beam performance
Proc. of Int. Conf. on Nuclear Data for Science and Technology,
Jülich, Germany, 13 -17 May 1991,
Ed. S.M. Qaim, Sringer-Verlag, Berlin, (1992), p.529

31 F. Tárkányi, F. Szelecsényi, P. Kopecky,
Excitation Function of Proton Induced Nuclear Reactions on Natural Nickel for Monitoring Beam Energy and Intensity,
Appl. Radiat. Isot., **42** (1991) 513

32 J. H. Zaidi, S.M. Qaim, G. Stöcklin,
Excitation functions of deuteron induced nuclear reactions on natural tellurium and enriched ^{122}Te: production of ^{123}I via the ^{122}Te(d,n)^{123}I process.
Appl. Radiat. Isot. **34** (1983) 1425

33 G. Piemental and G.J. Beyer,
Determination of excitation functions for (d,xn) reactions on natural tellurium.
Isotopenpraxis **24**(1988)369

34 B. Saam, M. Skalsey J. Van House,
Measuremet of the cross section ^{22}Ne(p,n)^{22}Na.
Phys. Rev. **40** (1989) R1563

35 B. Scholten, Z. Kovács, F. Tárkányi, S.M. Qaim,
Excitation functions of ^{124}Te(p,xn)^{123,124}I reactions from 6 to 31 MeV with special reference to the production of 124 I at small cyclotron.
Appl. radiat. Isot. **46** (1995) 255

36 N. V. Kurenkov, V. P. Lunev, V. S. Masterov, Yu. N. Shubin,
Excitation function for the formation of neutron deficient nuclei ^{123}I, ^{123}Xe and ^{123}Cs. Calculated and experimental data
Appl. Radiat. Isot. **28** (1993) 395

37 Yu. N. Shubin, P. Lunev,
Nuclear model calculations applied to medical radioisotope production.
Submitted to the First Research Coordination Meeting on "Development of Reference Charged Particle Cross Section Data Base for Medical Radioisotope Production", IAEA, Vienna, Austria, Nov. 15 - 17, 1995. (not published)

38 S.M. Qaim,
Recent developments in the production of ^{18}F, ^{75,76,77}Br and ^{123}I,
Appl. Radiat Isot., **37** (1986) 803

39 R.M. Lambrecht, M. Sajjad, M.A. Qureshi, S.J. Al-Yanbawi,
Production of Iodine-124
Radioanal. Nucl. Chem., Letters **127** (1988) 143.

40 H. L. Sharma, J. Zweit, S. Downey, A.M. Smith, A.G. Smith,
Production of ^{124}I for positron emission tomography
J. Lab. Compd. Radiopharm. **26** (1988) 165

41 R.M. Lambrecht, M. Sajjad, M.A. Qureshi, S.J. Al-Yanbawi,

Production of ^{124}I
J. Radioanalyt. Nucl. Chem **127** (1988) 143

42 M.L. Firouzbakht, D.J. Schlyer, .D. Finn, G. Laguzzi, A.P. Wolf,
Iodine-124 production: excitation functions for the $^{124}Te(d,2n)^{124}I$ and $^{124}Te(d,3n)^{123}I$ reactions from 7 to 24 MeV.
Nucl. Instr. Methods **B79** (1993) 909

43 M.A. Green, et al.,
Copper-62 -labeled pyruvaldehyde bis(N4-methylthiosemicarbazonato)copper(II): Synthesis and evaluation as a positron emission tomography tracer for cerebral and myocardial perfusion
Journal of Nucl. Med. **31** (1990) 1989

44 *The thin layer activation method and its applications in industry*
IAEA-TECDOC-924, International Atomic Energy Agency, Vienna, 1997

LIST OF PUBLICATIONS

Papers on which this thesis is based published in referred international journals and are referred to in the text by A1 to A18.

A1. **S. Takács**, M. Sonck, A. Azzam, A. Hermanne, F. Tárkányi
Activation cross section measurements of deuteron induced reactions of ^{nat}Ni with special reference to beam monitoring and production of ^{61}Cu for medical purpose
Radiochimica Acta **76** (1997) 15

A2. **S. Takács,** F. Tárkányi, A. Fessler, Z.B. Alfassi, S.M. Qaim
Excitation functions of ^{3}He-particle induced nuclear reactions on natural Ni with special reference to the monitoring of beam energy and intensity
Applied Radiation and Isotopes **46** (1995) 249

A3. **S. Takács,** F. Tárkányi, Z. Kovács
Excitation function of alpha-particle induced nuclear reactions on natural nickel
Nuclear Instruments and Methods **B113** (1996) 424

A4. **S. Takács**, M. Sonck, B. Scholten, A. Hermanne, F. Tárkányi
Excitation function of deuteron induced nuclear reactions on ^{nat}Ti up to 20 MeV for monitoring deuteron beams
Applied Radiation and Isotopes **48** (1997) 657

A5. **S. Takács,** L. Vasváry, F. Tárkányi
Remeasurement and compilation of excitation functions of proton induced reactions on iron for activation techniques
Nuclear Instruments and Methods in Physics Research **B89** (1994) 88

A6. **S. Takács,** F. Tárkányi, M. Sonck, A. Hermanne, S. Sudár
Study of deuteron induced reactions on natural iron and copper and their use for monitoring beam parameters and for thin layer activation technique
Nuclear Instruments and Methods **B**. (in print)

A7. F. Ditrói, **S. Takács,** F. Tárkányi, I. Mahunka
Study of the ^{nat}C(^{3}He,2α)^{7}Be and ^{9}Be(^{3}He,αn)^{7}Be nuclear reactions and their applications for wear measurements
Nuclear Instruments and Methods **B103** (1995) 412

A8. F. Ditrói, **S. Takács,** F. Tárkányi, A. Fenyvesi, J. Bergman, S.-J. Heselius, O. Solin
Investigation of the charged particle nuclear reactions on natural boron for the purposes of the thin layer activation (TLA)
Nuclear Instruments and Methods **B103** (1995) 389

A9. B. Scholten, **S. Takács,** Z. Kovács, F. Tárkányi, S.M. Qaim

Excitation functions of deuteron induced reactions on ^{123}Te: relevance to the production of ^{123}I and ^{124}I at low and medium sized cyclotrons
Applied Radiation and Isotopes **48** (1997) 267

A10. **S. Takács**, A. Azzam, M. Sonck, F. Szelecsényi, A. Hermanne, F. Tárkányi
Excitation function of ^{122}Te(d,n)^{123}I nuclear reaction: Production of ^{123}I at low energy cyclotron
Accepted for publication in Applied Radiation and Isotopes

A11. **S. Takács,** F. Tárkányi, S.M. Qaim
Excitation function of ^{22}Ne(p,n)^{22}Na reaction: possibility of production of ^{22}Na at a small cyclotron
Applied Radiation and Isotopes **47** (1996) 303

A12. F. Tárkányi, **S. Takács,** S.-J. Heselius, O. Solin, J. Bergman
Static and dynamic effects in gas targets used for medical isotope production.
Nuclear Instruments and Methods A. (in print)

A13. L. Vasváry, F. Ditrói, **S. Takács,** Z. Szabó, J. Szûcs, J. Kundrák, I. Mahunka
Wear measurement of the cutting edge of superhard turning tools using TLA technique
Nuclear Instruments and Methods in Physics Research **B85** (1994) 255

A14. **S. Takács,** F. Ditrói, I. Mahunka
Trace element analysis by using the direct CPAA method
Nuclear Instruments and Methods in Physics Research **B10** (1985) 1051

A15. **S. Takács,** F. Ditrói, I. Mahunka
Investigation of aluminium made by powder metallurgy by using CPAA method
Nuclear Instruments and Methods in Physics Research **B43** (1989) 99

A16. F. Ditrói, **S. Takács,** I. Mahunka, P. Mikecz, Gy. Tóth
Determination of oxygen in high purity gallium by using charged particle activation analysis
Nuclear Instruments and Methods in Physics Research **B68** (1992) 166

A17. F. Ditrói, **S. Takács,** I. Mahunka, Z. Gémesi
Trace element study of glass samples by using activation methods
Nuclear Instruments and Methods in Physics Research **B50** (1990) 62

A18. F. Ditrói, I. Mahunka, **S. Takács,** S.A.H. Seif El-Nasr,
Trace element analysis of motor oil by CPAA method on external proton beam
Journal of Radioanalytical and Nuclear Chemistry, Articles **130** (1989) 263

Papers published in referred international journals or conference proceedings and are referred to in the text by B1 to B20.

B1. B. Scholten, A. Hohn, **S. Takács**, Z. Kovács, F. Tárkányi, S.M. Qaim
Cross section measurements relevant to the production of medically interesting positron emitting radioisotopes ^{120g}I and ^{124}I
(Book of Abst.ENEA-ICTP, 1997, p.288) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B2. A. Hermanne, M. Sonck, **S. Takács**, F. Szelecsényi, J. Van hoyweghen, F. Tárkányi
Influence of secondary neutrons on cross section determination of proton and deuteron induced reactions on ^{nat}Ni targets
(Book of Abst.ENEA-ICTP, 1997, p.199) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B3. M. Sonck, **S. Takács,** F. Szelecsényi, A. Hermanne, F. Tárkányi
Excitation functions of deuteron induced nuclear reactions on ^{nat}Mo from threshold to 21 MeV: an alternative route for the production of $^{94m,\ 99m}Tc$ and ^{99}Mo
(Book of Abst.ENEA-ICTP, 1997, p.279) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B4. F. Szelecsényi, **S. Takács**, A. Fenyvesi, Z. Szûcs, F. Tárkányi, S.-J. Heselius, J. Bergman, T.E. Boothe
Study of the $^{197}Au(p,pn)\ ^{196m1,m2}Au$ and $^{197}Au(p,pn)^{197m}Hg$ reactions and their application for proton beam monitoring in radioisotope production
(Book of Abst.ENEA-ICTP, 1997, p.250) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B5. A. Fenyvesi, S. Merchel, S. Takács, F. Szelecsényi, F. Tárkányi and S. M. Qaim
Excitation Functions of $^{nat}Ne(\ ^3He,x)^{22,24}Na$ and $^{nat}Ne(\alpha,x)^{22,24}Na$ Processes: Investigation of Production of ^{22}Na and ^{24}Na at a Medium-Sized Cyclotron
Accepted for publication in Radiochimica Acta (1997)

A. Fenyvesi, **S. Takács**, G. Petõ, F. Tárkányi, T. Molnár, S. Merchel, S.M. Qaim
Excitation functions of charged particle induced reactions on neon: relevance to the production of $^{22,24}Na$ and ^{18}F
(Book of Abst.ENEA-ICTP, 1997, p.285) International Conference on Nuclear Data for Science and Technology. Trieste, Italy, May 19-24,1997 (1997)
Will be published in the proceedings of the conference

B6. M. Sonck, A. Hermanne, F, Szelecsényi, **S. Takács**, F. Tárkányi
Study of the $^{nat}Ni(p,x)^{57}Ni$ process up to 44 MeV for monitor purposes
Accepted for publication in Appl. Radiat. Isot. 1997

B7. F. Szelecsényi, T.E. Boote, S. Takács, E. Tavano, F. Tárkányi,
Evaluatedcross section and thick target yield data bases of Zn+p precesses for practical applications,
Appl. Radiat. Isot. 48 (1977) accepted for publication

B8. F. Tárkányi, S. Takács, Z. Kovács, L. Andó
Production of ^{124}I for positron emission tomograph
Turun Yliopiston Julkaisuja - Annales Universitatis Turkuensis,
Sarja - Ser.D., Osa - Tom.185, Medica - Odontologica (1995) 31

B9. F. Szelecsényi, T.E. Boothe, E. Tavano, A. Fenyvesi, **S. Takács,** F. Tárkányi
(p,xn) and (p,pn) processes on ^{197}Au: new proton monitor reactions up to 30MeV
Proceedings of Sixth Workshop on Targetry and Target Chemistry. Vancouver B.C. Canada, August 17-19,1995. Eds:J.M.Link, T.J.Ruth. Vancouver, Triumf, Publ. Office, (1996) 125

B10. A. Fenyvesi, F. Tárkányi, F. Szelecsényi, **S. Takács,** Z. Szûcs, T. Molnár, S. Sudár
Excitation function and thick target yield of the $^{40}Ar(\alpha, p)^{43}K$ reaction: Production of ^{43}K
Applied Radiation and Isotopes **46** (1995) 1413

B11. F. Szelecsényi, T.E. Boothe, **S. Takács,** F. Tárkányi, E. Tavano, M. Plitnikas,
Nuclear data relevant to the production of ^{67}Ga: A critical comparison of excitation functions/thick target yield data $^{67}Zn(p,2n)$ nuclear reactions
Proceedings of the Fifth International Workshop on Targetry and Target Chemistry. Upton, September 19 to 23, 1993. Eds:J.Robert Dahl et al. Upten, BNL (1994) 234

B12. F. Tárkányi, **S. Takács,** S.-J. Heselius, O. Solin, J. Bergman
Study of static and dynamic effects in gas targets
Proceedings of the Fifth International Workshop on Targetry and Target Chemistry. Upton, September 19 to 23, 1993. Eds:J.Robert Dahl et al. Upten, BNL (1994) 48

B13. F. Szelecsényi, T.E. Boothe, E. Tavano, M. Plitnikas, Y. Feijoo,
S. Takács, F. Tárkányi, Z. Szûcs
New cross section data for $^{66,67,68}Zn+p$ reactions up to 26 MeV
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 393

B14. F. Ditrói, A. Fenyvesi, **S. Takács,** F. Tárkányi, J. Bergman, S-J. Heselius, O. Solin
Measurement of excitation function of $^{nat}B(p,x)^{7}Be$ nuclear reaction
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 383

B15. F. Szelecsényi, T.E. Boothe, E. Tavano, M. Plitnikas, Y. Feijoo,
S. Takács, T. Molnár, F. Tárkányi
Compilation and evaluation of cross sections thick target yields for ^{111}In production

Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 1042

B16. A. Fenyvesi, F. Tárkányi, F. Szelecsényi, **S. Takács,** Z. Szûcs, T. Molnár, S. Sudár
Measurement of excitation function and thick target yield of the $^{40}Ar(\alpha,p)^{43}K$ reaction
Proceedings of the International Conference on Nuclear Data for Science and Technology. Gathlinburg, TN, USA, 9-13 May,1994. Ed.:J.K.Dickens. La Grange Park, American Nuclear Society, Inc. (1994) 406

B17. F. Tárkányi, F. Szelecsényi, **S. Takács**
Determination of effective bombarding energies and fluxes using improved stacked foil technique
Acta Radiologica. **Supplementum 376** (1991) 72

B18. I. Gál, **S. Takács,** F. Tárkányi, L. Andó.
Beam splitting for parallel isotope production
Acta Radiologica. Supplementum **376** (1991) 73

B19. **S. Takács,** F. Ditrói, M. Pankotai, P. Fodor
Microelemental measurement of tomato plants by using PIXE and ICP methods
Nuclear Instruments and Methods in Physics Research **B49** (1990) 195

B20. **S. Takács,** F. Ditrói, I. Mahunka
Measurement of oxide-layer thickness of internal granules in high-purity aluminium
Acta Physica Hungarica **65** (1989) 355

B21. **S. Takács,**
Trace element analysis of high purity aluminium by charged particle activation analysis
University doctorate thesis, KLTE, Debrecen, 1985

B22. I. Mahunka, **S. Takács,** J. Dahlbacka,
Search for optimum parameters of CPAA measurements.
Proc. of 3rd Meeting on Nucl. Anal. Methods, Dresden, GDR, 11-15 April, 1983 (1983) 337