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MASS DISTRIBUTION OF THE FISSION FRAGMENTS FOLLOWING THE DECAY OF HYPERDEFORMED STATES IN ^{236}U

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Abstract

The double time-of-flight (TOF) technique was used to study the mass distribution of the fission fragments produced by the reaction ^{235}U(d,pf) in the excitation energy region of E^{*}=5.0-6.5 MeV, where several hyperdeformed (HD) fission resonances had been observed previously. The mass distribution of the fragments produced by the decay of HD states was measured and compared to the mass distribution of the prompt fission products in order to confirm the theoretically predicted di-nuclear configuration of the HD states in ^{236}U. For this purpose a 4π TOF fission detector array has been installed at ATOMKI very recently. In this paper the result of a preparatory experiment is presented, which shows no significant differences (within 1σ) in the widths of the mass distributions.

I. Introduction

Experimental and theoretical studies on fission, especially the spectroscopy of fission transmission resonances [1, 2] using (n,f) and transfer reactions like (d,pf) or (^{3}He,df) in the region of the actinides, have already served extensive information on the structure of states having exotic nuclear shapes. In many uranium and thorium isotopes the observed fine structure of these resonances could be ordered into rotational bands with extremely large moments of inertia corresponding to states in a third, so-called hyperdeformed (HD) minimum of the fission barrier [3, 4, 5]. On the other hand important information can be obtained on the dynamics and on the scission-point configuration of the fissioning system by measuring the fission fragment mass and energy distributions.

Theoretical calculations showed that the density distribution of those nuclei having HD configuration resembles a di-nuclear cluster, consists of a doubly magic and a well-deformed nucleus [6]. In such a case one would expect that the mass distribution of the fission fragments produced by the decay of the HD resonance is influenced by the di-nuclear structure of the underlying well-deformed state. The mass distribution should have an increased yield around the cluster mass numbers A≈100 and A≈136, while the yield of any other configurations (fragment mass numbers) should be suppressed. The aim of our present experiment was to search for this predicted effect by measuring the mass distribution of the fission fragments following the decay of the HD states in ^{236}U. A possible sharpening of the mass distribution could be a dramatic manifestation of the fact that the shell effects have a strong influence also on the fission process.

II. Experimental methods

The experiment was performed at the Debrecen 103 cm isochronous cyclotron laboratory employing the ^{235}U(d,pf) reaction with a deuteron beam energy of E_d=9 MeV and beam current of $_d$=100 nA. An enriched (97.6%), 88 g/cm^2 thick $^{235}UO_2$ target with a 30 g/cm^2 carbon backing was used. The essence of the experiment was the measurement of the energy of the outgoing protons in coincidence with the fission fragments. The energy of protons was analyzed by a four-folded, high-resolution silicon detector array, while both the fragments flying opposite direction were detected by a 4π position sensitive fission detector array [7], which had recently been upgraded at our institute. The arrangement of the experimental setup together with some of the relevant dimensions can be seen in Figure 1.

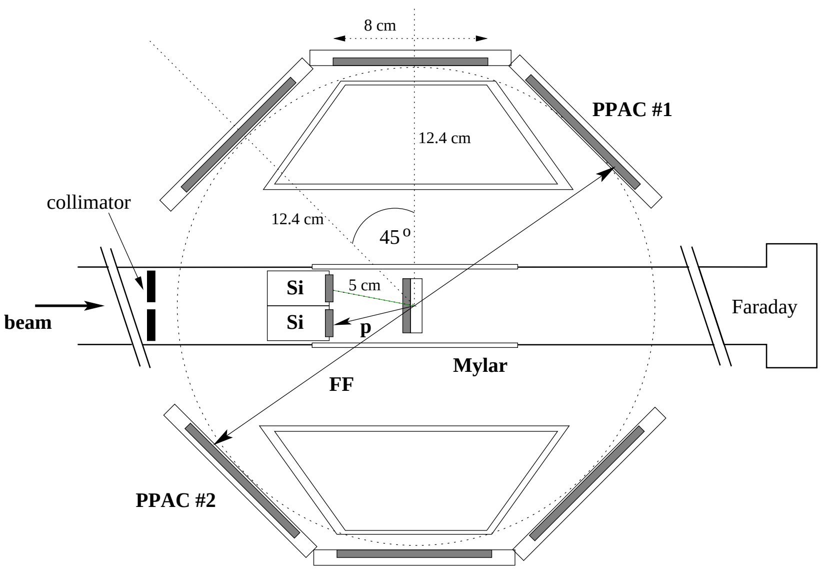

Figure 1: Schematic layout (viewed from above) of the experimental setup. The and abbreviations denote the fission fragments and protons, respectively.

The 4π fission detector array consists of low pressure, multi-wire, position sensitive PPAC units. The left and right hemispheres are covered by five PPACs, each arranged like an obelisk, one square detector and four trapezoidal detectors with an active area of =64 and 96 cm^2, respectively. The distance between the target and the outer detectors is =12.4 cm, so almost 50% of the complete solid angle (4π) is covered by the sensitive detector areas. The detector is typically operated at a gas pressure of =4-5 mbar of iso-butane (C H). Due to the low pressure an excellent time resolution can be achieved (Δ <0.4 ns), which allows to determine the mass distribution by applying the double time-of-flight (2) technique. In the present experiment the obtained mass resolution was mainly limited by the energy loss of the fragments in the 2 m thick Mylar foil of the inner chamber and by the energy loss in the detector gas volume. The final resolution amounted to about Δ =4 amu.

The energy of the protons was analyzed by high resolution Si detectors having a thickness of 500 m. A solid angle of Ω=30 msr was covered by each detector. The calibration of the array was performed by using an AMR-33 emitter source, which has lines at E_{α}=5.147 (^{23} Pu), 5.428 (^{2} Am) and 5.798 (^{2} Cm) MeV. An excellent energy resolution of ΔE=14 keV was achieved for the particles. The start signal for the TOF measurement was also provided by the proton detectors.

II. Results, discussion

The excitation energy of the compound ^{236}U nucleus was determined from the kinetic energy of the proton ejectiles. The ground state value for the reaction is =4.321 MeV, which was calculated using the NNDC Q-value calculator. The measured excitation energy spectrum of ^{236}U between E^{*}=5.0 and 6.5 MeV is shown in Figure 2. In the excitation energy region of E^{*}=5.0-5.6 MeV a number of transmission resonances have been observed in agreement with the results of a previous experiment [4], in which the rotational fine structure of these resonances had been resolved and their HD character had been proven. A continuous curve was drawn on the spectrum in order to guide the eyes.

The method for the fragment mass determination is the following. At the scission point the compound nucleus of mass $_{c}$ breaks into two fragments. Keeping the momentum and the mass conservation laws the fragments are emitted under 180 , so for the masses we found:

$${}_{,2} = \frac{{}_{2,}}{+\ {}_{2}}\ {}_{c} \qquad (1)$$

where $_{,2}$ and $_{,2}$ stand for the primary fragment masses and velocities, respectively. The primary velocities cannot be measured since the charac-

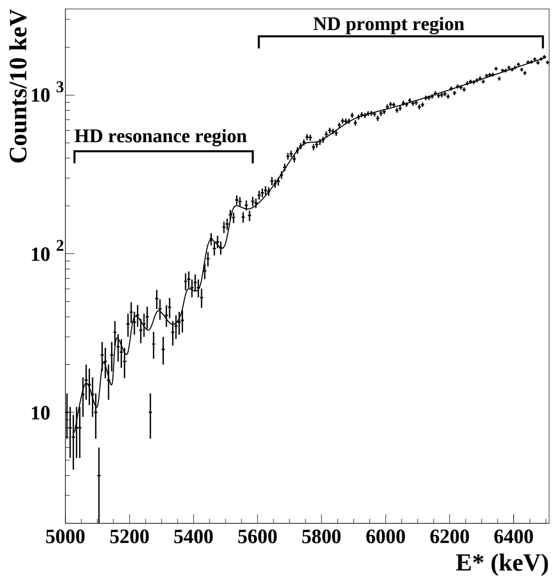

Figure 2: Excitation energy spectrum of ^{236}U between E^{*}=5.0-6.5 MeV. Fission resonances have been observed in the excitation energy region of E^{*}=5.0-5.6 MeV. These resonances have HD character according to [4]. The region of the prompt fission is also indicated. The continuous line is only for guiding the eyes.

teristic time of the neutron evaporation is about t=10 s after fission. However, if we assume an isotropic neutron evaporation, which takes place after the fragments reach their final velocities, then on the average there are no changes on the velocities. Certainly the resolution for the secondary fragment masses is still limited by the broadening that originates in the neutron emission.

For the determination of the fragment velocities one has to measure the time in an absolute manner. However, the precise measurement of the so-called time-zero (time difference in the delays of the different timing channels) is a very tedious task, and even a small initial error could finally induce a large systematic uncertainty in the deduced quantities. Thus we used the evaluated fragments mass parameters of ^{236}U for the mass calibration of the TOF array, which were taken from Ref. [8]. In this reference (n,f) experiment the mass distribution was measured by using the ($2E$,2) technique with a resolution of Δ =1 amu (FWHM). Having the mass calibration parameters mass distributions of ^{236}U were generated using the following conditions: gated by the excitation energy regions of the HD resonances (Figure 3.a) and gated by the prompt fission events (Figure 3.b).

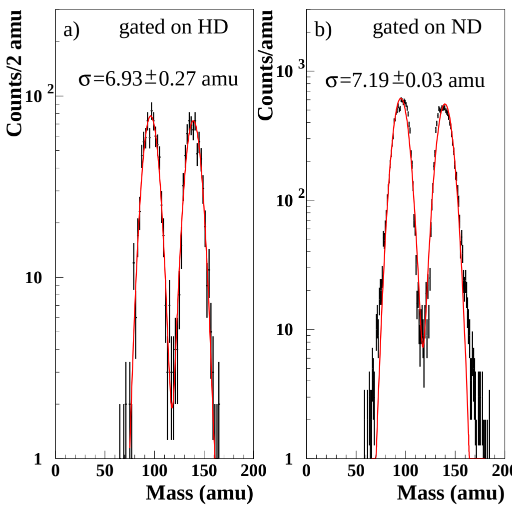

Figure 3: Mass distribution of ^{236}U gated by a) the HD resonances and by b) the prompt region. Double Gaussian functions were fitted to both experimental distributions in order the compare the widths.

Double Gaussian functions were fitted to our experimental data in order to extract the widths of the mass distributions. The following values have been obtained for the widths: σ_{HD}^{exp}=6.93±0.27 amu for the HD resonance region and σ_{ND}^{exp}=7.19±0.03 amu for the prompt region. Here, the error bars represent *only* the statistical uncertainty (1σ). The deduced widths are equal within 1σ, the observed small deviation cannot be considered as a conclusive evidence for a clusterization effect.

Based on the experiences of the present test experiment we propose a new measurement with an improved setup. A new layout of the inner chamber equipped with a thinner (0.9 m) Mylar foil is considered, which could drastically reduce the energy-loss in both the foil and the gas volume of the detector. On the other hand a proper fission event reconstruction with a precise energy-loss correction is mandatory in the data analysis; precise corrections for the fragment energy-losses in the target-backing, in the Mylar foil of the inner chamber, and in the gas volume of the detector are of great importance. Having all these improvements in both the setup and the data analysis an excellent mass resolution of Δm$\approx$2 amu (FWHM) could be achieved.

Acknowledgement

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