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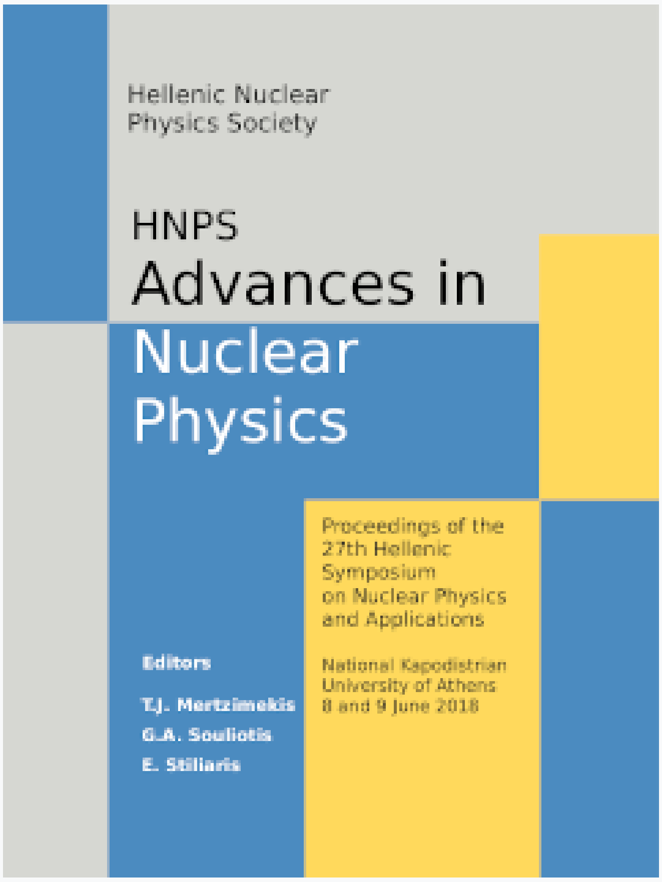

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Direct measurement of fission barrier height of unstable heavy nuclei at ISOL facilities

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Abstract Fission barrier height is one of the least known nuclear parameters, with experimental data, acquired decades ago, existing only close to beta-stability line. Availability of heavy radioactive beams offers possibility to investigate fission of more exotic nuclei and using the state of the art detection technique such as the active target we can even probe their fission barriers heights with precision has not been reached so far. The present status of fission barrier measurement is going to be explained in this paper. We are going to discuss the possibilities to stage experimental studies of fission barrier heights at new generation of ISOL facilities such as HIE-ISOLDE and active target ACTAR TPC. As an example we select the experiment IS581, being prepared for execution at the HIE-ISOLDE facility (CERN).

Keywords fission barrier height, transfer induced fission (d,pf), active target ACTAR TPC, ISOL facilities

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INTRODUCTION

The conditions created in explosion of neutron star marger enable r-process nucleosynthesis and thus creation of approximately half of the abundances of the atomic nuclei heavier than iron, usually synthesizing the entire abundance of the two most neutron-rich stable isotopes of each heavy element. Spontaneous fission is expected to contribute in environments with such large neutron densities when the fission barrier height may be low enough that neutron capture can induce fission instead of continuing up the neutron drip line. The most of fission barriers heights derived from experiments were obtained by more than 30 years ago. The summary of obtained fission barriers height we can find in the [1], Fig.1. However, due to methodology a very little progress was done up to the present. The most fission barriers were measured for nuclei from the vicinity of β-stability line. Measurement of fission barriers of Radium isotopes and more massive elements have been investigated via transfer-induced fission reactions (d,pf). Beside transfer reactions, compound nucleus reactions have been used to induce fission of Ytterbium and nuclei up to Radium. The experimental measurement of fission barriers and fission rates in induced fission is demanded in NuPECC Long Range Plan 2017 as precise measurements of fission barriers are very attractive for nuclear theory. In this paper we present fission experiment with radioactive ion beams and state-of-art active target detector ACTAR TPC, proposed to INTC commission (CERN) under title “Determination of the fission barrier height in fission of heavy radioactive beams induced by the (d,p)-transfer”. The first goal of our effort is to realize the experiment IS581, approved by INTC commission at CERN, at HIE-ISOLDE facilities using the ACTAR TPC detector where it is possible to collect experimental data of transfers and fission products with precision have not been accessed by other detection system or methodology so far. For the experiment the following odd-odd isotopes have been chosen as candidates for measurement of fission barrier: ^{194}Tl, ^{200}Bi, ^{202}At, ^{210}Fr, Fig.2.

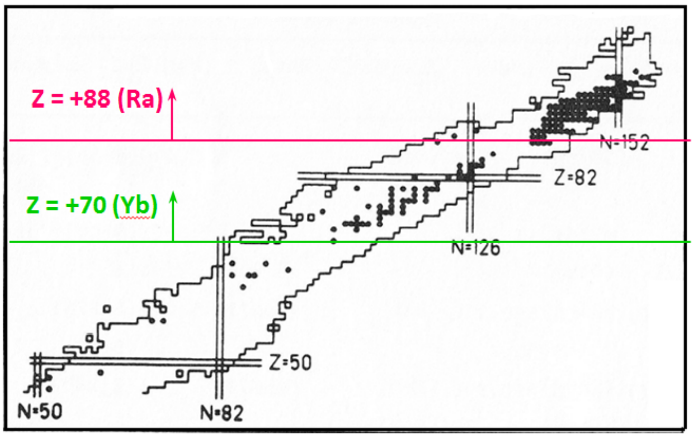

Figure 1. Chart of nuclides.
Nuclei for which the fission barrier was determined experimentally are indicated by an asterisk [Dah82].

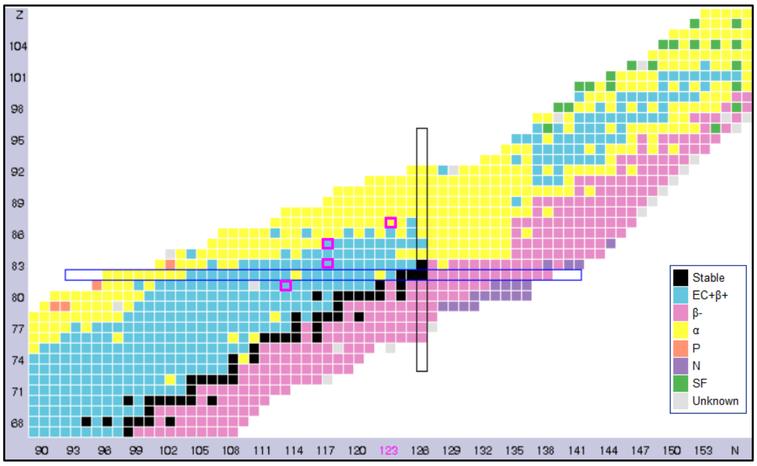

Figure 2. ^{193}Tl, ^{199}Bi, ^{201}At, ^{209}Fr [NNDC]: the ions proposed to induce fission in (d,pf) reactions

Probability of low energy fission

Typically, only the two most dominant channels, i.e. fission and γ-rays emission, are considered at sufficiently low excitation energies, such e.g. in β-delayed fission, where the upper limit of excitation energy E^*_{max} is determined by the value of decay energy Q_{EC}. Due to the high neutron separation energy in the neutron-deficient nuclei emission of neutron is hindered in such region of excitation energies. The emission of protons, which have lower separation energy than neutrons in the neutron-deficient nuclei, is hindered because of the Coulomb barrier. The β-delayed fission of ^{178,180}Tl was investigated at ISOLDE [2] and the fission barriers were determined using the experimental probabilities of β-delayed fission in the work [3], using the version of the formula (1) for β-delayed fission [4]

$$P_{LEf} = \frac{\int_0^{E^*_{max}} W(E^*) \frac{\Gamma_f(E^*)}{\Gamma_f(E^*) + \Gamma_\gamma(E^*)} dE^*}{\int_0^{E^*_{max}} W(E^*) dE^*}, \tag{1}$$

with $W(E^*) \propto F(Q_\beta - E^*) S_\beta(E^*)$ where $F(Q_\beta - E^*)$ is the statistical Fermi function, and $S_\beta(E^*)$ is β-strength function. In the work [3], the measured probabilities of the β-delayed fission for ^{178,180}Tl were used to deduce the fission-barrier heights of the daughter isotopes ^{178,180}Hg, undergoing low-energy fission. Four alternative β-decay strength functions and four variants of the statistical model of de-excitation of the daughter nucleus were used to determine the fission barrier height for ^{180}Hg. The fission barrier height of ^{180}Hg was estimated to be in the range of 6.76-8.96 MeV [3]. The estimation varies with different approach in calculation of the level densities at the intermediate state and at the saddle point of daughter nucleus after β-delayed fission. However, this range of energies is lower than all theoretical fission barriers which spread out in the range of 9.69-11.40 MeV [3]. Depending on the choice of the model, the deduced fission-barrier height appeared to be between 10 and 40 % smaller than theoretical estimates. This observation was verified also for fission-barrier heights extracted using the probability of β-delayed fission of ^{178}Tl. This confirms the well-known discrepancy between the experimentally deduced and calculated fission barriers for the extremely neutron-deficient nuclei. The spread in extracted fission-barrier heights resulted mainly from uncertainties in the magnitude of the pairing gap at the saddle configuration. For the intermediate state configuration, after β-decay, the pairing gap energy is relatively god knows instead of the saddle point. The discrepancies between statistical and theoretical models are shown on the Fig. 3.

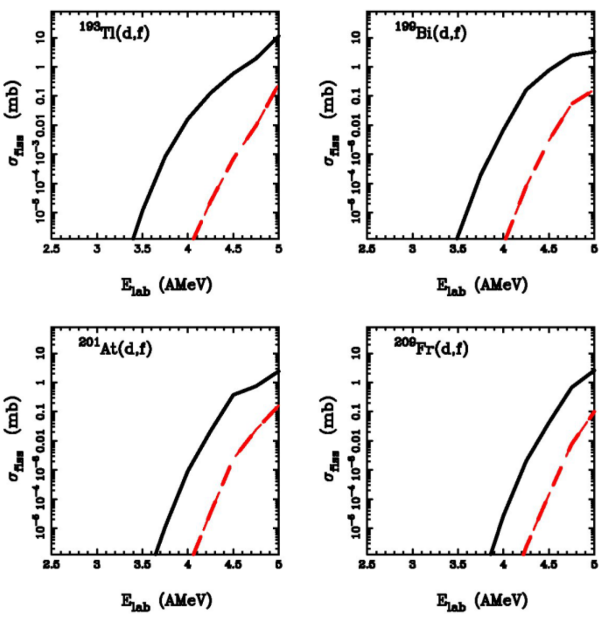

Figure 3. The visible shift of (d,pf) –transfer fission cross section between the statistical model (solid line) and model of Sierk (dashed line) is about 15-20 % higher. The experiment IS581 can clarify discrepancy between these models and to get precise data for short lived isotopes

EXPERIMENTAL DETAILS

In the field of fission barrier measurement the (d,pf)-reaction and β-delayed fission are the tools how we can measure them for exotic nuclei. β-delayed fission allows to study the low energy fission around the fission barrier of RIB in the region of the heavy neutron-deficient and in the neutron-rich nuclei. However, two conditions must be satisfied: non zero β-branchin ratio $b_\beta > 0$ and the $Q_{EC\beta-}$ value of the parent nucleus greater or equal to fission barrier, i.e. $Q_{EC\beta-} \geq B_f$. Because the condition $Q_{EC\beta-} \geq 0$ is usually filled the in even-even nuclei there is a restriction for measurement of even-odd, odd-even or odd-odd nuclei. The other point is that uncertainty of fission barrier measurement of even-even nuclei is higher due to uncertainty of the pairing energy at the saddle point configuration.
The use of the (d,pf)-reaction of the post-accelerated heavy RIB with energies up to 5.5 MeV AMeV, delivered by the HIE-ISOLDE, can overcome few limitations faced in the study of β-delayed fission with RIB. When using the RIB of odd-even nuclei, one can observe fission of odd-odd nuclei and thus remove the uncertainties due to unknown pairing gap in the saddle configuration. Furthermore, the use of experimental setup with the active target ACTAR TPC allows measuring the fission excitation function at once and thus getting more precise values of fission barriers. From measurement of excitation function we get multiple probabilities, obtained for different kinetic energies at different position of RIB in the ACTAR TPC. Such fission barriers are much better constrained.
The formula (1) needs to be converted by substituting the probability to populate a given excited state W(E*) by the differential cross section of the (d,pf)-reaction. Where the E* is excitation energy of projectile like heavy residue and Ebeam represents beam energy at a given position in the ACTAR TPC. Then the formula can be rewritten following

$$\boldsymbol{P_{LEf}} = \frac{\int_0^{E^*_{max}} \left(\frac{d\sigma_{(d,p)(E_{beam})}}{dE^*}\right) \frac{\Gamma_f(E^*)}{\Gamma_f(E^*) + \Gamma_\gamma(E^*)} dE^*}{\int_0^{E^*_{max}} \left(\frac{d\sigma_{(d,p)(E_{beam})}}{dE^*}\right) dE^*} \tag{2}$$

If statistics will be sufficient the values of $(d\sigma_{(d,p)(E_{beam})}\, dE^*)$ differential cross section can be determined directly from kinematics, or otherwise, from a measurement of inclusive cross section $(d\sigma_{(d,p)(E^*,E_{beam})})$ which is equal to the expression in the denominator of the formula (2). The differential cross section can be determined using the simple two-body kinematics of the reaction. The fission decay width of the excited nucleus in the formula (1) and (2) can be expressed

$$\Gamma_f = \frac{1}{2\pi\rho_c(E^* - \Delta)} \int_0^{E^*-B_f-\Delta_{sp}} \rho_{sp}(E^* - B_f - \Delta_{sp} - E')dE'. \tag{3}$$

The quantities $\rho_c(E^* - \Delta), \rho_{sp}(E^* - B_f - \Delta_{sp} - E')$ are level densities of the excited intermediate nucleus after β-decay and of its deformed saddle configuration, respectively, B_f is the fission barrier height, Δ represents the pairing gap in the level density of the daughter nucleus and Δ_{sp} is the pairing gap of nucleus at the saddle point configuration. The pairing gap is zero only for odd-odd nuclei and in other cases it plays a significant role in fission probability. As for the level density function two models can be applied, i.e. Fermi gas model and Gilbert and Cameron. Within the framework of the Fermi gas model the level density a_n can be expressed by Ignatyuk formula [5] taking into account the shell correction to the mass of the ground state and at high excitation energy the level density is asymptotic $\widetilde{a_n}$. At the saddle point, usually no shell correction is taking into account in level density function a_f and therefore its value is constant and equal to asymptotic value at intermediate state $a_f = \widetilde{a_n}$. Gilbert and Cameron model has zero shell correction at the saddle point configuration.
Based on the detailed analysis of Γ_f/Γ_n dependence, fission/neutron decay width, of neutron-deficient Ra nuclei as a function of excitation energy showed that the reduction of fission barrier using a fixed level-density parameter in the fission channel is preferred over the alternative possibility to enlarge a_f over $\widetilde{a_n}$.
To express the γ-decay width Γ_γ we can consider the empirical formula of Stolovy and Harvey [6] as a reasonable estimation at excitation energies up to 10 MeV. The reason is that it is build based on the experimental data of heavy nuclei. It was introduced as:

$$\Gamma_\gamma(E^*) = 0.00053\, A^{2/3} D(E^* - \Delta)^{0.25} (E^* - \Delta)^{4.3}\ [meV] \tag{4}$$

where $D(E^* - \Delta)$ is the level spacing in eV, determined as $D(E^* - \Delta) = \rho^{-1}(E^* - \Delta)$. The quantity $\rho\ \ (E^* - \Delta)$ can be calculated using the empirical formula Gilbert and Cameron. The excitation energy is in MeV and the final decay width in meV.
Using the stated formulas above fission barrier height can be determined from measurement of fission cross sections, measured in the (d,pf) reaction of heavy RIB´s at HIE-ISOLDE facility. The key role in such measurement plays active target ACTAR TPC where ACTAR TPC allows us to measure reaction kinematics, i.e. transfer products and fission fragment kinematics. However, the half-life of products should be sufficient enough. The events resulting from the (d,pf) reaction can be used, and, using the known two-body kinematics of the reaction, the two measured angles can be used to estimate the excitation energy of the residue. For (d,pf) reactions with heavy projectiles on deuterium target in inverse kinematics to measure angle of proton living the vertex of transfer is sufficient enough. If the position of transfer reaction vertex is known, appropriate to particular collision energy, than from the proton angle linear momentums of ejectile and recoil are determined using law of momentum conservation. From this point, it is easy to derive what is excitation energy of recoil undergoing fission almost immediately after transfer. Based on the expected angular resolution of the ACTAR TPC of 1° for proton tracks, and the laws of two-body kinematic, the expected uncertainty of the determined excitation energy of the projectile-like residue can be estimated as not exceeding 0.5 MeV. As for the fission fragments, spectroscopy of their kinetic energies is not necessary to measure but fission cross section is inevitable information.

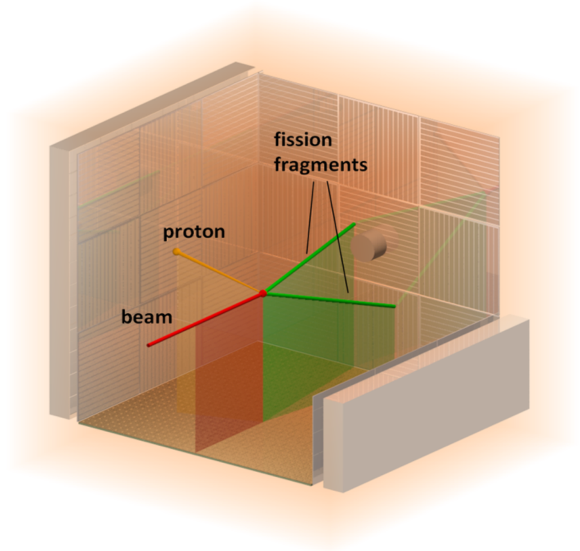

Figure 4. Drawing of kinematics reconstruction of (d,pf) reaction in inverse kinematics (lab. frame) inside the active target ACTAR TPC

RESULTS AND DISCUSSION

When combined, the methods, described above, provide a framework, allowing to determine the fission barrier height using the observed fission cross sections with accuracy, which is not achievable in another type of low-energy fission of neutron-deficient nuclei, the β-delayed fission. The experiments of this kind at ISOLDE facilities, using active targets, will thus provide the experimental information, which is not available at the moment and which is highly interesting for nuclear theory.

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