HIGH RESOLUTION SPECTROSCOPY IN THE THIRD MINIMUM OF ^{232}Pa*

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The fission probability of ^{232}Pa was measured as a function of the excitation energy in order to search for hyperdeformed (HD) transmission resonances using the (d,pf) transfer reaction on a radioactive ^{231}Pa target. The experiment was performed at the Tandem accelerator of the Maier–Leibnitz Laboratory (MLL) at Garching using the ^{231}Pa (d,pf) reaction at a bombarding energy of $E_d = 12\,\mathrm{MeV}$ and with an energy resolution of $\Delta E = 5.5\,\mathrm{keV}$. Two groups of transmission resonances have been observed at excitation energies of $E^* = 5.7$ and $5.9\,\mathrm{MeV}$. The fine structure of the resonance group at $E^* = 5.7\,\mathrm{MeV}$ could be interpreted as overlapping rotational bands with a rotational parameter characteristic to a HD nuclear shape ($\hbar^2/2\Theta = 2.05\,\mathrm{keV}$). The fission barrier parameters of ^{232}Pa have been determined by fitting TALYS nuclear reaction code calculations to the overall structure of the fission probability.

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1. Introduction

The observation of discrete γ transitions between hyperdeformed (HD) nuclear states represents one of the last frontiers of high-spin physics. Although a large community was searching for HD states with 4π arrays in very long experiments, no discrete HD γ transition was found in the mass region of $A \approx 100$–130 [1]. On the other hand, the existence of low-spin

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hyperdeformation in the third minimum of the fission barrier is firmly established both experimentally and theoretically in the actinide region [2]. 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 can specify the excitation energies of the HD states. Moreover, the observed states could be ordered into rotational bands and the moments of inertia of these bands can characterize the underlying nuclear shape proving that these states have indeed HD configurations.

Regarding hyperdeformation, the double-odd nucleus ^{232}Pa is of great interest. Even though low-spin hyperdeformation has already proven to be a general feature of the uranium and thorium isotopes [3,4], no HD state has been found in protactinium isotopes so far. In addition, the level scheme of ^{232}Pa is yet completely unknown in the 1$^{\text{st}}$ minimum of the potential barrier, presently only the ground-state properties are known ($\mathrm{I}^{\pi}_{\mathrm{gs}} = 2^-$) [5]. The fine structure of the fission resonances of ^{232}Pa has been studied so far only via the (n,f) reaction [7] with high resolution, but the results showed no convincing evidence on the existence of HD states. A possible reason was the rather limited momentum transfer of the (n,f) reaction at that low neutron energy ($E_n \approx 100\,\mathrm{keV}$), which did not allow for the population of rotational bands. In contrast, the (d,p) reaction can transfer considerable angular momentum, thus full sequences of rotational states with higher spins can be excited. In our recent experiment the fission probability of ^{232}Pa was measured as a function of the excitation energy with high resolution in order to search for HD rotational bands using the ^{231}Pa (d,pf) reaction.

2. Experimental setup

The experiment was carried out at the Tandem accelerator of the Maier–Leibnitz Laboratory (MLL) in Garching employing the ^{231}Pa (d,pf) reaction with a bombarding energy of $E = 12\,\mathrm{MeV}$ to investigate the fission probability of ^{232}Pa in the excitation energy region of $E^* = 5.5$–$6.2\,\mathrm{MeV}$. Enriched (99%), 70 μg/cm^2 thick radioactive target of ^{231}Pa was used on a 20 μg/cm^2 thick carbon backing. The ground-state Q-value for the reaction is $Q = 3.324\,\mathrm{MeV}$, which was calculated using the NNDC Q-value calculator. The excitation energy of the fissioning nucleus was derived from the kinetic energy of the outgoing protons, that was measured by a Q3D magnetic spectrograph set at $\Theta_{\mathrm{lab}} = 139.4^\circ$ relative to the beam direction. The well-known lines of the ^{208}Pb (d,p) reaction were applied to perform the energy calibration of the focal plane detector [6]. The experimental energy resolution was deduced to be $\Delta E = 5.5\,\mathrm{keV}$ (FWHM) in the energy region of our interest. Fission fragments were detected in coincidence with the outgoing protons by two position sensitive avalanche detectors (PSAD) with a solid angle coverage of 20% of 4π.

3. Results and discussion

3.1. HD fission resonances of ^{232}Pa

The measured high-resolution fission probability spectrum of ^{232}Pa is shown in Fig. 1 as a function of the excitation energy of the fissioning nucleus in the region of $E^* = 5.5$–6.2 MeV. The random coincidence contribution was subtracted by using the well-defined flight-time difference of protons and fission fragments. Two resonance groups can be clearly seen at $E^* = 5.7$ and 5.9 MeV in a fair agreement with the results of the (n,f) experiment [7]. In the (n,f) experiment, low-energy neutrons ($E_n = 120$–420 keV) were used to populate the states in the compound nucleus. In this case s-wave neutron capture is the main process and the transfer momentum is principally limited to $1\hbar$, thus rotational bands could not be excited. On the other hand, the fission fragment angular distribution (FFAD) data supported a $K = 3^+$ assignment for the resonance at $E_n = 156.7$ keV. Together with a possible $K = 3^-$ assignment for the resonance at $E_n = 173.3$ keV, which could not be ruled out by the FFAD data, these two resonances could be the bandheads of two close-lying K-bands with opposite parities, a well-known consequence of the octupole deformation in the third minimum of the fission barrier. However, having no information on the moment of inertia, this result could not be considered as a direct evidence on the existence of a HD minimum.

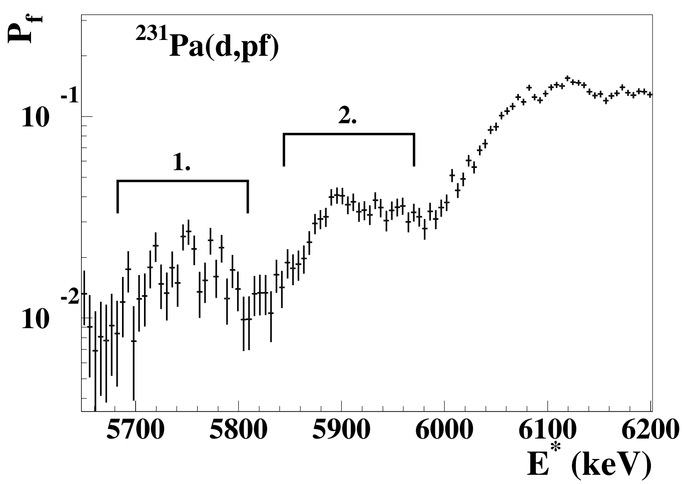

Fig. 1. The measured fission probability of ^{232}Pa in the excitation energy range of $E^* = 5.5$–6.2 MeV. Two resonance groups have been observed at around $E^* = 5.75$ and 5.9 MeV in agreement with the results of a previous (n,f) experiment [7].

Due to the low neutron separation energy of ^{232}Pa ($S_n = 5.455\,\mathrm{MeV}$), the fission probability is rather small (as can be seen in Fig. 1), which resulted in a very limited statistics at deep sub-barrier energies. To reduce the statistical fluctuations, we applied a widely used peak-searching method, the so-called Markov-chain algorithm [8]. This method can be also used to subtract the continuous fission background originating from the non-resonant tunneling process through the fission barrier. In the generated spectrum a number of sharp resonances could be clearly identified between $E^* = 5.7$ and $5.8\,\mathrm{MeV}$ (Fig. 2), moreover, the rotational structure of the resonances could be fitted with overlapping rotational bands. Gaussians were used to describe the different band members with a width equal to the experimental resolution ($\Delta E = 5.5\,\mathrm{keV}$). During the fitting procedure the energy of the bandheads and the intensity of the band members were treated as free parameters and a common (fixed) rotational parameter was adopted for each band. The result of the fitting procedure is presented in Fig. 2. The picket fence structure of the bands is also indicated in the figure. As a result, the observed fine structure could be described as a sequence of three overlapping rotational bands with a $K = 3, 4$ and 5 assignments for the bandheads at $E^* = 5717, 5740$ and $5744\,\mathrm{keV}$, respectively, and with a rotational parameter ($\hbar^2/2\Theta = 2.05\,\mathrm{keV}$) characteristic to HD nuclear shapes.

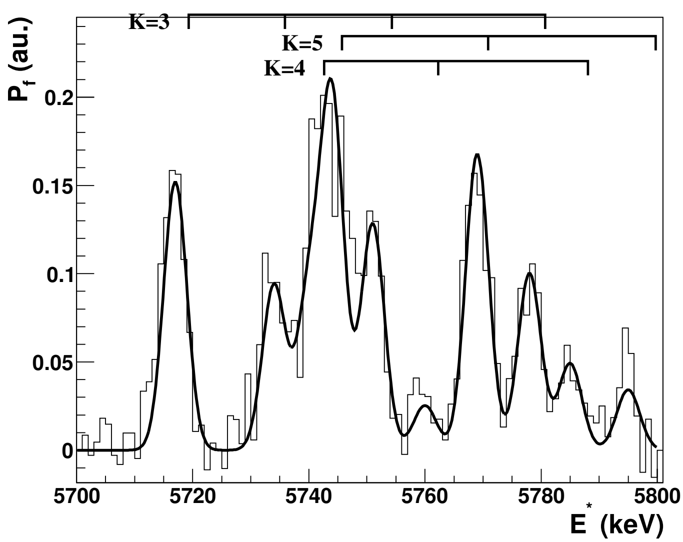

Fig. 2. The Markov-chain smoothed fission probability of ^{232}Pa as a function of the excitation energy between $E^* = 5.7$ and $5.8\,\mathrm{MeV}$. The continuous line represents the result of the fitting procedure. The picket fence structure of the bands is indicated as well as the corresponding K value of the band.

3.2. The fission barrier parameters of ^{232}Pa

In order to extract the fission barrier parameters of ^{232}Pa, we performed cross-section calculations on the ^{231}Pa (d,pf) reaction using the TALYS 1.2 nuclear reaction code [9]. In the code the fission transmission coefficient are calculated following the concept of the Hill–Wheeler formalism, which then enter the Hauser–Feshback statistical model to compete with the particle and photon emission. The fission barrier parameters, namely the barrier heights ($E_{A,B1,B2}$) and curvature energies ($\hbar\omega_{A,B1,B2}$) of a triple-humped fission barrier, are given as input parameters.

A very important ingredient of the cross-section calculations is the nuclear level density (NLD) both at equilibrium deformation and at the saddle points. The level density of a given nucleus at normal deformation can usually be determined by adjusting the level density parameters to obtain the best description of the low-energy, cumulative discrete level scheme as well as the s-wave neutron resonance spacings. However, in the case of ^{232}Pa no level scheme is available at present as already pointed out, so we could not extract the NLD parameters in this way. On the other hand, systematic investigations on the level densities showed that very simple analytic expressions can be used to estimate the NLD parameters involving some basic, nuclear quantities like the shell correction energy and the deuteron pairing energy [10]. In contrast to the level densities at normal deformation, the saddle level densities generally suffer from a serious lack of experimental information, however, good approximation can be achieved by introducing additional factors to the ground state NLD expressions to describe the rotational and vibrational enhancements at large deformations [11].

In Fig. 3 the experimental fission probability of ^{232}Pa is shown in the excitation energy region of $E^* = 5.2$–$7.5\,\mathrm{MeV}$ together with the result of the TALYS calculation (represented by a solid line) and the deduced fission barrier parameters. The measured data points of the present experiment ($E^* < 6.2\,\mathrm{MeV}$) were extended by the results of a previous, low-resolution ($\Delta E = 55\,\mathrm{keV}$) measurement [12] to cover a large energy interval. Class II (SD) and class III (HD) states were not introduced into the calculations, so the resonance region could not be reproduced at low excitation energies, however, at this level we only aimed at extracting the barrier parameters by taking the overall structure of the fission probability. A complete description of the cross-section was not a subject of the present work. Nevertheless, our final parameter set is in a good agreement (within $\approx \pm 220\,\mathrm{keV}$) with the results of Ref. [13], where the EMPIRE 2.19 nuclear code was used to extract the barrier parameters by calculating the neutron-induced fission cross-section of ^{232}Pa and fitting it to the experimental cross-section. It is important to point out, that beside the fission barrier parameters, no other adjustable parameters were involved into the calculation at any level.

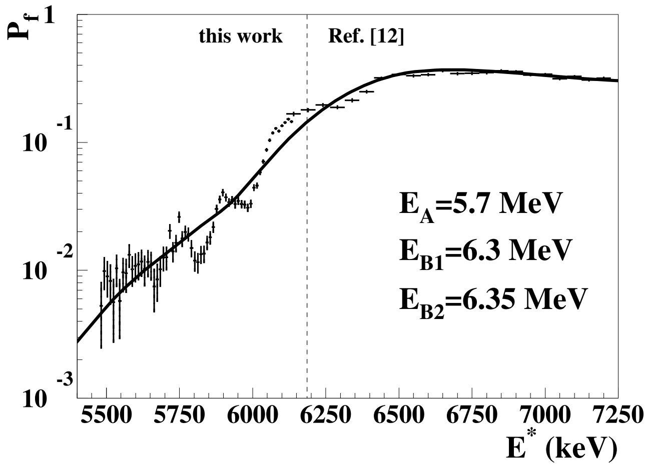

Fig. 3. Experimental fission probability of ^{232}Pa together with the result of the calculation (continuous line). The measured data points of the present experiment ($E^* < 6.2$ MeV) were extended by the results of a previous experiment [12].

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