Abstract of Ph.D. dissertation

EXPERIMENTAL STUDIES OF EXOTIC NUCLEI

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Overview

Our contemporary nuclear structure research has basically three main frontiers. The search for anticipated new phenomena requires to study "exotic" or "extreme" states, where the excitation energy or the spin (and often the deformation) or the isospin (the proton-neutron ratio) takes extreme values. Remarkable support of these fields are all involved in the previous long range plans of the Nuclear Physics European Collaboration Committee (NuPECC), which indicates the importance of these fields. As a Ph.D. student my main topic was to examine nuclei having extreme deformations [R1,R2,R3], however, in the last four years I participated in many experiments focusing on subjects of both of the other two directions [R3,R4,O2,O4,O5].

Hyperdeformed states

The recently developed, high efficiency 4π germanium detector arrays such as EUROBALL or AGATA have provided great facilities and opportunities for the high resolution study of nuclear states associated to extremely elongated nulcear shapes. In the mass region of $A \approx 130$ more than one hundred superdeformed (axis ratio of $\sim$ 2:1) rotational bands have been identified so far. In this mass region the centrifugal force related to the fast rotating motion is responsible for the large deformation that can be stabilized by the notable shell effects. Contrary to the observations of discrete superdeformed (SD) transitions, the identification of discrete γ rays from hyperdeformed (HD) nuclear states having an axis ratio of $\sim$3:1 represents one of the frontiers of high-spin physics. Although a large community with 4π gamma arrays have been searching for HD states in very long experiments, no discrete HD states have been identified so far. However, prominent structures have been found in the quasi-continuous γ energy region of many nuclei implying the existence of such HD states in these cases. Unlike the mass region of A$\approx$130, in the actinide region, the appearance of fission resonances gives a special possibility for the identification and examination of SD and HD states. In this mass region the formation of the SD and HD states can be explained by the appearance of a second and a third potential well in the potential energy surface which has been calculated by the shell correction method introduced first by Strutinsky.

Observing transmission resonances as a function of the excitation energy caused by resonant tunneling through excited states in the third minimum of the potential barrier allows us to identify the excitation energies of the HD states. Moreover, the observed states could be ordered into rotational bands, with moments of inertia proving that the underlying nuclear shape of these states is a HD configuration indeed. For the identification of the rotational bands the spins and their projections onto the nuclear symmetry axis (K values) can be obtained by measuring the angular distribution of the fission fragments.

The Experimental Nulcear Physics Group of the Institute of Nuclear Research of the Hungarian Academy of Sciences (Atomki, Debrecen) together with the Physics Department of the Ludwig Maximilians University (LMU, München) have performed many successful experiments aimed at the better description of the fission process and studying exotic nuclear shapes for more than one decade. I joined to these experimental campaigns as a Ph.D. student.

Calculations for the potential energy surfaces of the uranium isotopes indicated HD minimum at a large quadrupole and octupole deformation ($\beta_2 = 0.9$ and $\beta_3 = 0.36$) while the depth of the third well was estimated to be much larger than previously believed. In contrast to the theoretical expectations as well as to the ^{234,236}U isotopes where sharp HD transmission resonances have already been identified, no clear resonance structures have been observed so far in ^{232}U.

The aim of our first experiment was to search for such sub-barrier fission resonances in ^{232}U and to assign the resonances to rotational bands via the determination of their rotational parameters ($\hbar^2/2\Theta$) [R1]. The experiment was carried out at the the Tandem accelerator of the Maier-Leibnitz Laboratory (MLL) at Garching employing the reaction ^{231}Pa(^{3}He,d) at a bombarding energy of $E = 38$ MeV. In the experiment we determined the fission probability of ^{232}U as a function of the excitation energy. The excitation energy of the compound nucleus was determined from the kinetic energy of the ejectiles in coincidence with the fission fragments which was analyzed by a Q3D magnetic spectrograph. For the detection of the fission fragments I constructed two pieces of low-pressure, position sensitive avanlache detectors (PSAD) in ATOMKI allowing for the determination of the fission fragment angular correlation.

Besides the thorium and uranium isotopes in respect to the hyperdeformation of the double-odd nucleus ^{232}Pa is of great interest. The broad structure of the fission resonances of this nucleus have been studied so far only via the (n,f) reaction but the results of these experiments showed no conclusive evidence for the existence of a triple-humped fission barrier of ^{232}Pa. The aim of our second experiment was to search for HD rotational structure in the fission probability of ^{232}Pa applying the ^{231}Pa(d,pf) reaction using the same experimental setup and technic as it was used in the first experiment [R2].

The aim of our third experiment was to determine the width of the mass distribution of the fission fragments emitted from the previously identified well-known HD states of ^{236}U and to compare it with the width associated to normal deformed nuclear states. A possible sharpening of the mass distribution could be a dramatic manifestation of the fact that the shell effects have a strong influence on the fission process. The experiment was performed at the Cyclotron Laboratory of ATOMKI in Debrecen using the ^{235}U(d,pf) reaction, in which the fission probability of ^{236}U was measured as a function of the excitation energy. The kinetic energy of the protons was measured by a split-pole magnetic spectrograph while the fission fragments were detected by two PSADs placed 180° relative to each other. This arrangement provided a coincidence detection of both fission fragments coming from the same fission event with the possibility of determining the mass differences based on Time-of-Flight (TOF) method. Meanwhile, the excitation energy of the fissile nuclei could be also derived from the measured kinetic energy of the protons.

Giant resonances

Unlike the previous cases, the structure of the giant resonances can be examined at higher excitation energy (E^* ≈10-40 MeV), which can serve us especially valuable information on the features of the nuclear matter. On the other hand, the same experimental technic (coincidence measurement with magnetic spectrograph) can be used for these examinations.

From all the giant resonances investigated so far, the isoscalar giant dipole resonance (ISGDR) has remained one of the most interesting collective vibrational modes of nuclei. The first term of the isoscalar giant dipole transition operator is associated with a spurious center-of-mass motion, so only the higher-order terms lead to intrinsic excitation of the nucleus. Macroscopically, the ISGDR can be described as a density oscillation (squeezing mode), whose oscillator frequency is determined by the compression modulus of the nucleus. As a consequence, the excitation energy of the ISGDR can be directly related to the nuclear incompressibility, a key term of the nuclear equation-of-state, which plays an important role in the theoretical descriptions of astrophysical processes and heavy ion reactions. The features of this resonances have only been investigated by inclusive experiments so far in which the parameters of the resonances could be determined with huge uncertainty. The coincidence measurement of the direct particle decay of these resonances could reduce this uncertainty which is originating from the large continuous background.

In our fourth experiment we studied the proton decay of the isoscalar giant resonance of ^{208}Pb with the reaction of ^{208}Pb(α,α'p). The energy of the inelasticly scattered α particles was measured by a QQD magnetic spectrograph (Big Bite magnetic Spectrograph - BBS) while protons were identified and their kinetic energy was measured by a 2π detector array consisting 16 pieces of Si(Li) detector [R3,R4]. The experiment was performed at the superconducting cyclotron laboratory of the University of Groningen (The Netherlands).

New scientific results

1. **We observed sharp ($\Delta E \approx 30$ keV) transmission resonances in the fission probability of ^{232}U in the excitation energy region of E^*=4.2-4.85 MeV for the first time. We succeed to assign these resonances to HD rotational states lying in the third well of the fission barrier.**

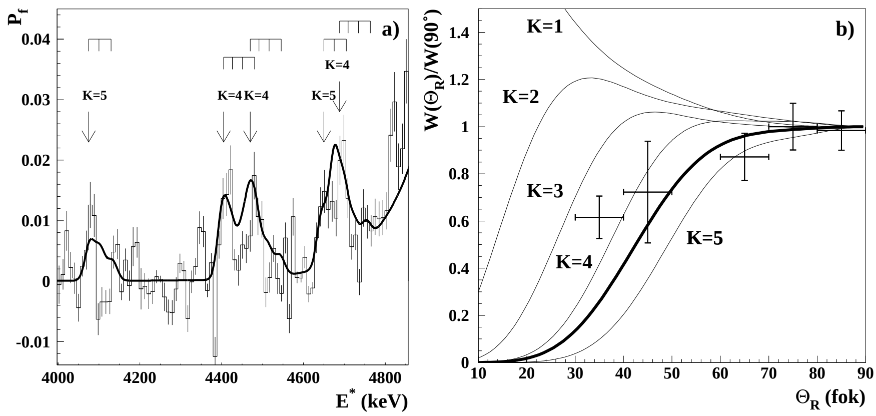

Figure 1: *a) Fission probability of ^{232}U as a function of the excitation energy, b) experimental angular distribution of the fission fragments gated on the resonances and the theoretical distributions calculated for different K values*

a) In order to describe the rotational structure of the observed resonances, I fitted five overlapping rotational bands with K=4 and K=5 to the experimental fission probability with the same moment of inertia and with the same intensity ratio for the different band members. During the fitting procedure the excitation energies of the band heads and the absolute intensities of the bands were treated as free parameters while a common rotational parameter characterizing HD nuclear shape ($\hbar^2/2\Theta \approx 2.1$ keV) was adopted for each band. As a result of the fitting procedure I obtained $E^* = 4080, 4402, 4468, 4651$ and 4678 keV for the excitation energies of the band heads using K value assigments of $K = 5, 4, 4, 5$ and 4 for the rotational bands, respectively (Figure 1.a). The experimental angular distribution of the fission fragments was compared to the theoretical one. The theoretical distribution was calculated by assuming K values that were used in the fitting procedure. The experimental and calculated values were in a very good agreement (Figure 1.b, thick, continuous line) which also confirmed my analysis of the excitation energy spectrum.

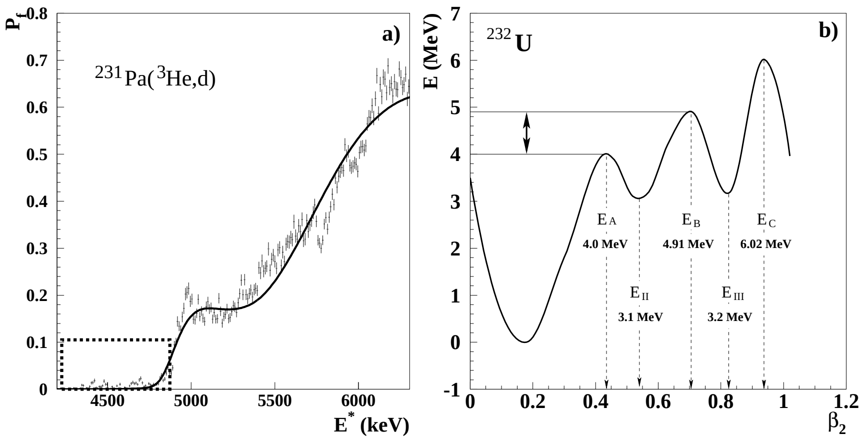

Figure 2: *a) Fission probability of ^{232}U with the fitted analytical function (continuous line) and b) the triple-humped fission barrier of ^{232}U as a result of the fitting procedure*

b) For the determination of the fission barrier parameters of ^{232}U I deduced an analytical expression for the fission probability that was fitted to the overall structure of our experimental fission probability (Figure 2.a). Within the calculation, the optical model for fission was used, which was extended to describe the fission of the light actinides featuring a triple-humped fission barrier. As a result of the fitting procedure the fission barrier parameters of ^{232}U could be deduced. My result on the depth of the third potential well ($E_{III} = 3.2 \pm 0.2$ MeV) was in a good agreement with recent theoretical predictions and suggested that in the case of ^{232}U fission proceeds via strong reflection asymmetric shapes (Figure 2.b).

c) Our new result on the inner barrier height of ^{232}U ($E_A = 4.0 \pm 0.3$ MeV) contradicts to the previous experimental results. However, it fits into the systematic trend of the experimental fission barrier parameters of the uranium isotopes determined in the last few years: the data for the inner barrier heights E_A reveal a clear, decreasing trend with decreasing neutron number within the isotopic chain. This trend gives rise to expect so far unobserved short lived fission isomers in low-N actinide nuclei due to the increasing probability of back decay to the first minimum with lower E_A.

d) Finally, we observed sharp fission resonance structures at excitation energy around $E^* = 5.0$ MeV, which resonances could be assigned to transition states (low excited states built upon the second barrier) taking into account our new results on the fission barrier parameters of ^{232}U.

2. **We observed the so far unresolved fine structure of the broad fission resonances of ^{232}Pa that had been previously found in (n,f) reaction for the first time. We could describe this structure with four HD rotational bands having a rotational parameter of $\hbar^2/\theta = 2.0^{+1.5}_{-1.0}$ keV [R2].**

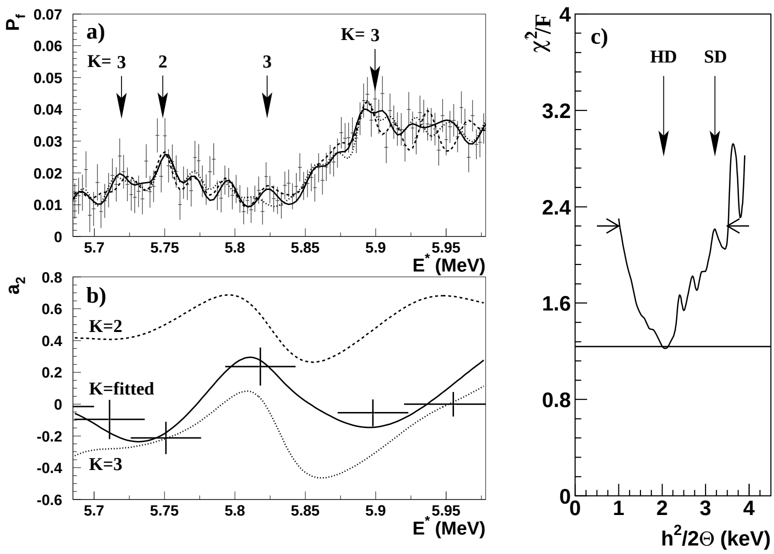

Figure 3: *a) Fit of the fission resonances of ^{232}Pa with HD rotational bands, b) experimental and theoretical angular correlation coefficient (a_2) in the function of the excitation energy, c) χ^2 analysis of the fitting procedure*

a) We resolved the fine structure of the broad resonances in the fission probability of ^{232}Pa at excitation energies around $E^* \approx 5.75$ and $E^* \approx 5.9$ MeV. In order to describe the rotational structure of the observed resonances, I fitted four overlapping rotational bands to the experimental fission probability. Energies of the band heads as a result of the fitting procedure are the following: $E^* = 5.72, 5.74, 5.82$ és 5.9 MeV with $K = 3, 2, 3$ and 3, respectively (Figure 3.a).

b) I analyzed the experimental angular correlation data by fitting it with even Legendre-polynomials up to fourth order: the angular coefficients a_2 and a_4 were determined for the most prominent structures parametrized by a series of rotational bands with K value assignments. The theoretical fission fragment angular correlation was calculated (a_2 as a function of the excitation energy) for the rotational bands using the same K value assigments as in the fitting procedure and it was compared to the experimental a_2 points (Figure 3.b). The theoretical and the experimental values were in a very good agreement, which also confirmed my results on the identification of the fission resonances. Thus, the transmission resonance structures around 5.7 and 5.9 MeV can be interpreted as HD rotational bands.

c) I determined the rotational parameter to be $\hbar^2/\theta = 2.0^{+1.5}_{-1.0}$ keV based on the χ^2-analysis of the fitting procedure (Figure 3.c).

d) In the experiment we also measured the excitation energy of the low-lying excited states of ^{232}Pa. More than fifty new excited states were identified at excitation energy below 800 keV meanwhile.

3. **We determined the width of the mass distribution of the fission fragments emitted from the well-known HD states of ^{236}U, which was compared to the width related to the normal deformed states. We have not found any significant differences between the two widths.**

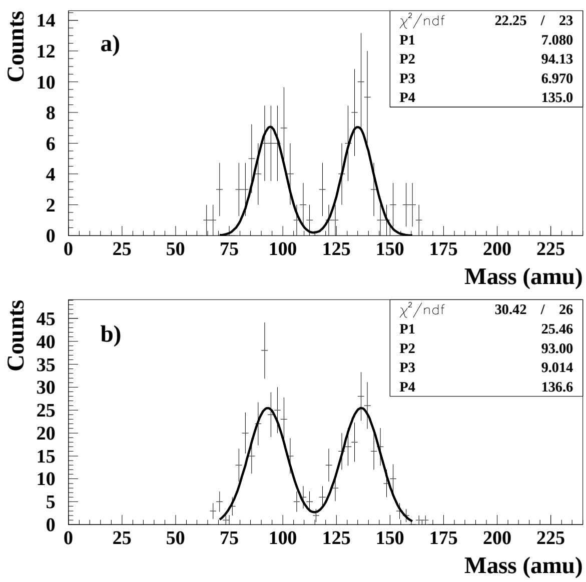

Figure 4: *Mass distribution of fission fragments emitted from a) HD states and b) from normal deformed (ND) states*

a) To determine the width of the mass distribution I fitted a double Gaussian function to our experimental data gated by the excitation energy regions of the HD resonances (Figure 4.a). During the fitting procedure the common amplitude and σ parameters were treated as free parameters.

For comparision the width of the mass distribution gated by the excitation energies higher than the fission barrier ($E^*>6.0$ MeV) was also determined (Figure 4.b). I obtained the following widths: $\sigma_{HD}^{exp} = 6.97 \pm 1.65$ amu and $\sigma_{ND}^{exp} = 9.01 \pm 0.97$ amu. The mass resolution was deduced to be σ_{kis} =6.6±0.5 amu from the comparision of σ_{ND}^{exp} to the width established previously and taken from the work Müller *et al.* ($\sigma_i = 6.14 \pm 0.07$ amu).

b) Considering the mass resolution the two widths were deduced to be $\sigma_{HD} = 2.24 \pm 3.58$ amu and $\sigma_{ND} = 6.1 \pm 0.65$ amu. Due to the large error bars, which mainly comes from the poor statistics of the experiment, this difference cannot be considered as a conclusive evidence for a sharpening effect.

4. **Proton decay channels of the ISGDR of ^{208}Pb were observed for the first time, the branching ratios of the direct-decay channels from the ISGDR in ^{208}Pb to the hole states in ^{207}Tl have been determined.**

   a) The branching ratios of the direct-decay channels from the ISGDR in ^{208}Pb to the hole states in ^{207}Tl were compared to the theoretical values for both decay branches and showed a rather satisfactory agreement within the statistical uncertainties (Table 1.).

   b) The experimental angular distributions of the ISGDR strength were determined and compared to the calculations performed with DWBA using the code CHUCK. A χ^2-analysis of the fits for the angular distributions of the ISGDR unambiguously confirmed the L=1 character in both decay branches. The fitted centroid energy of the ISGDR, after proper deconvolution of transmission probabilities and E_x-dependence of the excitation cross section, is E_x=22.1±0.3 MeV, and the fitted width is Γ=3.8±0.8 MeV.

   c) The angular distribution of the high-lying bump is consistent with an $L = 2$ transition. If this is true, then this high-lying bump could possibly assigned to the overtone of the isoscalar giant quadrupole resonance. Its excitation energy and width are 26.9±0.7 MeV and 6.0±1.3 MeV, respectively, very close to the previous calculations.

final state	b_μ(%) (present work)	b_μ(%) (theory)
$3s_{1/2}+2d_{3/2}$	2.3±1.1	1.23
$1h_{11/2}+2d_{5/2}$	1.2±0.7	0.83

Table 1: *Branching ratios for the proton decay of ISGDR of ^{208}Pb*

Publications related to the thesis

Refeered Journals

R1 **L. Csige**, M. Csatlós, T. Faestermann, Z. Gácsi, J. Gulyás, D. Habs, R. Hertenberger, M. Hunyadi, A. Krasznahorkay, R. Lutter, H.J. Maier, P.G. Thirolf, H.F. Wirth

Hyperdeformed sub-barrier fission resonances observed in ^{232}U

Physical Review C **80** (2009)011301. (IF:3.302)

R2 **L. Csige**, M. Csatlós, T. Faestermann, Z. Gácsi, J. Gulyás, D. Habs, R. Hertenberger, M. Hunyadi, A. Krasznahorkay, R. Lutter, H.J. Maier, P.G. Thirolf, H.F. Wirth

New excited states and fission resonances in the actinide region

Acta Physica Polonica **B38** (2007)1503-1507. (IF:0.664)

R3 M. Hunyadi, C. Baumer, A.M. van den Berg, N. Blasi, M. Csatlós, **L. Csige**, B. Davids, U. Garg, J. Gulyás, M.N. Harakeh, A.M. de Huu, B.C. Junk, A. Krasznahorkay, S. Rakers, D. Sohler, H.J. Wörtche

Particle decay of the isoscalar giant dipole resonance in ^{208}Pb

Nuclear Physics **A731** (2004)49-56. (IF:2.108)

R4 M. Hunyadi, A.M. van den Berg, N. Blasi, C. Baumer, M. Csatlós, **L. Csige**, B. Davids, U. Garg, J. Gulyás, M.N. Harakeh, A.M. de Huu, B.C. Junk, A. Krasznahorkay, S. Rakers, D. Sohler, H.J. Wörtche

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Physics Letters **B576** (2003)253-260. (IF:4.066)

R5 A. Krasznahorkay, **L. Csige**, M. Csatlós, Y. Eisermann, T. Faestermann, Z. Gácsi, G. Graw, J. Gulyás, D. Habs, M.N. Harakeh, M. Heil, R. Hertenberger, F. Kappeler, A. Krasznahorkay Jr., H.J. Maier, Z. Máté, R. Reinfarth, P.G. Thirolf, J. Timár, H.F. Wirth

Hyperdeformation and clusterization in the actinide region

Acta Physica Hungarica New Series - Heavy Ion Physics **18** (2003) 323-330. (IF:0.097)

Conference talks

T1 **L. Csige**, M. Csatlós, Z. Gácsi, J. Gulyás, M. Hunyadi, A. Krasznahorkay, *et al.*

Hyperdeformed fission resonances observed in ^{232}U

European Nuclear Physics Conference

Bochum, Germany, 16-19 March 2009.

T2 **L. Csige**, M. Csatlós, Z. Gácsi, J. Gulyás, M. Hunyadi, A. Krasznahorkay, *et al.*

Maghasadás egzotikus állapotokon keresztül

"ELFT Fizikus Vándorgyűlés"

Eger, Hungary, 22-24 August 2007.

T3 **L. Csige**, M. Csatlós, Z. Gácsi, J. Gulyás, A. Krasznahorkay, *et al.*

New excited states and fission resonances in the actinide region

41st. Zakopane Conference on Nuclear Physics

Zakopane, Polska, 4-10 September 2006

Publications not related to the thesis

O1 A.Cs. Vitéz, A. Krasznahorkay, J. Gulyás, M. Csatlós, **L. Csige**, Z. Gácsi, A. Krasznahorkay Jr., B.M. Nyakó, F.W.N. de Boer, T.J. Ketel, J. van Klinken

Anomalous internal pair creation in 8Be as a signature of the decay of a new particle

Acta Physica Polonica **B39** (2008)483. (IF:0.664)

O2 M. Hunyadi, A.M. van den Berg, N. Blasi, M. Csatlós, **L. Csige**, B. Davids, M. Fujiwara, U. Garg, J. Gulyás, M.N. Harakeh, A.M. de Huu, A. Krasznahorkay, D. Sohler, H.J. Wörtche

Recent results from the decay studies of high-energy isoscalar giant resonances

Acta Physica Polonica **B38** (2007)1479. (IF:0.664)

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Lepton pairs from a forbidden M0 transition: Signaling an elusive light neutral boson?

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Overtones of isoscalar giant reonances studied in direct particle decay measurements

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Decoupling of valence neutrons from the core in ^{16}C

Physics Letters **B586** (2004)34. (IF:4.619)