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IFIN -
NP-6-1978 October

Critical angular momentum dependence of the fission barriers and the stability of superheavy nuclei

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Abstract : Measured complete fusion and evaporation cross section data are used to determine the critical angular momenta for which the fission barriers are vanishing in the region of nuclei with $Z = 102 \div 116$ It is shown that, in order to fit these data, larger values of the critical angular momenta are obtained for superheavy nuclei ($Z = 110 \div 112$) than for heavy ones ($Z = 102 \div 107$), what indicates a relatively higher stability against fission for superheavy nu - clei, in agreement with the theoretically predicted island of stability.

1. INTRODUCTION

The possible existence of an island of stability in the region of superheavy nuclei was predicted earlier than a decade ago /1,2/. Theoretical works devoted to this subject, show that such an island of stability may be associated with the doubly closed shell nucleus $^{298}114$ /3,4/. Calculations of ground state masses and potential energies for nuclei in the vicinity of the $^{298}114$ nucleus support the existence of superheavy spherical nuclei having a different from zero fission barrier. Although the values of the fission barrier height depend on the single-particle level schemes used in the calculations it was shown that the theory predicts relatively stable nuclei against spontaneous fission in the considered region /3,4/.

Much experimental work has been performed in order to put into evidence the existence of superheavy nuclei in the nature as studies of lead glass from old cathedrals, manganese modules from the bottom of the ocean, water from hot springs meteorites or moon rocks or to produce them in the laboratory, by complete fusion of two nuclei and by multinucleon transfer in deep inelastic collisions of two heavy nuclei. All these methods are looking for some half-lifes of new nuclides in the considered mass region, but up to now no direct evidence has been obtained /5,6/.

In the present paper a semiempirical method is proposed which offers an indirect proof of the increased stability of the superheavy nuclei.

The main idea is the following. The complete fusion processes in heavy ion interactions are limited by the dynamical effects in the entrance channel and by the stability conditions of the formed compound nucleus /7/. Therefore the critical angular momentum may be assigned either to dynamical effects (let us call it ℓ_{cr} (dyn)) or to the stability of the rotating compound nucleus, namely the one for which the fission barrier vanishes (let us call it $\ell_{cr}(B_f = 0)$). In the usual case of nuclei with masses up to 200 and lower excitation energies, $\ell_{cr}(dyn) < \ell_{cr}(B_f = 0)$ so that complete fusion limitations arise only from dynamical effects in the extrance channel. On the contrary, in the case of heavy nuclei, of high fissility, $\ell_{cr}(dyn) > \ell_{cr}(B_f = 0)$ and the complete fusion is limited due to the inability of the compound nucleus to take over angular momenta higher than the critical one. By comparing the measured cross sections with the calculated ones for transfermium nuclei, we can determine critical angular momenta for which the corresponding fission barriers vanish. In this way we obtain an indication on the stability of the involved nuclei because more larger is this critical angular momentum more stable is the nucleus.

Starting from this idea we have analyzed various systems of heavy ions leading to compound nuclei in the transfermium region and extracted the critical angular momenta $\ell_{cr}(B_f = 0)$. We obtained larger values of $\ell_{cr}(B_f = 0)$ for superheavy nuclei (Z = 110-112) than for the heavy ones (Z = 102-107) what indicates a relatively higher fission stability for these nuclei.

2. ANALYSIS OF EXPERIMENTAL DATA, RESULTS

The experimental data used in the analysis include complete fusion cross sections and evaporation cross sections measured in Berkeley /8,9,10/ and Dubna /11,12,13,14/. The computer code OVERLAID ALICE /15/ was used to perform the calculations. Complete fusion cross sections are calculated with the following relation :

$$\sigma_{CF} = \pi \lambda\!\!\!^{-2} \sum_{\ell=0}^{\ell_{cr}} (2\ell+1) T_\ell \qquad (1)$$

where $\lambda\!\!\!^{-}$ is the reduced wavelength, and T_ℓ is the transmission coefficient corresponding to the ℓ^{th} partial wave. The transmission coefficients were calculated in the approximation of the parabolic method /16/. The sum in eq.(1) ends up to the critical angular momentum ℓ_{cr} , which is determined by comparing the calculated cross sections with the measured ones. The critical angular momentum determined on the basis of dynamical considerations using the Bass method /17/ was found to lead to cross section values larger than the experimental cross sections. Then the critical angular momentum was determined so as to realize a good agreement between theory and experiment.

The evaporation cross sections are calculated within the code ALICE in the frame of the statistical model, the fission competition being given by the Bohr-Wheeler expression. The ratio of the fission to total width for a compound nucleus excitation energy E^* and angular momentum J is given by the following expression /18/ :

$$\frac{\Gamma_f(J)}{\Gamma_{tot}(J)} = N \left[N + 2 \sum_{\nu=n,p,\alpha} \int_0^{E^*-E_{min}(J)-B_\nu} g_\nu \sigma_\nu(\epsilon) \mu \epsilon \rho(E^* - E_{min}(J) - B_\nu - \epsilon) d\epsilon \right]^{-1} \quad (2)$$

where

$$N = \pi \hbar^2 \int_0^{E^*-E_{sp}(J)} \rho(E^* - E_{sp}(J) - K)\, dK \quad (3)$$

$$\rho(E) = E^{-2} \exp(2\sqrt{aE}) \quad (4)$$

Here $E_{min}(J)$ represents the energy of the nuclear rotating liquid drop in its stable configuration at angular momentum J and $E_{sp}(J)$ the energy of the saddle-point configuration and are calculated within the liquid drop model with pairing and shell effects. K is the kinetic energy of the fragments and ϵ the energy of the emitted particle ν. The level density parameter a was taken equal to A/8. Compound nucleus decay by neutron, proton and alpha particle emission and fission is calculated for each partial wave in the entrance channel so that the calculation can be stoped in order to achieve agreement with experiment. The angular momentum in exit channel is treated approximately assuming that each evaporated particle carries a constant amount of angular momentum namely $2\hbar$, $3\hbar$ and $10\hbar$ for the case of neutrons, protons and α-particles respectively.

Care must be taken in the choice of the parameters introduced in calculations as more as for the nuclei involved there is not much experimental information. In order to establish a consistent set of parameters we have analyzed the existing experimental data, as shown in earlier papers /7,19/. Particularly, the parameters defining the nuclear potential entering in the calculation of the transmission coefficients were chosen so as to reproduce the complete fusion excitation function and the threshold energy. They are in good agreement with the parameters obtained in Dubna /20/. The ratio of the level density parameters for the saddle point configuration and the residual nucleus after the emission of a particle (a_f/a_ν) has a large influence on the cross section values /19/.

By comparing calculated to measured cross sections we concluded that a_f/a_ν = 1 achieves the best fit. It is interesting to remark that the same situation appears in the case of heavy ion reactions involving nuclei in other mass regions /21/.

Following this procedure we have analyzed data of complete fusion cross sections*) for the following systems :

$^{238}U + {}^{40}Ar \rightarrow {}^{278}110$ /10/ , $^{232}Th + {}^{48}Ca \rightarrow {}^{280}110$ /12/ ,

and $^{238}U + {}^{40,44}Ca \rightarrow {}^{278,282}112$ /12/. Evaporation cross section data of the following systems were also analyzed :

$^{205}Tl + {}^{50}Ti \rightarrow {}^{255}103$ /13/ , $^{203}Tl + {}^{50}Ti \rightarrow {}^{253}103$ /13/ ,

$^{207}Pb + {}^{48}Ca \rightarrow {}^{255}102$ /14/ , $^{208}Pb + {}^{48}Ca \rightarrow {}^{256}102$ /14/ ,

$^{208}Pb + {}^{50}Ti \rightarrow {}^{258}104$ /11/ , $^{209}Bi + {}^{50}Ti \rightarrow {}^{259}105$ /13/ ,

$^{208}Pb + {}^{51}V \rightarrow {}^{259}105$ /13/ , $^{207}Pb + {}^{51}V \rightarrow {}^{258}105$ /13/ ,

$^{206}Pb + {}^{51}V \rightarrow {}^{257}105$ /13/ , $^{209}Bi + {}^{54}Cr \rightarrow {}^{263}107$ /13/ ,

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*) *Completed fusion cross section for the involved nuclei are estimated here from fission cross sections, because fission after fusion represents the predominant mechanism.*

$^{208}Pb + ^{55}Mn \rightarrow ^{263}107$ /13/ and $^{248}Cm + ^{48}Ca \rightarrow ^{296}116$ /8,9/ .

The obtained critical angular momenta are given in Fig.1 versus the atomic number of the compound nucleus. An interesting case represent the reactions leading to the same compound nuclei $^{259}105$ and $^{263}107$. As the critical angular momentum is determined by the stability conditions of the compound nucleus, its value must be independent on the entrance channel, as far as close regions of the E^{*} - J plane are reached in both reactions. It happens indeed so, as one can see in Fig.1, this fact supporting our method. We remark the J_{cr}-values for the element 103 which are much differing in the case of the two studied isotopes : 253 and 255. This fact could be explained by the stabilizing effect of the N = 152 subshell, which was already put into evidence by the systematics of the widths for spontaneous fission /11/. Much larger J_{cr}-values are obtained for the elements 110 and 112, indicating an increased stability of these nuclei against spontaneous fission. In fact, a theoretical calculation of the fission barrier variation with angular momentum shows that in the case of the $^{298}114$ nucleus the fission barrier has still a height of 1 MeV for an angular momentum as large as 90 $\hbar$ /22/.

3. CONCLUSIONS

The critical angular momenta for which the fission barrier is vanishing have been determined for various transfermium nuclei on the basis of an analysis of available measured cross sections. Of course, the employed method is disputable because of the approximations introduced in the calculations and also the problem of the choice of the parameters.

The use of a consistent set of parameters, with no free parameters through calculations assures the reliability of the method, which was also checked by comparing the results for different systems which lead to the same compound nucleus.

Acknowledgements

We take this opportunity to express our thanks to Profs. M.Lefort and Yu.Ts.Oganessian for very useful discussions and suggestions concerning this work.

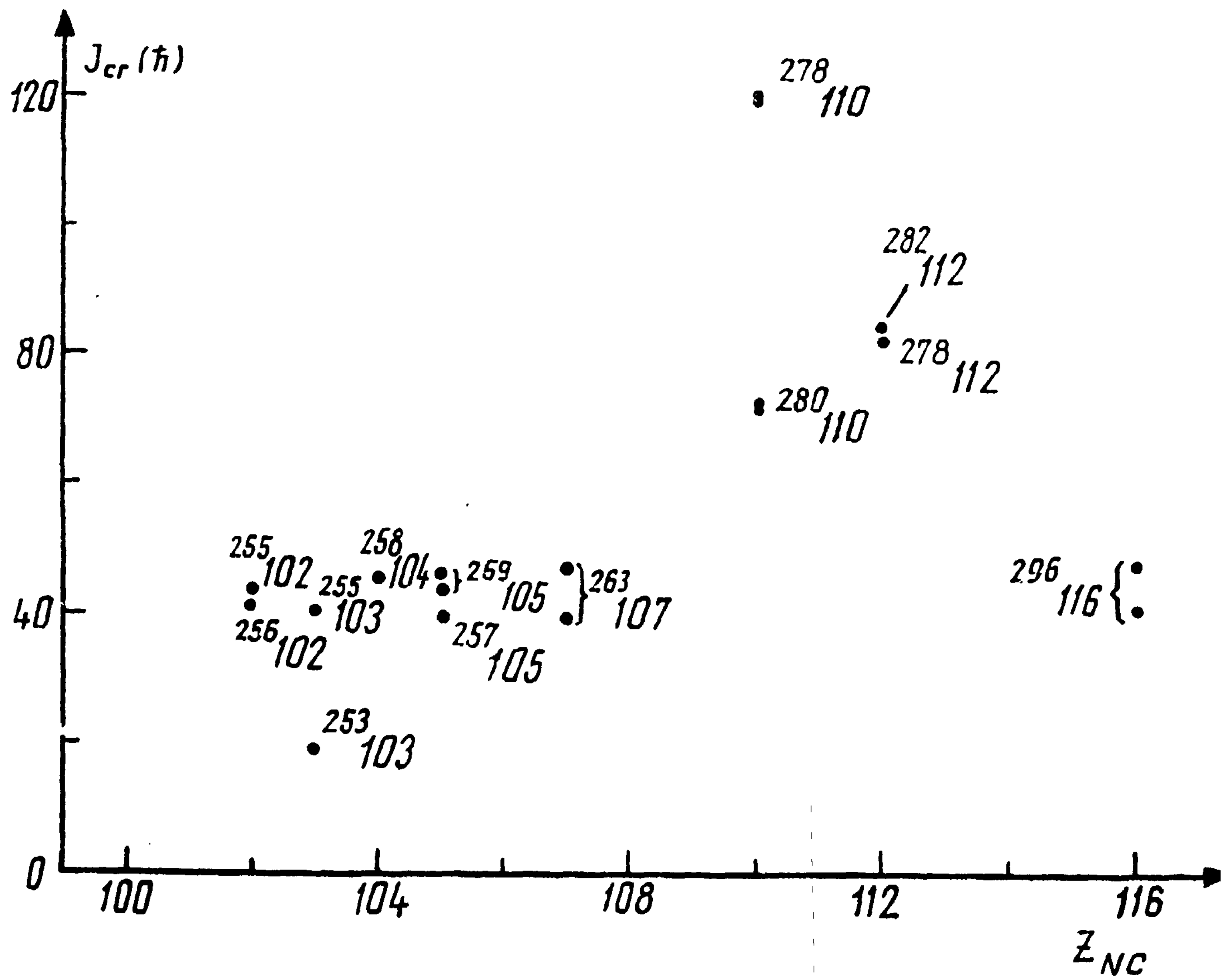

Fig.1. Semiempirical values of the critical angular momenta for transfermium nuclei.

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