Entry distribution of ^{220}Th: A method to determine the fission barrier of an unstable nucleus

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In a fusion-evaporation reaction the total gamma-energy and multiplicity after particle evaporation - the so-called entry distribution - can be used to estimate the height of the fission barrier as function of angular momentum. This method is especially favorable for unstable nuclei, for which the fission barrier is otherwise very difficult to measure. Here, we have measured the entry distributions of ^{220}Th at beam energies of 206 MeV and 219.5 MeV in the ^{176}Yb(^{48}Ca,4n) reaction. The results are compared to a previous measurement using photofission.

1. INTRODUCTION

The height of the fission barrier is an important property of heavy nuclei, controlling their stability against spontaneous fission. In particular the life-times and decay modes of super-heavy elements are determined by the hight and shape of the fission barrier. Measuring this quantity for a wide range of nuclei is obviously important for the understanding of the structure of heavy nuclei.

The fission barrier plays also an important role in understanding the production cross sections of heavy nuclei in fusion-evaporation and in fragmentation-type reactions. Moreover, the renewed interest in the production of neutron-rich nuclei via in-flight fission of a relativistic primary ^{238}U beam requires also a knowledge on the fission barriers of nuclei, which might fission after abrasion and ablation of some nucleons.

Experimentally, the fission barrier is often very difficult to determine. High-precision

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experiments to determine the effective height of the fission barrier require stable or long-lived targets for measurements of the fission probability as a function of the excitation energy. Fission induced by neutrons or light-charged particles is very well suited for this method, as the formation of the compound nucleus in these types of reactions is very well understood. Unfortunately, this is not the case for heavy-ion induced reactions.

One method to determine the height of the fission barrier of proton-rich light actinides and preactinides has been proposed by Grewe et al. [1], who used electromagnetic excitation of relativistic secondary beams. Here, the measured fission cross section was matched with a model calculation of the excitation process, with the fission barrier as the only free parameter. The agreement with earlier measurements using conventional techniques is very good. The disadvantage of this method is, besides its model-dependence, the fact that it is not useful for isotopes which cannot be produced in fragmentation reactions.

Another attempt is to extract the height of the fission barrier from beta-delayed fission (see e.g. [2]). Here a beta-unstable nucleus populates states in its daughter nucleus, which are above the fission barrier. This method possess two drawbacks: first it is limited to isotopes, which populate the above-mentioned states after beta-decay. A second complication is that the extraction of the fission barrier height requires a detailed knowledge of this population, which is then again model-dependent.

A new alternative approach to estimate the height of the fission barrier of ^{254}No was proposed by Reiter et al. [3]. ^{254}No nuclei produced by the ^{208}Pb(^{48}Ca,2n) reaction were identified in a recoil separator. The recoil decay tagging technique confirmed that the mass identification is sufficient to separate the fusion gamma-rays from nobelium from a large background. The calorimetric properties of GAMMASPHERE were used to measure the total gamma-ray sum energy and multiplicity. The entry distribution (the two-dimensional distribution in spin and excitation energy after neutron evaporation) was obtained by correcting for the detector response. This method is applicable when the saddle-point energy (the fission barrier height plus the yrast energy) is below the neutron-separation energy. As the fission probability is expected to be dominant over the much slower deexcitation by gamma emission, the entry distribution is limited by the fission barrier, thus allowing an estimate of its height, which was in the case of ^{254}No at least 5 MeV.

One major advantage of this method is the fact that it is the only way to study the spin-dependence of the fission barrier. For ^{254}No, the data show the fission barrier to be remarkably stable against spin, which is attributed to the fact that the ground-state shell correction is predominantly responsible for the fission barrier.

To test this entry-distribution method for the determination of the fission barrier height, a measurement on a nucleus whose fission barrier has been determined with a different experimental technique is necessary. Unfortunately, nuclei which were studied with neutron or light-charged particle emission are not accessible for fusion-evaporation reactions. The ^{220}Th system was chosen however because this nucleus has been studied by Grewe et al. [1], using electromagnetic excitation as described above. As theoretical expectations for the height of the fission barrier of this nucleus do not agree (see discussion in ref. [1] and references therein) it is also interesting from the theoretical point of view. The fission barrier of ^{220}Th is expected to show a much stronger spin dependence than for ^{254}No, as it is derived largely from a liquid-drop term that decreases with spin.

2. EXPERIMENT AND DATA ANALYSIS

The ATLAS accelerator at Argonne National Laboratory provided a ^{48}Ca beam, impinging on a ^{176}Yb target with a thickness of 0.81 mg/cm^2. For the measurement, beam energies of 206 MeV and 219.5 MeV were chosen. The lower beam energy is centered at the maximum production cross section; the higher beam energy was used to test whether additional angular momentum could be brought into the system. Gamma radiation was detected using GAMMASPHERE, an array of 101 BGO-shielded germanium detectors. The recoils were selected and identified with the Argonne Fragment Mass Analyzer (FMA) using a position-sensitive parallel-grid avalanche counter (PGAC)to measure the mass-over-charge spectrum for identification of the residues. This identification was confirmed by implanting the recoils into a double-sided silicon strip detector (DSSD) and measuring the subsequent alpha-decay. Due to the short half-life of ^{220}Th (9.7 μs) the use of the recoil decay tagging (RDT) technique was not possible, as it would reduce the efficiency too much. In the case of the lower beam energy this is not a problem because ^{220}Th was the most dominant channel. For the higher beam energy the production rate of ^{219}Th is about as high as that of ^{220}Th, but mass identification was sufficient to separate the two products. Later, an RDT condition will be used to test whether the tails of the ^{219}Th peak in the focal-plane spectrum have an influence on the entry-distribution of ^{220}Th at all. Scattered beam particles at the focal plane were excluded by measuring the energy loss of the recoils in the DSSD as a function of the time-of-flight between the PGAC and the DSSD. In this spectrum, recoils and scattered beam particles were clearly separated. Using the above-mentioned conditions and additional conditions on the time-of-flight between the accelerator RF and the firing germanium or BGO detectors to suppress random events, the measured gamma sum-energies and the module multiplicity for ^{220}Th residues was obtained. A module is defined as one germanium detector of GAMMASPHERE with its surrounding BGO shields.

2.1. Unfolding and conversion

The measured gamma sum-energy as well as the multiplicity have to be corrected for the response of GAMMASPHERE in order to obtain the total gamma energy and multiplicity. The sum-energy and multiplicity responses of GAMMASPHERE to 898-keV photons was measured with a ^{88}Y source, using an event-mixing technique [4]. The response was used to unfold the measured data using a Monte-Carlo simulation procedure [5]. The final energy-multiplicity distribution was also corrected for the multiplicity dependence of the trigger efficiency, as the trigger of GAMMASPHERE required a minimum of two detectors firing in coincidence.

To convert multiplicity into spin (I) we used the relation:

$$I = \Delta I * (m - m_{stat}) + \Delta I_{stat} * m_{stat} + I_{elec}$$

Here, ΔI_{stat} is the spin carried away by a statistical gamma ray, m_{stat} is the multiplicity of statistical gamma rays, ΔI and m are the respective quantities for non-statistical gamma rays. For the calculation the values $\Delta I_{stat} = 0.5$, $m_{stat} = 4$ and $\Delta I = 1.75$ were chosen. I_{elec}, the spin carried by conversion electrons, is, for the moment, taken to be zero, but needs to be added later (after the electron contribution has been determined).

3. RESULTS AND DISCUSSION

The measured entry distributions of ^{220}Th for the two beam energies are shown in figure 1. The two distributions look very similar, which is remarkable. The larger amount of fluctuations for the higher beam energy is due to the fact that the statistics for the entry distribution is about one order of magnitude lower than that for $E_{Beam} = 206$ MeV. It is significant that the maximum spin appears to be about $20\hbar$ in both cases, which suggests that this is the maximum angular momentum that this nucleus can withstand. The entry distribution does not follow the yrast line as might be expected, but is tilted with respect to it. This is similar to the results obtained for ^{254}No [3]. This behavior is not understood, as the phase space for low energies and low angular momenta is expected to be small. Reiter *et al.* [3] proposed the emission of pre-compound neutrons as an explanation.

Concerning the excitation energy, the entry distribution does not reach below the yrast line, as it is expected. The saddle point energy is the sum of the fission barrier and the yrast energy [8]. The saddle point energy shown in figure 1 is calculated as the sum of the ground-state shell effect [6] and a spin-dependent liquid-drop component [7]. The entry distribution reaches well beyond the boundary given by the saddle-point energy, which indicates a fission barrier higher than the expected value.

The neutron separation energy shown is the sum of the neutron-separation energy at spin zero [6] and the yrast energy. The neutron separation energy is not a hard cutoff in excitation energy either, which is expected, as the neutrons carry kinetic energy and the phase-space close to the threshold is very small.

It is important to note that in ^{220}Th the fission barrier and the neutron separation energy are expected to be much closer than in the ^{254}No case. Thus, the upper limit of the entry distribution might be determined by either of the two.

In figure 2 projections of the entry distributions of figure 1 on the spin and energy axis are shown. The cutoff in spin at $20\hbar$ is again revealed. The excitation energy distribution drops less sharply for the higher beam energy and shows a rather slow decrease.

The maximum excitation energy, which is the kinetic energy in the center-of-mass system minus the Q-value, is 14.9 MeV in the for $E_{Beam} = 206$ MeV and 25.1 MeV at $E_{Beam} = 219.5$ MeV. The maximum excitation energies were calculated for the center of the target.

The maximum of the energy of the entry distribution at $E_{Beam} = 206$ MeV and at $E_{Beam} = 219.5$ MeV are comparable, which means that the average kinetic energy of the neutrons is significantly higher in the latter case as it is expected due to the higher excitation energy.

To obtain an estimate for the fission barrier the half-maximum values at a given spin were used. The data suggest a fission barrier of at least 10 MeV at a spin of 15 $\hbar$, which is closer to the value of 9 MeV calculated by Pashkevich [9].

Further analysis is in progress to confirm the multiplicity-spin conversion and to compare our results with a statistical model calculation. A subtraction of random events will be done as well. For the future it would be very interesting to study the entry distribution of ^{220}Th by using different projectile-target combination in order to gain a deeper understanding of the reaction mechanism.

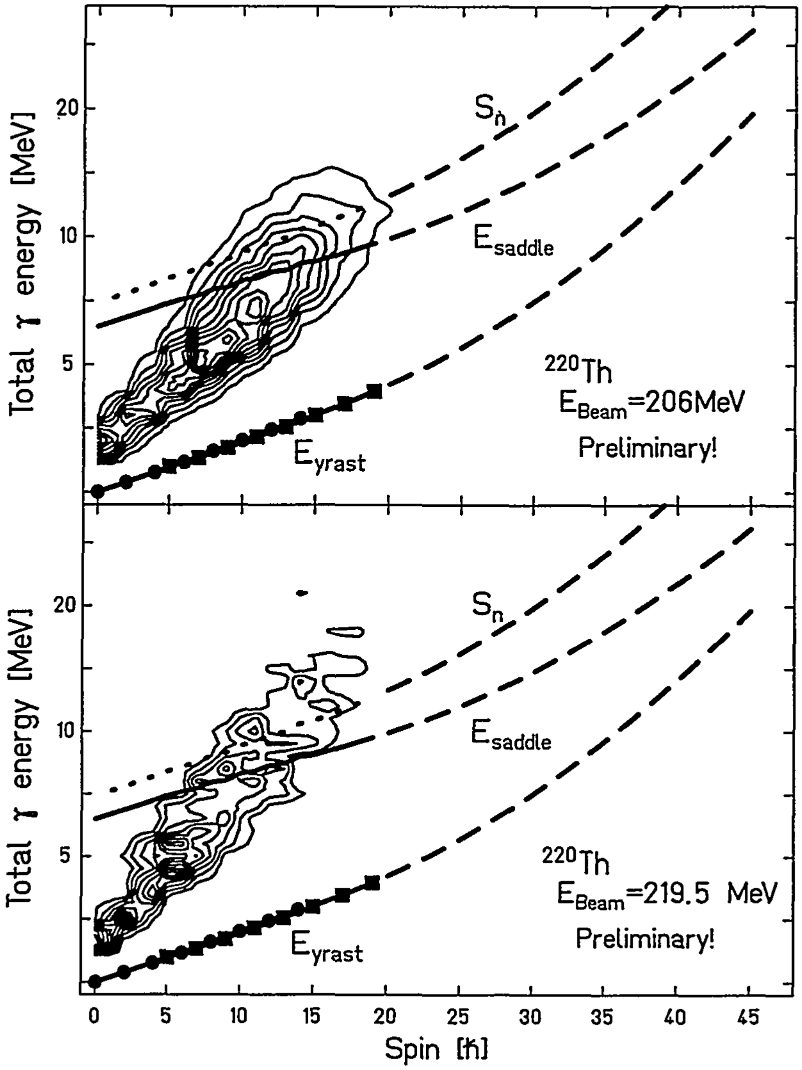

Figure 1. Preliminary entry distributions of ^{220}Th at a beam energy of 206 MeV and 219.5 MeV. In the figure, the yrast line, the neutron-separation energy S_n and the saddle-point energy E_{saddle} are shown. The saddle point energy is defined as $E_{saddle}(I) = E_{yrast}(I) + B_f(I)$, with $B_f(I)$ being the fission barrier at a given angular momentum I. $B_f(I)$ is calculated as the sum of a liquid drop component [7] and the ground-state shell effect [6]. The dashed lines are extrapolations. The yrast line data have been taken from reference [8]. The neutron separation energy shown is calculated according to $S_n(I) = S_n(I=0) + E_{yrast}(I)$. $S_n(I=0)$ is calculated by using masses from reference [6]. The lowest cut in both figures corresponds to a limit of 20 in yield (arbitrary units).

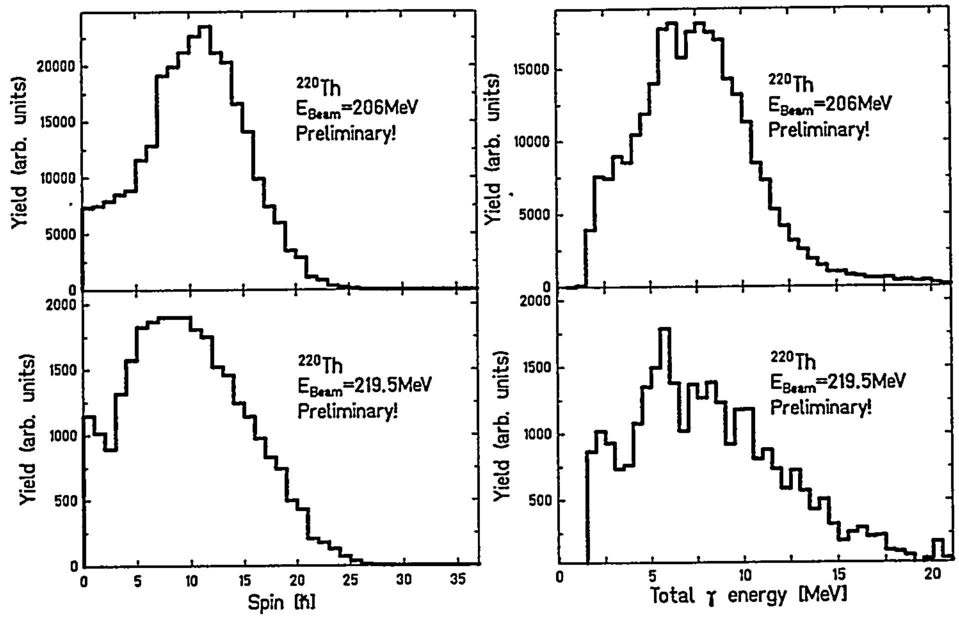

Figure 2. Projections of the entry distributions (preliminary data) shown in figure 1 with respect to spin and total gamma-energy.

4. ACKNOWLEDGEMENTS

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