Resonance parameters of the reaction $^{12}C(d,p\gamma)^{13}C$ in the vicinity of 1450 keV for accelerator energy calibration

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Abstract

The observed resonance parameters of the $^{12}C(d,p\gamma)^{13}C$ reaction in the vicinity of 1450 keV deuteron energy have been determined in a thorough procedure, fitting our recent experimental excitation curve, as well as earlier literature data with the Root Software Package. The resulting energy and width (FWHM) of resonance are 1445.8 ± 0.2 keV and 5.3±0.4 keV, respectively. We propose the application of this resonance as a precise and simple method for accelerator energy calibration when performing DIGE analysis.

PACS: 29.30.-h; 25.45.-z; 82.80.Ej; 25.45.De

Keywords: $^{12}C(d,p\gamma)^{13}C$ reaction, resonance parameters, accelerator calibration, DIGE

Introduction and motivation

The accurate energy calibration of low energy particle accelerators is a basic requirement in the field of Ion Beam Analysis (IBA) and low energy nuclear physics.

Several absolute methods can be applied for particle accelerator energy calibration, for example measuring narrow nuclear reaction resonances and/or neutron threshold [1], using

non-resonant nuclear reactions [2], cross over techniques at higher energies [3], and techniques based on Rutherford backscattering spectrometry (RBS) [4].

To our best knowledge, using deuteron beams, only the $^{16}O(d,n)^{17}F$ reaction at 1829.2±0.6 keV threshold energy has been applied for the precise absolute energy calibration of accelerators [5]. The implementation of the neutron threshold reaction is rather complicated since the high background of neutrons from d+d reactions can hide the small neutron yield around the threshold energy, as we observed earlier [6]. Therefore, a narrow nuclear reaction resonance, detecting gamma-rays, is preferable.

In our laboratory, we are continuously working on the precise determination of thick target gamma ray yields and excitation functions of several nuclear reactions for analytical purposes [7-12].

In the framework of a Coordinated Research Project organized by the International Atomic Energy Agency (IAEA-CRP) [13], we measured the excitation function for the 3089 keV gamma line of the $^{12}C(d,p\gamma)^{13}C$ reaction, as well as for the particles from the $^{12}C(d,p_1)^{13}C$, $^{12}C(d,p_0)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions in the 0.74-2.0 MeV energy range. The results were presented in ref. [12].

For the ^{12}C+d nuclear reactions in the studied energy range, a pronounced compound nucleus mechanism is present besides the direct mechanism. Consequently, certain resonances appear in the excitation function. Close to 1450 keV deuteron energy, a fairly narrow and quite intense resonance can be observed. The existence of this kind of narrow and strong resonance with well-defined energy is unique among the deuteron induced nuclear reactions. As the preparation of a carbon target is simple, this nuclear resonance is a possible option for accelerator energy calibration using gamma-ray detection. With this method, the necessity of measuring a narrow proton resonance before switching to a deuteron beam can be avoided. Nevertheless, to apply this resonance for energy calibration, its position has to be determined as accurately as possible. The energy of this resonance had been established earlier as 1449.5±1.5 keV with a width of 7.0±0.5 keV [14] based on the work of Tryti et al. [15]. Tryti's work focused on the angular distributions of protons, obtained from the shape of the Doppler-shifted γ-lines, aiming to gain insight to the complex character of the reaction. The resonance energy parameters were obtained by a meticulous procedure of expressing the differential cross-sections in terms of Legendre polynomials and studying the energy dependence of the polynomial coefficients [15, 16]. This work gave invaluable information on the nature of the reaction; however, looking at all the present time available experimental data, we think that it is indispensable to re-assess this resonance and establish the resonance

energy (and the other resonance parameters) anew, with a straightforward approach which is also applicable in a routine analytical setting.

The observed shape of resonance in the excitation function depends on several parameters, such as the energy of resonance (E_R), the width of the resonance (Γ), the cross section at the resonance energy (σ_R) and the loss of energy in the target (ξ). The dependence of the excitation function of these parameters was given in ref. [17], and a detailed mathematical description of the problem was also presented there.

Beside the compilation and evaluation of the existing literature data, we measured the excitation function of the $^{12}C(d,p\gamma)^{13}C$, $^{12}C(d,p_1)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions in the 1410-1500 keV energy range using a self-supporting carbon foil with 20 μg/cm^2 thickness.

Moreover, in order to check the reliability of our experimental set-up and the applied fitting and evaluating process, the excitation function of the $^{23}Na(p,p'\gamma)^{23}Na$ reaction was measured in the 1900-1959 keV energy range and the parameters of the 1931 keV resonance were determined and compared with literature data. This work was carried out as a part of the measurement of the excitation function of the $^{23}Na(p,p'\gamma)^{23}Na$ reaction in the 1800-3000 keV energy range. The final excitation function with the detailed description of the experimental condition will be published later.

Experimental procedure

The measurements were carried out at the 5 MV Van de Graaff accelerator of MTA Atomki. The available ions for analysis are H^+, D^+, and $^4He^+$. The assortment of ions and their energy range provided by the accelerator make it possible to apply most of the ion beam analytical techniques: PIXE, PIGE, RBS, Scanning Transmission Ion Microscopy (STIM), Elastic Recoil Detection Analysis (ERDA) etc.

A self-supporting carbon foil (thickness: 1.0×10^{18} atom/cm^2) with an evaporated palladium layer on its surface (thickness: 2.2×10^{17} atom/cm^2) was used as a target for the measurement of the excitation functions of ^{12}C+d reaction. Due to some properties of the sample, the measurements of the ^{12}C+d reaction were carried out on the target with the top of the Pd layer, which caused a systematic alteration in the resonance parameters. Therefore, the correction of the resonance energy was necessary based on the stopping power of deuteron beam in the Pd layer. The energy loss (4.4 keV) was calculated with the SRIM code [18].

Moreover, a thin film of NaCl (thickness: 8.4×10^{17} atom/cm^2) evaporated on a self-supported thin film of Ag was used for the measurement of the excitation function of the ^{23}Na(p,p'γ)^{23}Na reaction in the 1900-1959 keV energy range. Since the parameters of the included 1931 keV resonance have well established values in the literature, the reliability of our experimental arrangement, fitting and evaluating process could be checked.

The number of target nuclei was determined with RBS technique using alpha beam of 1.5MeV energy. The uncertainty of target thickness determination was 2.5%. For the detection of gamma-rays, a Canberra Model GR4025-7600SL coaxial type HPGe detector (crystal: 59.5 mm diameter, 170 cm^3 volume) was applied at an angle of 55° relative to the incident beam direction with a distance of 9.5 cm between the front face of the crystal and the target. Particles from Rutherford backscattering and nuclear reaction were detected with an ORTEC Ion Implanted Silicon detector with 13 keV energy resolution. For the elimination of high intensity backscattered particles, we used a copper collimator with a diameter of 3 mm in front of the particle detector. The number of bombarding particles ($\mathbf{N_p}$) was determined via the measurement of the incident charge on the target chamber, which was an ideal Faraday cup. For a more detailed description of the experimental setup and also for the procedure of the determination of the absolute efficiency of HPGe detector ($\boldsymbol{\varepsilon_{abs}}$) and the solid angle of the Si detector ($\boldsymbol{\Omega}$), see ref. [11]. The uncertainty of the determination of $\mathbf{N_p}$ (stochastic and systematic uncertainties together) was taken into account with 3%. The uncertainty of $\boldsymbol{\varepsilon_{abs}}$ and $\boldsymbol{\Omega}$ were taken into account also with 3%.

The energy of the beam, as well as its energy stability was regularly assessed measuring the 991.81±0.04 keV resonances in the ^{27}Al(p,γ)^{28}Si reaction.

Data fitting process

The fitting process of the excitation function of the ^{12}C+d and ^{23}Na(p,p'γ)^{23}Na reactions around the resonance energies (~1450 keV and ~1931 keV, respectively) was performed using the Minuit part of the Root Software Package [19] after careful background subtraction. This software is capable to take the uncertainties of cross section data into account, thus to calculate the uncertainties of the fitted resonance parameters. We followed basically two different ways of background subtraction.

In the case of the ^{12}C+d reaction, the excitation function was fitted with the model function p(E) given by Equation 1 typically in the 1440-1470 keV energy range using linear background subtraction (see Equation 2).

$$p(E) = \frac{\sigma_R \Gamma}{2} \frac{\left(tan^{-1}\frac{E-E_R}{\Gamma/2} - tan^{-1}\frac{E-E_R-\xi}{\Gamma/2}\right)}{\xi} \quad (1), \quad Iinbg(E) = aE + b \quad (2)$$

where E is the incident particle energy, Γ is the full width of resonance at half maximum intensity, E_R is the resonance energy, σ_R is the cross section at the resonance energy and ξ is the loss of energy in the target. Figure 1 shows an example for the fitted excitation function in the case of $^{12}C(d,p\gamma)^{13}C$ reaction (our measurement). Thus the excitation function (excit (E)) can be modelled as:

$$excit(E) = p(E) + linbg(E) \quad (3)$$

We derived Equation 1 from Equation 14 in literature [17] converting the expressions to give cross section values instead of yields.

In the case of the $^{23}Na(p,p'\gamma)^{23}Na$ reaction, the excitation function was also fitted with the model function p(E) (equation 1.) typically in the 1900-1959 keV energy range after the subtraction of a two order polynomial background (equation 4., Figure 2).

$$polbg(E) = cE^2 + dE + f, \quad (4)$$

Thus, the excitation function can be modelled as:

$$excit(E) = p(E) + polbg(E), \quad (5)$$

In the case of the excitation function of Tryti [15, 16] and Elekes [20], all the parameters (E_R, σ_R, Γ, ξ) were fitted together due to the uncontrolled or obviously incorrect target thicknesses (ξ). In the case of our recent measurement and ref [12], because of the reliable experimental target thickness data, only three parameters (E_R, σ_R, Γ) were fitted and ξ was a fixed parameter. For the details of the computations we refer to the software manual, available online [Minuit 2, Fred James and Matthias Winkler, CERN, Geneva/http://root.cern.ch/drupal/content/minuit2-manual-600].

Results and discussion

Table 1 shows the integrated result of the fitting process in the case of the ~1450 keV and ~1931 keV resonance of the ^{12}C+d and ^{23}Na(p,p'γ)^{23}Na reactions, respectively, complemented with some other experimental and literature data. The data included in Table 1 are the following:

- source of data,
- type of nuclear reaction,
- energy loss in the target at 1450 keV or 1931 keV incident particle energy calculated from published or measured experimental thickness data using SRIM 2013 software (the given uncertainties include the uncertainty of thickness measurement (~3%) and SRIM calculation (<4%).
- number of data points in the resonant peak (expected minimum number for the fitting process is 4),
- parameters fitted with Root Software: resonance energy, resonance width, cross section at the resonance energy, energy loss in the target at 1450 keV or 1931 keV particle energy, square of the correlation coefficient (R^2). We note that in the case of our measurements, the resonance energies were corrected with the energy loss in the palladium layer.

The calculated values of E_R=1931.8±0.1and Γ=5.7±0.2 in the case of the ^{23}Na(p,p'γ)^{23}Na reaction are consistent (within two sigma uncertainty) with the literature data (E_R=1930.7±0.8 and Γ=6.9±0.5 [21]). This result confirms the reliability of our experimental set-up and the applied fitting and evaluating process.

From the data for the ^{12}C(d,pγ)^{13}C reaction (ref. 12, 15, 16, 20 and Csedreki et al.) in Table 1, we determined the resonance energy and width (FWHM) of the ~1450 keV resonance calculating the weighted averages.

The final uncertainty of the resonance energy and width was calculated as:

$$\sigma = \sqrt{\frac{1}{\sum_{i=1}^{n} \frac{1}{\sigma_i^2}}} \qquad (7)$$

where σ is the error of the weighted average, σ_i is the uncertainty of each parameters.

The final, accepted data are the following:

$$E_R = 1445.8 \pm 0.2 \text{ keV}, \qquad \Gamma = 5.3 \pm 0.4 \text{ keV}$$

To determine these new values, all the available, well-established experimental data that we could find in the literature and we succeeded to fit were taken into account. Some data were omitted from the fitting process because of the obviously incorrect energy calibration or insufficient number of data points in the resonant peak. Moreover, in one case we were unable to fit the excitation function. The omitted data are presented in Table 2.

In the case of particle production cross sections, the angular dependence of the reactions may affect the observed resonance parameters through the interference of different resonances. Thus, to determine the resonance parameters, the complex description of the reaction is necessary, using R-matrix calculations. However, this time-consuming and in-depth approach is hardly applicable in the IBA practice.

Conclusion

In this work, we systematically studied the resonance of the $^{12}C(d,p\gamma)^{13}C$ reaction in the vicinity of 1450 keV as a potential choice for accelerator energy calibration for deuterons.

On the one hand, we measured the excitation functions of the $^{12}C(d,p\gamma)^{13}C$, $^{12}C(d,p_1)^{13}C$ and $^{12}C(d,d_0)^{12}C$ reactions, simultaneously detecting the resulting particles and gamma-rays. On the other hand, we collected the literature data on the ~1450 keV resonance of the above reactions.

On the basis of 5 different datasets (3 from literature and 2 from our own measurements, using gamma-ray detection) for the region around 1450 keV, applying a fitting and weighted averaging process, we obtained 1445.8± 0.2 keV and 5.3±0.4 keV for the resonance energy and width, respectively. The fitting process, which was performed with the Root Mathematics Software, proved to be capable of the determination of resonance energy, resonance width, target thickness and cross section value at resonance energy, simultaneously. We recommend the use of the above resonance – accepting the newly determined 1445.8 ± 0.2 keV value of resonance energy – for the energy calibration of accelerators for deuteron beams.

Acknowledgements

The support of the IAEA Coordinated Research Project “Reference Database for Particle-Induced Gamma-ray Emission (PIGE) Spectroscopy” (Contract No. 16967/R1) is acknowledged.

The authors would like to thank Micaela Fonseca for the preparation of the sodium sample and Prof. Á.Z. Kiss for his valuable suggestions.

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Figure and Table captions:

Fig 1. Fitting process of the excitation function of the $^{12}C(d,p\gamma)^{13}C$ reaction around 1450 keV deuteron energy. The experimental data are from our own measurements detecting gamma rays from the 3089 keV line. The obtained E_R=1451.3±0.2 keV should be corrected with the Pd layer thickness. The correction resulted in the value E_R=1446.9±0.2 keV. Error A and B dashed lines show the 1sigma uncertainty of the resonance energy.

Fig. 2 Fitting process of the excitation function of the $^{23}Na(p,p'\gamma)^{23}Na$ reaction at ~1931 keV. The figure includes the results of the fitting process with the calculated and literature data of resonance parameters and also the polynomial background. Error A and B dashed lines correspond to the 1sigma uncertainty of the resonance energy.

Table 1 Summary of the experimental and fitted parameters concerning the ~1450 keV resonance of the ^{12}C+d reaction. The bold type data were used in the calculation of the final resonance energy and width.

Table 2 Omitted data from the fitting process.

Figure:

Fig. 1

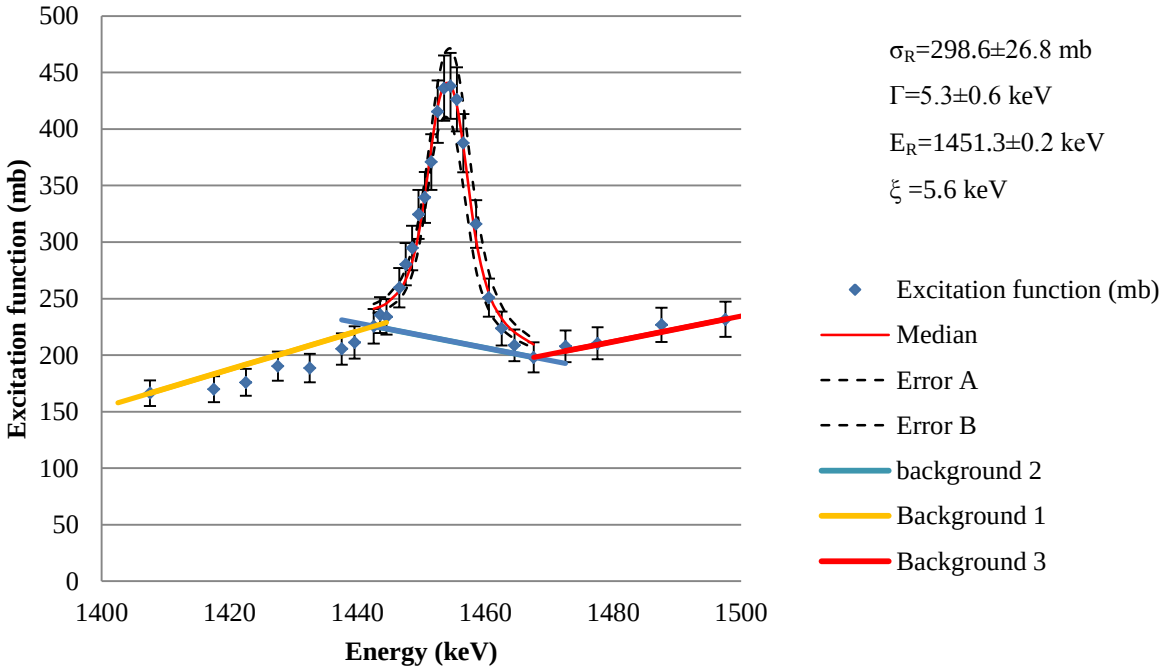
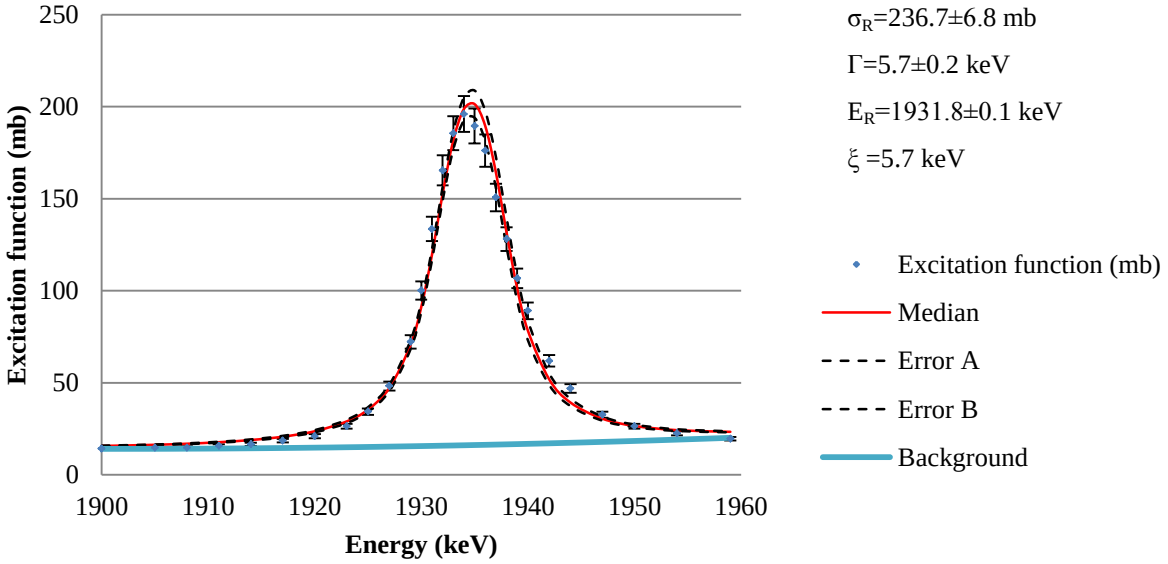


Fig. 2



Tables:

Table 1

	Experimental parameters			Parameters fitted by Root Software				
Source of data	Reaction	ξ [E_d=1450 keV]	Number of data points in the resonant peak	E_R [keV]	Γ [keV]	σ_R [mb or mb/sr]	ξ [E_d=1450 keV]	R^2
[16]Tryti et al. (1973)	**$^{12}C(d,p\gamma)^{13}C$**	**<2.2**	**7**	**1445.1±0.9**	**5.7±0.9**	**167.7±22.2**	**5.8±1.7**	**0.994**
[15]Tryti et al. (1975)	**$^{12}C(d,p\gamma)^{13}C$**	**7.3±0.4**	**6**	**1443.3±0.6**	**5.1±1.0**	**192.7±82.2**	**7.7±1.2**	**0.999**
[20]Elekes et al. (2002)	**$^{12}C(d,p\gamma)^{13}C$**	**6.0±0.3**	**4**	**1445.2±0.5**	**4.1±2.3**	**651.6±19.7**	**12.0±1.4**	**0.999**
[12] Csedreki et al. (2014)	**$^{12}C(d,p\gamma)^{13}C$**	**10.5±0.5**	**8**	**1444.6±0.3**	**5.2±1.0**	**246.3±35.4**	**10.5±0.5**	**0.996**
[12] Csedreki et al. (2014)	$^{12}C(d,d_0)^{12}C$	10.5±0.5	8	1444.5±0.2	4.8±0.1	125±1.5	10.5±0.3	0.943
[12] Csedreki et al. (2014)	$^{12}C(d,p_0)^{12}C$	10.5±0.5	8	1447.9±0.2	6.0±0.7	24.6±2.2	10.5±0.4	0.955
[12] Csedreki et al. (2014)	$^{12}C(d,p_1)^{12}C$	10.5±0.5	8	1448.7±0.5	7.5±1.5	25±3.6	10.5±0.5	0.976
Csedreki et al.	**$^{12}C(d,p\gamma)^{13}C$**	**5.6±0.3**	**19**	**1446.9±0.2***	**5.3±0.6**	**298.6±26.8**	**5.6±1.8**	**0.985**
Csedreki et al.	$^{12}C(d,d_0)^{12}C$	5.6±0.3	19	1446.4±0.1*	4.9±0.2	129.3±6.1	5.6±0.1	0.956
Csedreki et al.	$^{12}C(d,p_1)^{13}C$	5.6±0.3	19	1449.4±0.2*	4.1±0.5	27.4±2.6	5.6±0.2	0.944
Csedreki et al.	$^{23}Na(p,p'\gamma)^{23}Na$	5.7±0.3	23	1931.8±0.1	5.7±0.2	236.7±6.7	5.7±0.1	0.988

*Corrected with Pd layer thickness

Table 2

Source of data	Reaction	Reason for excluding from the fitting process
[22] Kashy et al. (1960)	$^{12}C(d,p_0)^{13}C$	Missing of uncertainties of the cross section data
[23]Papillon and Walter (1997)	$^{12}C(d,p\gamma)^{13}C$	Incorrect energy calibration
[24]Debras et al. (1977)	$^{12}C(d,p_0)^{13}C$	Incorrect energy calibration, less than 4 data points in the resonant peak
[25]Jarjis (1979)	$^{12}C(d,p_0)^{13}C$	Less than 4 data points in the resonant peak
[26]Kokkoris et al. (2006)	$^{12}C(d,p_0)^{13}C$	Less than 4 data points in the resonant peak
[27]Carvalho et al. (2008)	$^{12}C(d,p_0)^{13}C$	Unsuccessful fitting
[28]Kokkoris et al. (2007)	$^{12}C(d,p_1)^{13}C$	Less than 4 data points in the resonant peak
[29]Jeronimo et al. (1963)	$^{12}C(d,d_0)^{12}C$	Incorrect energy calibration
[26]Kokkoris et al. (2006)	$^{12}C(d,d_0)^{12}C$	Less than 4 data points in the resonant peak