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Experimental study of the neutron skin and hyperdeformation of the nucleus

Doktori (PhD) értekezés tézisei

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Background and aims

The investigation of neutron skin and of strongly deformed nuclear shapes are in the forefront of recent nuclear structure research. In both cases we study some general properties of the nucleus.

Due to the forces acting in the nucleus and to the Pauli principle governing the buildup of fermionic systems, the shape of density distribution function of protons and neutrons of a nucleus is different. A most appearent sign of this difference may be the presence of excess neutron on the nuclear surface. If excess neutrons are located on the nuclear surface like a pile then we talk about neutron skin. The study of neutron skin has become very interesting in the investigation of neutron-rich nuclei far from the stability line, and could provide more accurate information about some basic nuclear parameters.

Recently two new methods have been developed by Attila Krasznahorkay and his collaborators for the determination of neutron skin. Both methods are based on the collective excitation of the neutron-rich nuclei and by studying the behaviour of these collective states we can obtain information about the ground-state nucleon distribution. By measuring the cross section of the isovector giant dipole resonances, excited in inelastic α scattering, the thickness of neutron skin can be determined. Our aim was to make new measurement in order to check the reliability of the method. At higher excitation energies, where we have larger cross sections, we can determine neutron skin thickness using data measured with better statistics.

The measurement of the strength of isovector spin-dipole giant resonance excited in ^{3}(He,t) reactions can be used for the determination of relative values. Our aim was to measure the angular distributions of tritons for tin isotopes using higher beam intesity and better statistics, and by refining evaluation of data, to extract more accurate neutron skin values.

Another exciting topic of nuclear structure research is the study of nuclei with exotic shapes. The development of large-efficiency, high-energy- resolution 4π γ spectrometers made it possible to study the high-spin, strongly deformed states with axis ratio 2:1. Recently the main aim of the use of such spectrometers is the study of hyperdeformed states with axis ratio 3:1.

The aim of our investigation is the study of hyperdeformed pre-fission states. The calculations of the deformation potential surface in Strutinsky's shell correction method predict a third local minimum for the light actinide nuclei where the produced states have an 3:1 axis ratio and octupole-deformed, mirror-asymmetric nuclear shape. Such hyperdeformed states were first observed in the fine structure of fission resonances of some Th isotopes. While the predictions for both thorium and uranium are similiar, the experimental results obtained for uran isotopes are contradictory. Our aim was to find hyperdeformed states by performing high-resolution measurements for uranium isotopes.

The realization of our project is based on the use of the magnetic spectrograph settled from the Netherlands to the Institute of Nuclear Research, Debrecen. Our investigation was started with the study of the fission resonances in ^{236}U nucleus. Our results provided the first evidence for the existence of hyperdeformed states in ^{236}U. On the basis of this result we continued the investigations in collaboration with Ludwig-Maxmilian University in Munich in the LMU laboratory, extending the study to the superdeformed states of ^{240}Pu and to the hyperdeformed states of ^{234}U.

The aim of my present work was the study of the fission resonances of ^{236}U nucleus with a better resolution and in wider excitation energy range, and find information on the depth of the third valley.

Recently the deformation potential in the third valley for the ^{232}Th nucleus was described as a cluster of a presumably spherical heavy nucleus ^{132}Sn and a strongly deformed light nucleus ^{100}Zr. If so, the fission probabilities may show a difference between the fission patterns for hyperdeformed and non-hyperdeformed states. Our aim was the investigation of fission fragments produced in the ^{232}Th(n,f) reaction at the neutron energy region which included the hyperdeformed resonance at E_n=1.6 MeV.

Experimental methods

The experiments for the determination of the neutron skin were carried out at the Kernphysik Versneller Instituut (KVI) in Groningen.

The neutron skin of the ^{208}Pb was measured in the $^{208}Pb(\alpha,\alpha'\gamma_0)$ reaction at incident energy $E_\alpha = 196MeV$. The inelastically scattered α particles were detected with the Big-Bite Spectrometer (BBS) which was set at angle 2.8^o and a focal plane detection system of EuroSuperNova Collaboration. The contribution of the isovector giant dipole resonance is supressed by the continuous background of the monopole and quadrupole giant resonances and of the inelastically scattered α particles. The selection of the isovector giant dipole contribution was performed by measuring $\alpha - \gamma_0$ coincidence. The gamma rays were detected by NaI(Tl) and Ge Clover +BGO spectrometers. In the measurement of the spin-dipole resonance strength, a 177 MeV ^{3}He beam was used.

The investigation of neutron skin by measuring the strength of the isovector spin-dipole giant resonance excited by 177 MeV ^{3}He beam in ^{3}(He,t) reaction was performed for the longest stable isotopic chain, for the tin isotopes. Tritons were detected with the Big-Bite Spectrograph which was set at 0° with respect to the beam direction and with the focal-plane detector system of EuroSuperNova Collaboration.

For the investigation of hyperdeformed states of ^{236}U the target nucleus ^{235}U was excited in (d,p) reaction. The proton and the fission products from ^{236}U states were detected in coincidence. Protons were identified with a Q3D spectrograph and by measuring the proton energy with the catode-strip detector of the spectrograph, the excitation energy of the ^{236}U nucleus could be determined. For detection of fission fragments gas-filled avalanche detectors produced in Debrecen were used.

For the study of mass and total kinetic energy distribution of fission fragments, produced in the fission of ^{232}Th induced by neutrons, monoenergetic neutrons were produced in the $^7Li(p,n)$ reaction in the $E_p = 3.2-3.425MeV$ range which corresponds to the neutron energy range of $E_n = 1.5-1.7MeV$. Incident energy was changed in 25-keV steps. To measure the kinetic energy of fission products, we constructed a double ionization chamber.

Results

The results of the neutron-skin measurements can be summarized as follows:

1. By evaluating experimental data, I determined the cross section of the $^{208}Pb(\alpha,\alpha'\gamma_0)$ reaction. The averaged cross section is $336 \pm 34\mu b/sr$. I have compared the measured cross section to coupled-channel calculations which depend on the thickness of the neutron skin. The result of this analysis for the neutron-skin thickness of ^{208}Pb is 0.12±0.07 fm. This result is in good agreement with previous result measured in the KVI at $E_\alpha = 120MeV$ with a cross section which was smaller by an order of magnitude and consistent with the value of 0.14± 0.04 fm extracted from the (p,p) scattering. With this result I presented proofs in favour of the method introduced by Krasznahorkay et al.

2. I determined the isovector spin-dipole giant resonance cross sections for all even tin isotopes found in nature in one experiment. Using the relation between the resonance strength and the neutron-skin thickness, I determined the neutron-skin thicknesses for the ^{112}Sn, ^{114}Sn, ^{116}Sn, ^{118}Sn, ^{120}Sn, ^{122}Sn and ^{124}Sn isotopes as 0.11±0.01, 0.14±0.01, 0.16 ± 0.01, 0.19 ± 0.01, 0.22 ± 0.01, 0.24 ± 0.01, and 0.28 ± 0.01 fm, respectively. I compared these values with the results of other measumerements and the available theoretical calculations and I have found a good agreement.

   The results from the analysis of the $^{236}U(d,pf)$ reaction can be summarized as follows:

3. Using the spectra of protons from the $^{236}U(d,pf)$ reactions measured with a resolution of 8 keV, I have determined the fission probabilities of ^{236}U as a function of the excitation energy in the range of $4.9MeV < E^* < 5.6MeV$.

4. At excitation energies above 5.2 MeV, I have fitted the resonance fine structure by the use of overlapping alternate parity rotational bands with bandhead of $K = 4^-$. The χ^2 analysis of the fit for the value of

the rotational parameter gives $\hbar^2/2\theta = 2.3^{+0.2}_{-0.45}$ keV which corresponds to the one for hyperdeformed states. Using alternate parity K=3,4 and 5 bandheads I described the A_2 angular correlation coefficients, too. The obtained value of moment of inertia is $\Theta = 217 \pm 38\hbar^2/MeV$, in good agreement with the value predicted for hyperdeformed states.

5. I have compared the average distances of the J=5 spin states of the K=4,5 rotation bands with the average distances calculated by a modified Fermi-gas formula. For the ground-state energy in the valley III., I have obtained the value of 3.3±0.4 MeV in good agreement with the values calculated for the third valley in ^{236}U and the value extracted from the experimental data for ^{234}U.

6. By describing the structure of resonances about 5.1 MeV excitation energy by rotational bands, I obtained the value for the moment of inertia $\Theta = 208 \pm 70\hbar^2/MeV$, which corresponds to hyperdeformed resonance. In contrdiction with the earlier assumptions, we can interpret this structure as a hyperdeformed state of the third valley. According to our results the height of the inner barrier should be lower than 5.2 MeV.

   The results of investigation of fission fragments produced in the $^{232}Th(n, f)$ *can be summarized as follows:*

7. I have determined the mass distribution and the total kinetic energy of the fission products at all incident energies. The total kinetic energy is the sum of kinetic energy for the light and heavy fission fragments. I fitted the mass distributions as a sum of two Gaussian of identical σ values. The fitted σ values as a function of incident neutron energies at 1.6 MeV shows a decrease of a few percent. Then a small increase follows and at the 1.7-MeV resonance again a small decrease appears.

8. Integrated over the incident kinetic energy, the total kinetic energy as a function of mass distribution is analysed. I found a well-defined shrinking in the mass distribution at higher total kinetic energies. Light fragments are grouped at A=100, heavy fragments are grouped at A=132.

I presented the total kinetic energy distributions in 10 MeV regions as a function of the incident kinetic energies. I found that with the increase of the total kinetic energies the mass distributions are shrinking, approaching the 1.61 MeV incident energy, the values of σ are decreasing and then they increase. Restricted to the events of total kinetic energies higher then 180 MeV, a considerably larger shrinking is manifested. The value of σ at incident energy of 1.5 MeV is 7.79 ± 0.47 amu and at the resonance of 1.61 MeV we have $\sigma = 5.86 \pm 0.47$ amu. I selected two regions at $A = 132$ (with $A = 132 \pm 2$ and with $A = 132 \pm 4$, respectively) and I analysed the total kinetic energies as a function of the incident energies in these two regions. In these regions the average energy of the fission fragments is about a 10 MeV value higher than in the whole mass region and, in addition, a well-defined increase appears at the hyperdeformed resonance region.

9. The results I deduced from the investigation of fission fragments produced in the $^{232}Th(n,f)$ process for cold fission support the hypothesis of $^{132}Sn +^{100} Zr$ nuclear molecule structure for hyperdeformed states.

Published articles related to the thesis

1. **M. Csatlós**, A. Krasznahorkay, M. Hunyadi, J. Gulyás, Z. Máté, J. Molnár, J. Timár and J. Végh : Properties of ^{236}U at the third-minimum deformation.

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8. **M. Csatlós**, A. Krasznahorkay, P.G. Thirolf, D. Habs, Y. Eisermann, T. Faestermann, G. Graw, J. Gulyás, M.N. Harakeh, R. Hertenberger,

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2. **M. Csatlós**, A. Krasznahorkay, A.M. van den Berg, M.N. Harakeh, M.N. de Huu, S.Y. van der Werf, M. Hagemann, H. Akimune, H. Fujimura, M. Fujiwara, K. Hara and T. Ishikawa: Neutron-skin thickness from excitation of spin-dipole resonance.

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