BETA-DELAYED FISSION AND THE PRODUCTION OF VERY HEAVY NUCLIDES FROM RAPID NEUTRON CAPTURE PROCESSES

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Abstract

Results from recently measured fission probabilities are included in the model presented earlier (12), for calculating beta delayed fission in neutron rich nuclides. The experimental probabilities are larger than expected, indicating an increase in level densities above the fission barriers due to the loss of symmetry at the inner barrier. As a consequence beta delayed fission may occur also in the r-process path. When discussing the production of superheavy nuclides by the r-process, beta delayed fission has therefore to be considered not only in the decay back but also for the cut-off. The results from earlier calculations on the yield of stable nuclides from nuclear explosions and r-process production ratios for chronometric pairs are carried over into the new model with only small changes.

1. Introduction

Berlovič and Novikov (1) were the first to point out the possible existence of a large area of neutron-rich nuclides, where fission may follow the beta decay to an excited state. Their arguments were based on comparisons of fission barrier height, Qβ-values and halflives for beta decay and spontaneous fission. No branching ratios were calculated and no quantitative estimates could be made of the impact on the production of beta stable nuclides from nuclear explosions or from the astrophysical r-process. Today there is, however, more information available from recent work, which motivates a more detailed study of beta-delayed fission (BDF).

The OSIRIS experiments (2), in which the beta strength function was determined for fission fragments, show that this function is strongly energy-dependent. For heavy nuclides with high Qβ-values, most of the beta daughters will therefore be left in excited states only 1 - 2 MeV below the maximum possible energy given by the Qβ-value. This is the prime reason why beta-delayed fission plays such an important role in neutron-rich nuclides.

The fission probability as a function of excitation energy has been measured for a large number of nuclei using direct reaction fissioning techniques (3,4). Quite recently this technique has been extended up to excitation energies around 11 MeV (5). The results show much higher fission probabilities than expected indicating an increase in the level densities above the fission barriers due to the loss of symmetry.

Fig. 1 Areas where beta delayed fission is energetically favourable. Area for neutron-poor nuclides are from Habs (15), area for neutron-rich nuclides are from this work.
at the inner barrier (6). The calculations of the fission potential surface (7,8) indicate that this barrier that will be the highest one in the area of interest. The high fission probability therefore expected for these nuclides will further enhance beta-delayed fission.

Fig. 1 shows areas where BDF is expected to be energetically favourable and indicates how this area can be reached. The first indication of beta-delayed fission was found in 1966 in an experiment by Flérov and collaborators (9). Experiments on BDF are now being performed at Dubna and at Heidelberg (10,11). Due to the constant beta-strength function for 8°-decay and electron capture and the increasing importance of a-decay, the BDF-branching ratio is small on the neutron-poor side of the stability line.

Earlier work (12,13) has studied the effect of BDF on the production of beta-stable nuclides from nuclear explosions and from the astrophysical r-process. The possible production of superheavy elements from the latter process has also been considered. The production of transuranium nuclides from the r-process is important in view of the present interest in cosmochronological calculations (14) and the possibility of finding remnants of 249Cm in meteorites. The occurrence of transuranium nuclides in ultraheavy cosmic rays and Ap-stars has also been discussed (15).

In this paper the implications of the recent results on fission probability (5) are discussed and the effect on the production of beta-stable nuclides from nuclear explosions and from the r-process are reviewed. As the analysis of (5) is still going on, the results reported here should only be considered as preliminary.

2. The Model

2.1 General

Fig. 2 gives in a compact form the information needed for the calculations. Following the results from the OSIRIS experiments (2), the beta strength function is taken to be proportional to the level density within the energy range of interest to this work. Apart from the new evaluation of fission probabilities described below no changes have been made in the model described in ref. (12).

2.2 Fission probability

In (12) a reduced barrier and a simple statistical model based on level density considerations (16) were used to describe the variation of fission probability with excitation energy, $P_F(E)$. Although this description is sufficient for an introductory survey, it is too simple for more detailed work. Compared to the recent work on fission probabilities, the statistical model seems to give too small values for $P_F$. In principle one could, of course, use the same type of sophisticated model for the penetration of the double-humped barrier as is used in the analysis in refs. (3-5). This would, however, lead to forbiddingly large computer times. As a compromise

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**Fig. 2** Information needed for the calculation of BDF branching ratios. Mass formula from (19), fission barriers from (7,8), fission probability from (3-5) and beta strength function from (2).

$P_F(E)$ is parametrized and the experimental data from refs. [3-5] are used to determine the parameter values.

The individual fission barriers in our model are characterized only by one variable:

$$E_F^N = \max(E_A^N, E_B^N)$$

where $E_A$ and $E_B$ are the heights of the first and second barrier. This is a practical limitation in view of the present accuracy of fission barrier calculations for the BDF nuclides. In most cases, interest is also limited to the form of $P_F(E)$ around and above $E_F^N$, where the dependence on other barrier parameters is small.

Assuming a Hill-Wheeler form of barrier penetration we write (cf. fig. 3)

$$P_F(E) = \begin{cases} P_{\text{MAX}} & \text{all } E \text{ if } E < E_F^N \\ \frac{1 + \exp((E - E_F^N)/\Delta_E)}{1 + \exp((E - E_F^N)/\Delta_L)} & \text{if } E \geq E_F^N \end{cases}$$

where $E_N$ is the neutron separation energy. Eq. (2) imitates the form of practically all of the experimental curves in refs. (3-5). In our parametrization not only $P_{\text{MAX}}$ and $P_{\text{LIM}}$ have to be fitted to the experimental data, but also $E_F$, $\Delta_E$, $\Delta_L$ and $A_F$. Their influence on the BDF branching ratio is, however, very small in most cases. The most important parameter for our calculations is $P_{\text{MAX}}$. We write this parameter as

$$P_{\text{MAX}} = P(E_F^N) \cdot P(E_F^N)$$

where

$$P(E_F) = E_F - E_N$$

$P(E_F)$ accounts for the competition between fission and gamma emission, $P(E_F)$ for the competition between fission and neutron emission. $P(E_F)$ is close to one and varies very little.
obtained using the parametrisation of $P_F(E)$ described above. There are two differences compared with those ratios published earlier:

1. Close to the line of beta stability the ratios are slightly decreased indicating that the earlier use of a reduced barrier might have overestimated BDF.

2. Further out towards the r-process path there is a clear increase in the BDF ratio. Delayed fission may now occur in the r-process path given by Schramm and Fowler (17). The BDF ratio will depend quite strongly on the calculated fission barrier height, but the results indicates that BDF also has to be considered when the cut-off of the r-process is discussed.

Fig. 6 shows the decay of $Z = 87$, $A = 254$. Note that this nuclide feeds into $^{248}\text{Cm}$.

3.2 Nuclear explosives

The results reported in ref. (11) on the yield of beta-stable nuclides from a nuclear explosion are carried over practically unchanged into this new formulation of the model. Fig. 7 shows the relation between the beta-stable nuclides and the uranium isotopes. Note the reversal of the odd-even effect in the yield curve around $A = 250$.

3.3 Nucleo-cosmostronochronology

The r-process production ratios for chronometric pairs reported earlier are slightly decreased. Table 1 shows these ratios including $^{248}\text{Cm}/^{232}\text{Th}$ calculated using fission barriers from the harmonic oscillator potential (7).

<table>
<thead>
<tr>
<th>Chronometric pairs</th>
<th>Standard ratios adopted by Schramm (14)</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{249}\text{Pu}/^{232}\text{Th}$</td>
<td>$0.47 \pm 0.1$</td>
<td>$0.31$</td>
</tr>
<tr>
<td>$^{235}\text{U}/^{238}\text{U}$</td>
<td>$1.5 \pm 0.1$</td>
<td>$0.89$</td>
</tr>
<tr>
<td>$^{232}\text{Th}/^{238}\text{U}$</td>
<td>$1.9 \pm 0.2$</td>
<td>$1.7$</td>
</tr>
<tr>
<td>$^{248}\text{Cm}/^{232}\text{Th}$</td>
<td>$0.34$</td>
<td>$0.15$</td>
</tr>
</tbody>
</table>

a) 20t odd-even effect due to post event neutron exposure.

4. Conclusion

The beta-delayed fission branching ratios have been calculated using a parametrisation of the fission probability based on recent measurement. Those measurements show very large fission probabilities. The most important consequence of this change from the model described earlier is the extension of BDF into the r-process path. Delayed fission may therefore have to be considered when discussing the cut-off of the r-process. The results from earlier calculations regarding the yield of stable nuclides from nuclear explosions and r-pro-
cess production ratios for chronometric pairs are carried over into the model with only small changes.

The beta strength function is treated in a phenomenological way using the data from the OSIRIS experiments (2). The basic assumption is that the strength function, as indicated by these data, will increase very strongly with excitation energy up to 6 - 8 MeV. Our results are consistent with resonances in the strength function below the Isobaric Analog State. As more experimental data become available, e.g. high resolution spectra of delayed neutrons (21), a more detailed treatment of the strength function will be possible, for instance as outlined by Klapdor in a contribution to this Conference (22). Although such a treatment may change branching ratios for individual nuclides it is not expected to have more than a minor influence on the conclusions drawn about the odd-even A yield in nuclear explosions, production ratios of chronometric pairs or the production of superheavy elements from the p-process, as these conclusions are based on the integrated effects from several nuclides.

Note added in proof:

Results on BDF in uranium neutron rich nuclides obtained at Dubna by Gangskyy et al. were presented at the Conference. For 238Pa and 236Pa (parent nuclides) branching ratios of 10^-6 and 10^-7 were reported. Preliminary calculations using the reported ratios and detailed experimental information about the penetrability of the first and second barriers indicate that the beta strength function increases strongly with energy for these nuclides. Sub-barrier beta delayed fission may provide a direct experimental test for the beta strength function for heavy neutron rich nuclides, provided that detailed information of the fission barriers and the fission isomers is available.
Fig. 6 Decay paths of an r-process nuclide.

Fig. 7 The yield of uranium isotopes after the thermonuclear explosion, inferred from the measurements of the yield of beta-stable nuclides. From the PAR event (20). Note the reversal of the odd-even effect around A = 250!

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