TRANSMISSION RESONANCE SPECTROSCOPY OF THE DOUBLY ODD ^{238}Np IN (d,pf) REACTION*

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The fission probability of ^{238}Np was measured as a function of the excitation energy in the energy range of $E^* = 5.4$–6.2 MeV in order to search for hyperdeformed rotational bands using the (d,pf) transfer reaction on a radioactive ^{237}Np target. The experiment was performed at the Tandem accelerator of the Maier-Leibnitz Laboratory at Garching employing the ^{237}Np(d,pf) reaction at a bombarding energy of $E_d = 12$ MeV. Overlapping resonances have been observed at excitation energies around $E^* = 5.5$ MeV. These resonances could be ordered into a hyperdeformed rotational band by the preliminary analysis of the high-resolution excitation energy spectrum. The existence of a third minimum in the fission barrier of ^{238}Np is also supported by nuclear reaction code (TALYS1.4) calculations which was used to describe the experimental data.

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1. Introduction

The observation of discrete γ transitions between hyperdeformed (HD) nuclear states in the region of $A = 100$–130 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 this mass region [1]. On the other hand, the existence of low-spin hyperdeformation in the 3$^{\rm rd}$ minimum of the fission barrier is firmly established both experimentally and theoretically in the actinide region [2]. Observing resonances in the fission cross section as a function of the excitation energy caused by resonant tunneling through excited states in

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the 3rd minimum of the potential barrier can specify the excitation energies of the HD states, moreover, the observed states could be ordered into rotational bands. The moments of inertia of these bands can characterize the underlying nuclear shape proving that these states have indeed HD configuration. The measured high resolution fission cross section can also be used to explore the structure of the potential energy landscape of the fissioning nucleus.

Even though low-spin hyperdeformation has already proven to be a general feature of the light even–even actinides [3, 4], no such systematics has been established for the odd–odd actinides. However, in a recent experiment [5], we found conclusive evidences on the existence of HD bands in an odd–odd nucleus (^{232}Pa) [5], which suggested to start a systematic investigation of the odd–odd actinides. ^{238}Np is a very interesting isotope regarding hyperdeformation: it is an isobar of ^{238}U, where a hyperdeformed third minimum has already been settled [6].

2. Experimental setup

The experiment was carried out at the Tandem accelerator of the Maier-Leibnitz Laboratory (Garching) employing the ^{237}Np(d,pf) reaction with a bombarding energy of $E = 12$ MeV. The fission probability of ^{238}Np was measured in the excitation energy region of $E^* = 5.4$–6.2 MeV. Enriched (99%), 200 μg/cm^2 thick radioactive target of ^{237}Np was used on a 25 μg/cm^2 thick carbon backing. The ground-state Q-value for the reaction is $Q = 3.264$ MeV. 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 $\Theta_{\rm lab} = 139.4^\circ$ 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 [7]. The experimental energy resolution was deduced to be $\Delta E = 8$ 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

The measured high-resolution fission probability spectrum of ^{238}Np is shown in Fig. 1 (a) as a function of the excitation energy of the compound nucleus in the region of $E^* = 5.4$–6.2 MeV. The random coincidence contribution was subtracted by using the well-defined flight-time difference of protons and fission fragments. The experimental data of a previous, low-resolution ($\Delta E = 150$ keV) experiment [11] is also indicated. Overlapping transmission fission resonances can be seen around $E^* = 5.5$ MeV.

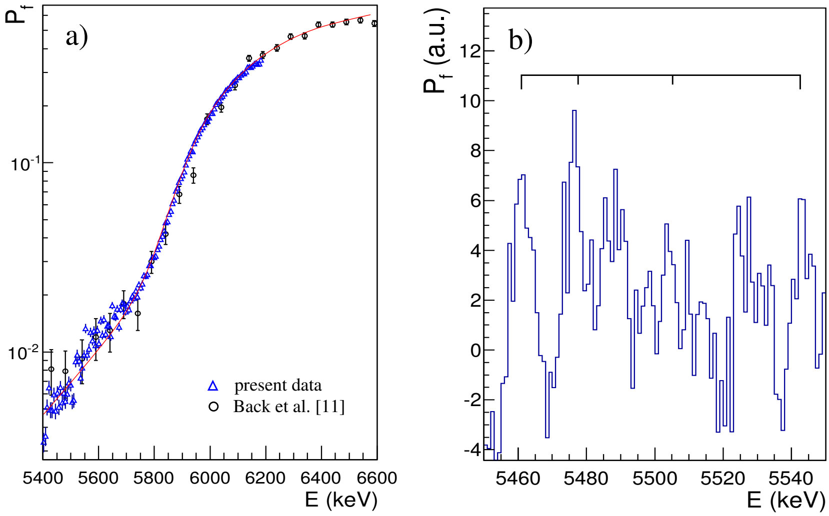

Fig. 1. (Color online) (a) Experimental fission probability of ^{238}Np in the excitation energy range of $E^* = 5.4$–6.2 MeV (open triangles) together with the result of the reaction code calculation (continuous line). Overlapping fission resonances have been observed around $E^* = 5.5$ MeV. The experimental data of a previous, low-resolution experiment [11] is also shown by open circles. (b) The Markov-chain smoothed fission probability of ^{238}Np as a function of the excitation energy between $E^* = 5.45$ and 5.55 MeV. The picket fence structure of a HD rotational band is indicated.

Due to the low neutron separation energy of ^{238}Np ($S_n = 5.488$ MeV), the fission probability is rather small (as can be seen in Fig. 1 (a)), which resulted in a very limited statistics at deep sub-barrier energies. To reduce the statistical fluctuations and to identify significant resonances, 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 $E^* = 5.45$ and 5.55 MeV (Fig. 1 (b)) which could be ordered into a rotational band. The rotational parameter of the band is characteristic to HD nuclear shape the corresponding picket fence structure of the band is highlighted in Fig. 1 (b).

In order to extract the fission barrier parameters of ^{238}Np, we performed cross section calculations of the ^{237}Np(d,pf) reaction using the TALYS1.4 nuclear reaction code [9]. In the code, the fission transmission coefficient is 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. An important ingredient of the cross section calculations is the nuclear level density (NLD) both at equilibrium deformation and at the saddle points. Since the level scheme of ^{238}Np is scarcely known, the NLD parameters were taken from systematics [10]. The result of the TALYS1.4 calculation is shown in Fig. 1 (a) (solid line). The fission barrier parameters were deduced to be $E_A = 5.5$, $E_{B1} = 6.2$, and $E_{B2} = 6.3$ MeV.

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