The influence of shell effects on the fissility of neutron deficient uranium isotopes at $N \approx 126$.

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Abstract

Production cross sections and excitation functions of neutron deficient isotopes of U, Pa and Th have been measured in the reaction of $^{22}\text{Ne} + ^{208}\text{Pb}$. The comparison of experimental production cross sections of uranium isotopes with the neutron number $126 \leq N \leq 134$ to the values calculated using statistical model of nuclear deexcitation has been carried out. There is shown, that none of the commonly used methods of introduction of shell effect influence on the production cross sections of evaporations residues allows to reproduce unambiguously used set of experimental data. Simple semiempirical method of introduction of shell effect influence in fission channel is proposed and good agreement with production cross sections of neutron deficient isotopes in the region from Bi to U is reached.

Introduction

The investigated production cross sections of Th - U isotopes with $N \approx 126$ are interesting for several reasons. At first, the shell correction energy to the ground state of these isotopes is large and comparable to their liquid drop fission barrier. This is a good reason to assume that the comparison of experimental cross sections for xn-, pxn- and $\alpha$xn-reactions with calculated values, obtained using the statistical model of compound nucleus deexcitation, will allow to determine the role and influence of shell effects on the fission probability of an excited compound nucleus and, consequently, to determine the values of production cross sections of different evaporation products. Correct shell correction values are very important for transfermium nuclei. On the other side the available experimental data allow model dependent interpretations based on different physical principles. We measured the production cross sections of evaporation residues produced in xn-, pxn- and $\alpha$xn-reaction channels bombarding $^{208}\text{Pb}$ targets with $^{22}\text{Ne}$ ions having energies from 110 MeV to 155 MeV. The data obtained in these experiments, together with the data on cross sections of neutron deficient isotopes of U, Pa, Th, from the reactions of $^{20,22}\text{Ne} + ^{208}\text{Pb}$ and $^{27}\text{Al} + ^{197}\text{Au}$ [1, 2, 3, 4], allow to
follow in details the changes in production cross sections of nuclei in the Th-U region at the variation of neutron numbers from 134 to 124. The analysis of experimental data and the comparison with the statistical model of compound nucleus deexcitation is the aim of this article.

**Experimental methodologies and results of measurements**

The experiments have been performed with the use of the external beam of the cyclotron U400 at JINR Dubna. The $^{22}$Ne beam with initial energies of 130 MeV and 160 MeV had a mean intensity of $2 \times 10^{11} s^{-1}$. The energy of the beam was varied by steps of 3-6 MeV using aluminium and titanium degraders. The energy of the projectiles was determined by measuring the energy of ions scattered on a $250 \mu g/cm^2$ gold foil and on the target foil to $30^\circ$ using Si-detectors, placed in front and behind the target foil. As target enriched $^{208}Pb(99\%)$ was used having a thickness of $400 \pm 150 \mu g/cm^2$ evaporated onto a $66 \mu m$ Al foil.

The complete fusion reaction products were separated from deep inelastic transfer products and from projectiles with the kinematic separator VASSILISSA [5]. This three-stage electrostatic separator have an angle of acceptance of 15 mstr and an energy acceptance of $\pm 10\%$ of electric rigidity. At a transit time about $1 \mu s$ the separator is able to separate very effectively complete fusion reaction products, transfer reaction products and projectiles. The evaporation residues and their $\alpha$-decay energies were detected and measured in the separator’s focal plane with a detector system [6] consisting of two time-of-flight detectors ($0.5$ ns time resolution) and eight strip Si-detector array ($60 \times 60$ mm$^2$, $\approx 15$ keV energy resolution for 6 - 9 MeV $\alpha$-particles). For fine calibration of the Si-detector strips implanted $\alpha$-decay products of the reactions $^{22}$Ne + W, Os, Pt were used. The electronic device allowed to register all events, related to the evaporation residues and their $\alpha$-decay products, including their time consequence. The time-amplitude correlation analysis of the whole set of registered events allowed to determine genetically related $\alpha$-decay chains and to identify the initial nucleus. From the time distribution of $ER - \alpha_1 - \alpha_2$ correlation it was possible to determine the half-life of the daughter nucleus.

The statistical accuracy of yield determinations in our experiments was $\pm (15 - 20)\%$ for the uranium and protactinium isotopes and $\pm (5 - 10)\%$ for the thorium isotopes. Taking into consideration all the parameters having influence, the absolute cross section values for the evaporation residues were in our experiments determined to be $\pm 50\%$. The accuracy of relative cross section measurements were two - three times better.

The excitation energies of compound nuclei were calculated on the basis of ex-
perimental mass values of nuclei, taken from [7]. The cross section values for the isotopes of U, Pa and Th, measured in the excitation energy region from 30 MeV to 80 MeV of the $^{230}$U compound nucleus, are given in tab. 1.

Table 1. Cross sections for evaporation products in $^{22}$Ne+$^{208}$Pb reaction.

| $E_{Lab}$ MeV | $E^*$ MeV | xn-channels, $\mu$b | pxn-channels, $\mu$b | $\alpha$xn-channels, $\mu$b |
|---------------|-----------|-----------------------|----------------------|---------------------|
| 101           | 31        | 0.7                   | 4n                   | 210                 |
| 109           | 38        | 6.0                   | 5n                   | 310                 |
| 112           | 41        | 3.1 0.5               | 6n                   | 60                  |
| 116           | 45        | 0.8 1.9               | 7n                   | 40                  |
| 122           | 50        | 0.2 1.8 0.3           | 8n                   | 20                  |
| 130           | 57        | 0.9 0.9 1.4 0.1      | 9n                   | 30 250 250 20       |
| 137           | 64        | 0.4 0.2 0.1 3.7 0.3  | 10                   |
| 142           | 68        | 0.1 0.3 1.1 1.9 0.4  | 10                   |
| 148           | 74        | 0.2 0.9 2.6 0.4      | 10                   |
| 153           | 78        | 0.1 0.7 2.2 0.8      | 10                   |

The comparison of experimental data and statistical calculations, conclusions

For the analysis of experimental data the HIVAP code [8] was used, where the production cross sections of evaporation residues, created in complete fusion reactions, are calculated in the framework of the statistical model of compound nucleus deexcitation. The level densities were calculated using the well known equations of the Fermi gas model (neglecting the effects of collective amplification) taking the shell effects in level densities into consideration in a phenomenological way, according to Ignatyuk [9].

$$a_\nu(E^*) = \tilde{a}_\nu(1 + (1 - exp(-E^*/D))\Delta W_\nu(A, Z)/E^*)$$

(1)

where $E^*$ - the compound nucleus excitation energy, $D = 18.5$ MeV - the shell effects attenuation, and $\Delta W_\nu(A, Z)$ - the shell correction to the nucleus mass after the evaporation of particle $\nu$ (neutron, proton, or $\alpha$ - particle). We considered the level density parameter $\tilde{a}_f$ to be equal to the asymptotic value of the level density in the channel of $\tilde{a}_\nu$ particles evaporation and to be independent of the excitation energy. In this way the ratio of asymptotic values of the level density parameter in the fission and evaporation channels - $\tilde{a}_f/\tilde{a}_\nu$ were in the calculations considered to be equal one. The experimental arguments for such a choice of the $\tilde{a}_f/\tilde{a}_\nu$ value were discussed in details in an earlier work [10]. The full fission barrier was calculated as the sum of the liquid drop and shell effect components.

$$B_f(l) = CB_f^{LD}(l) + \Delta B_f^{Shell}.$$  

(2)
The liquid drop component of the fission barrier \((B^{LD}_f)\) was calculated after the charged liquid drop model of Cohen-Plasil-Swiatecki [11]. The shell component of the fission barrier \((\Delta B_f^{\text{Shell}})\) was taken as the difference between the liquid drop [12] and measured [7] mass of the nucleus, i.e. as the module of \(\Delta W_{\nu}(A,Z)\). Coefficient C in the liquid drop component of the fission barrier was used to achieve full agreement.

As can be seen from the experimental data, given in tab. 1, the \(\alpha xn\) reaction channel is dominant. Even at relatively low excitation energies \((\approx 35 \text{ MeV})\) the cross section of the \(\alpha xn\)-channel is two orders of magnitude higher than for the \(xn\)- and \(pxn\)-channel. With increasing excitation energy the difference in cross sections reaches three orders of magnitude as the consequence of the fast drop of the cross section for the \(xn\)-channel. Such a large difference in cross sections makes it very difficult to describe these reaction channels using only one set of model parameters. We believe, that for the investigated types of reactions for correct calculations of cross sections it is not enough to make careful calculations of the fission process, but because of an important role of the charged particle evaporation, this process have to be also correctly calculated.

The experimental and calculated cross section values were compared for the reactions of \(^{22}\text{Ne} + ^{208}\text{Pb}\) and \(^{27}\text{Al} + ^{197}\text{Au}\). From the three deexcitation channels, \(xn\), \(pxn\), and \(\alpha xn\), the first one is the most important. This channel undergoes the most radical changes in cross sections and therefore is less sensitive to errors in cross section measurements. In Fig. 1 the experimental cross sections for neutron deficient isotopes of uranium, created in \(xn\)-reactions with light ions \((A \leq 40)\) are shown. The figure contains data from the present work and also from ref [1, 2, 3, 4], where cross section values for the reactions \(^{22}\text{Ne} + ^{208}\text{Pb}\) and \(^{27}\text{Al} + ^{197}\text{Au}\) are presented. Points denote experimental values at maximum yields, full lines denotes values of HIVAP calculations. The dash-dotted line in Fig. 1 (line 1) denotes the results of calculations, made using the standard approach, described above in this paragraph. In this calculations only one parameter - the factor \(C = 0.65\) was used. This value of C is typical for the liquid drop fission barrier of nuclei for the region of Pb -U [10, 13]. These calculations give good agreement with experimental values only for isotopes with \(130 \leq N \leq 134\). The calculated cross sections for \(^{218,219}\text{U}\) with \(N = 126, 127\) are \(10 -20\) times higher than the experimental ones. Additional calculations have showed that for correct cross sections for these isotopes coefficient C should be as low as 0.45 (line 3 in Fig. 1). But in this case the cross section values for heavier isotopes of uranium are running far down.

We also tested the sensitivity of the calculations to systematic errors in the determination of shell effects corrections to the ground state. For this purpose the shell effect corrections in formulas for the level density and fission barrier for all the nuclei of the evaporation cascade were at the same time increased or
Figure 1: Experimental and calculated values of maximal production cross sections of xn-reactions. For details see text.

decreased by 30%. In absolute measures such a variation is equivalent to shell correction of $\pm 0.8$ MeV for the end nucleus of the evaporation cascade. The result of calculations for the decreased value of shell correction is shown in Fig. 1 (line 2). As we can see, even such a strong change of shell correction leads only to cross section deviation by a factor of 2 - 3 and do not give an explanation for the very low cross section values for $^{218,219}U$. This is understandable because the role of shell correction in level densities leads to the decrease of the evaporation width and in the fission barrier to the decrease of fission width. Therefore simultaneous change of the shell effect corrections in the evaporation and fission channels has a consequence of strong mutual elimination of both effects in cross section calculations.

Very good agreement between experimental and calculated cross section values can be achieved using the approach, recommended in refs. [14, 15] and the decrease of parameter D for the level density calculation in the particle evaporation channel. The results of such calculations, with $D = 10.5$ MeV and $C = 0.65$ are shown in Fig. 1 as a dashed line. As in the figure shown, at such a choice of param-
eters it is possible to describe equally well the production cross section of isotopes with both, considerable and negligible shell corrections, but this approach does not seem to have unambiguous physical meaning. There is the another, very simple variant how to take into account the shell effects in the fission channel for the production cross section of evaporation products. The full line in Fig. 1 is the result of calculations, where with the free parameter C = 0.65 not only the liquid drop component but all the formula was multiplied.

\[
B_f(l) = C(B_f^{LD}(l) + \Delta B_f^{shell}).
\] (3)

As we can see, this variant of calculations gives the best agreement with the experimental data for the \(\alpha\)-channel through all the investigated region of nuclei. To test the universality of this new approach to the problem we applied it to cross section calculations of evaporation nuclei, experimentally investigated in work [13]. The investigated set contains data for about 50 product nuclei, created in more than 15 reactions. The results of calculations are presented in figures 2a and 2b, where the optimum values of C are given, obtained from the comparison of experimental and calculated cross section values. Fig. 2a shows the results of calculations, where the free parameter C was applied to the whole fission barrier. The results shown in Fig. 2b, taken from ref. [13], are completed with data for the uranium isotopes, and represent the calculations where the shell effects are accounted in the standard way. The comparison of both figures shows that the new approach to account the shell effects in the fission channel describes better the set of analyzed data. When applying this approach, there is no need for the variation of C to get correct description of production cross sections for nuclei with \(N \approx 126\). This approach gives also reasonable reproduction of production cross sections of Th isotopes produced in \(\alpha\)xn- channels.

According to our opinion the mathematical simplicity of the new approach to the production cross section calculations of evaporation nuclei does not mean the simplicity of the investigated physical process itself. The obtained results indicate some limitations for the use of the given set of experimental data to try explain the presence of several physical effects in the same process and even from the experimental data to try to determine the value of their parameters.

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Figure 2: Optimum values of parameter C necessary for correct calculation of production cross section of neutron deficient isotopes in the region from Bi to U in the reactions with the heavy ions with A ≤ 40. (a) Parameter C used to scale the whole fission barrier. (b) Parameter C used to scale the macroscopic part of fission barrier.

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Figure 3: Values of liquid drop components (a) and shell components (b) of fission barriers of uranium isotopes. Dependence of level density parameter on excitation energy for three values of parameter D (c): D = 18.5, 10.5 and 6.0 MeV.
Figure 4: Experimental and calculated values of maximal production cross sections of αxn-reactions. Symbols and lines as in Fig. 2.