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Influence of Angular Momentum on Shell Effects of Pre-scission Particle Emission of a Light Closed Shell Nucleus ^{132}Sn *

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Abstract Based on the Smoluchowski equations, we study the influence of angular momentum on the shell effects of pre-scission particle emission for a light closed shell nucleus ^{132}Sn. It has been found that the shell effects of pre-scission particle multiplicity depends on the angular momentum in a complicated way. Possible reasons are discussed.

Key words shell effects of pre-scission particle emission, angular momentum, doubly magic nucleus ^{132}Sn, diffusion model

1 Introduction

Recently shell effects in the fission fragment anisotropies[1,2], the mass and energy distributions of fission fragments[3], the evaporation residue cross sections[4—6] and the particle evaporation in fission processes[7] have been discovered. However, more measurements and theoretical studies are still needed to understand the shell effects in some aspects of fission processes. In Ref. [7] we reported the shell effects of pre-scission particles as a function of excitation energy, where we found an introduction of shell-corrected fission barrier enhances particle emission and this shell effect fades out with increasing excitation energy. In this paper we used a light shell closure nucleus ^{132}Sn ($Z = 50, Z = 82$) to investigate the influence of angular momentum on the shell effects of pre-scission particle emission.

2 Theoretical model

To study particle emission in the diffusion process, we employ the following Smoluchowski equation[8,9]

$$\frac{\partial P(x,t)}{\partial t} = \theta \frac{\partial}{\partial x}\left(\frac{\partial U}{\partial x}P(x,t) + \frac{\partial P(x,t)}{\partial x}\right) - \sum_{i=n,p,\alpha} \lambda_i P(x,t). \qquad (1)$$

Here, $P(x,t)$ represents the probability of the system at fission deformation coordinate x and time t. $U = V/T$ is a dimensionless potential, V is fission potential and $\theta = T/(\mu\beta)$, where T is the nuclear temperature, μ the reduced mass of the system, and β the viscosity coefficient. Fission potential V is a function of coordinate x, consisting of a well and a barrier. The second term on the right-hand side of the equation (1) represents light particle emissions, where $\lambda_i = \Gamma_i/\hbar$, Γ_i ($i = n, p, \alpha$) is the particle emission width.

In this work decay chain is defined as follows. Because a mother nucleus may evaporate neutrons or protons or α particles, correspondingly, three possible daughter nuclei are produced with different probabilities. Then each of the newly born daughter nuclei yields three possible granddaughter nuclei by evaporating these three light particle.... By this way various possible decay chains are formed and they are ended by fission. Each decay chain can be described by a set of coupled equations as follows:

$$\frac{d}{dt}P_s(t) = \sum_{i=n,p,\alpha} \lambda_{i,s-1} P^{i}_{s-1}(t) - \left[\sum_{i=n,p,\alpha} \lambda_{i,s} + \lambda_{f,s}(t)\right] P_s(t). \qquad (2)$$

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$$s = 1, 2, \cdots, s_m$$

Here, P_s is the probability of the s-th daughter nucleus. The first term on the righthand side is the "source" term which results from the decay of the $(s-1)$-th nucleus through emission of particles. The second term represents its decay probability via fission or particle emission. The maximum number of evaporating particles for a decay chain is denoted by s_m, over which the residual nuclei is cold enough to have no any particle emission.

Generally, the number of particles such as neutrons n_s released by the s-th daughter nucleus is

$$n_s = \frac{\Gamma_{n,s}}{\hbar}\int_0^\infty P_s(t)\mathrm{d}t, \qquad (3)$$

where $\Gamma_{n,s}$ is neutron emission width of the s-th daughter nucleus. The particle multiplicity M_i ($i = n, p, \alpha$) is defined as the total number of particles emitted from all the decay chains by emitting neutrons, protons and α particles:

$$M_i = \sum_{d=1}^{dm}\sum_{s=1}^{sm} n_{ds}, \qquad (4)$$

The inner sum here is over the particle multiplicity for a single decay with the proper probability, and the outer sum is over all possible decay chains. n_{ds} represents particle multiplicity evaporated in the s-th on a decay chain denoted by d.

The time dependent fission width is defined as:

$$\Gamma_f(t) = \hbar\lambda_f(t) = \hbar J_f(t)/\pi_f(t). \qquad (5)$$

Here, $J_f(t)$ is the probability flow passing over the saddle point, $\pi_f(t)$ is the surviving probability of system on the left-hand side of the saddle point.

Via this set of extended Smoluchowski equations, survival probabilities, fission rates and various particle multiplicities can be calculated numerically with the initial conditions $P_s(0) = \delta_{s,1}$, i.e. at beginning, the probability of the mother nucleus is 1, while probabilities of daughters are zero. Concerning the detailed steps of deriving the above-mentioned quantities, the reader can be found in Ref.[8].

3 Calculated results and discussions

If the shell effects in fission processes are taken into account, the fission barriers should be modified accordingly. Besides liquid-drop barriers, shell-correction barriers are also included. Moreover, the damping of shell correction with temperature is considered in this work. Therefore, the total fission barrier $B_f(T)$ is

$$B_f(T) = B_{DM} - \delta U \cdot \Phi(T), \qquad (6)$$

where B_{DM} is the part of droplet model, and δU is the part of shell correction at $T = 0$, which are taken from Ref.[10]. For ^{132}Sn, shell-correction barrier value is -11.55 MeV. $\Phi(T)$ is the temperature-dependent factor of shell correction, which is parametrized as

$$\Phi(T) = \exp(-aT^2/E_d). \qquad (7)$$

Following the work by Ignatyuk et al.[11], where a denotes the level density parameter and is chosen as $A/8$ MeV^{-1} with the mass A of the nucleus. The shell-damping energy E_d is set as 20 MeV[12]. It should be mentioned that in calculations the shell corrections for fission barriers of various nuclei produced in decay processes are considered.

In this paper we assumed that a neutron or a proton carries away angular momentum of $1\hbar$, whereas an α particle carries away angular momentum of $2\hbar$. Particle emission widths are assumed to be independent of time and position and calculated by a detailed balance principle method[13]. The emission barriers of protons and α particles are taken from Ref.[14]. The effects of angular momentum on the particle emission width is taken into account by removing the rotational energy from the excitation energy and modifying the angular momentum of daughter nuclei. The change of the liquid-drop fission barrier with angular momentum is evaluated with the finite range model of Sierk[15], which considers the finite-range effects in the nuclear surface energy by means of a Yukawa-plus-exponential potential and finite surface diffuseness effects in the Coulomb energy. This model provides a rather satisfactory description for the change of fission barriers of various nuclei with mass number (A), atomic number(Z) and angular momentum (L). Fig.1 displays the fission barrier corrected by shell correction for ^{132}Sn nucleus as a function of angular momentum at two different excitation energies. One can see that due to the effects of shell, the fission barriers are not rather low at larger angular momenta. We also notice that the values of barriers decrease with increasing of excitation energy. As shown in Fig.2

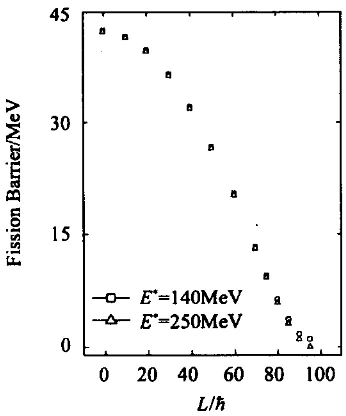

Fig.1. Fission barriers of ^{132}Sn nucleus calculated according to equation (6) as a function of angular momentum at two different excitation energies.

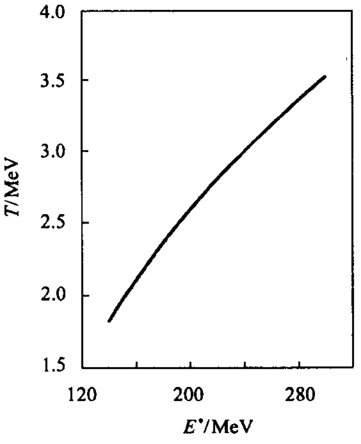

Fig.2. Temperature of fissioning system ^{132}Sn at angular momentum $L = 90\hbar$ varies with its excitation energy.

the temperature of the nucleus as a function of excitation energy. As expected, temperature rises with excitation energies. Here, it should be worth mentioning that shell correction is related to temperature obviously. After a compound system evaporates particles, the system is cooled that results in a restoration of shell correction to fission barrier. Fig.3 shows the variations of shell-correction and liquid-drop fission barrier of the ^{132}Sn system with evaporated neutron numbers N_n at an angular momentum of $90\hbar$ for two different excitation energies and at a 140 MeV excitation energy for two different angular momenta. As shown in Fig.3, at an excitation energy of 140 MeV and before ^{132}Sn compound nucleus decays, shell-correction barrier is about 60% of liquid-drop barrier. After this compound system evaporates two neutrons, the barrier from shell correction closes to the value of liquid drop. If three neutrons are evaporated, then shell-correction barrier is larger than that of liquid-drop model. This is because the emitted particles carry away a part of excitation energy that decreases the temperature of the compound system. As the result, shell-correction barrier has a larger value. However, by comparing the change of the shell-correction fission barrier at two different excitation energies, i.e., 140 MeV and 250 MeV, one can easily find that the lower the initial excitation energy of the compound nucleus is, the larger the shell-correction barrier is. In other words, the speed of restoration of shell correction to fission barrier depends on the initial excitation energy of compound system. From Fig.3 (a) and (b) one can note that as angular momentum is decreased from $90\hbar$ to $75\hbar$ and further decreased to $60\hbar$, the weight of the shell-correction part in the total fission barrier becomes more and more smaller compared to the liquid-drop one. This implies that the shell effects in lower angular momenta are not evident.

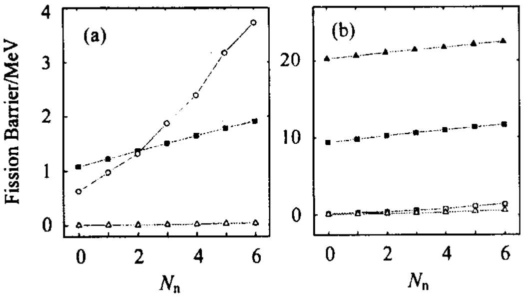

Fig.3. The change of shell-correction and liquid-drop fission barrier as a function of the number of emitted neutrons of the ^{132}Sn system (a) at a fixed angular momentum $L = 90\hbar$ for two excitation energies 140 MeV (○) and 250 MeV (△), and (b) at a fixed excitation energy $E^* = 140$ MeV for two angular momenta $60\hbar$(△) and $75\hbar$ (□). Here, full and open symbols represent the liquid-drop and shell-correction fission barrier, respectively.

Consequently, the introduction of angular momentum will carry away a part of excitation energies in the rotational energy, which suppress the temperature of fissioning system and increase the shell-correction of the fission barrier. It implies that a large angular momenta will enhance the shell effects on particle emission. However, we know that the particle multiplicity decreases as increasing of angular momentum[16,9], which indicates that a high angular momentum is unfavorable to enhance the shell effect in particle emission. The role of angular momentum in the shell effects of particle emission depends on the competition of the two opposite factors.

Table 1 presents for the cases with and without shell correction the calculated results concerning the dependence of light particle multiplicities of the ^{132}Sn nucleus on the excitation energy at an angular momenta $L = 90\hbar$ and at viscosity coefficient $\beta = 5\times10^{21}\,\mathrm{s}^{-1}$. From this table one can see the inclusion of shell correction does not alter the trend of the emission of light particles with excitation energy though the magnitude of particle multiplicity has a change. In addition, we also see that for this system charged-particle multiplicity is very small. At other angular momenta such as $70\hbar$ and $95\hbar$, a similar situation for the small multiplicity of protons and α particles is also observed and not shown here. We think lower M_p and M_α is a consequence of a higher neutron-to-proton ratio N/Z of ^{132}Sn system. Hence, our attention is paid only on the neutron emission.

Table 1. Pre-scission neutron (M_n), proton(M_p) and α particle (M_α) multiplicity of the ^{132}Sn nucleus with and without shell correction at angular momentum $L = 90\hbar$ and viscosity coefficient $\beta = 5\times10^{21}\,\mathrm{s}^{-1}$ for different excitation energies.

E^* /MeV	without shell correction			with shell correction		
	M_n	M_p	M_α	M_n	M_p	M_α
140	1.93807	0.00036	0.00015	2.83532	0.00043	0.00018
150	2.50949	0.00109	0.00049	3.34162	0.00123	0.00056
160	3.09442	0.00256	0.00124	3.80874	0.00283	0.00136
170	3.65454	0.00516	0.00261	4.25057	0.00559	0.00284
180	4.16453	0.00926	0.00486	4.64743	0.00989	0.00521
190	4.60269	0.01527	0.00823	4.97958	0.01613	0.00872
200	4.95609	0.02346	0.01285	5.24524	0.02455	0.01349
210	5.23027	0.03399	0.01878	5.45267	0.03526	0.01953
220	5.43950	0.04663	0.02579	5.61260	0.04802	0.02661
230	5.59792	0.06122	0.03368	5.73455	0.06268	0.03454
240	5.71720	0.07735	0.04213	5.82644	0.07884	0.04299
250	5.80594	0.09479	0.05090	5.89422	0.09628	0.05175
260	5.87042	0.11322	0.05975	5.94238	0.11468	0.06057
280	5.94338	0.15210	0.07704	5.99212	0.15344	0.07776
300	5.95870	0.19217	0.09284	5.99216	0.19334	0.09345

To survey the influence of angular momentum on the shell effects of particle emission, we make a detailed computation concerning particle multiplicity as a function of angular momentum. Fig. 4 shows the differences ($\mathrm{d}M_n$) of neutron multiplicity with and without shell correction as a function of excitation energy at four different angular momenta $L = 80, 85, 90$ and $95\hbar$. From Fig.4 we found the shell effects on the neutron emission are sensitive to the angular momentum. Fig.4 reveals the behavior of $\mathrm{d}M_n$ with angular momentum. Some interesting phenomena are observed. As L varies from $80\hbar$ to $95\hbar$, $\mathrm{d}M_n$ does not change monotonically. This is different from the behavior of M_n with L, for which the higher the L is, the smaller the M_n is. We notice that $\mathrm{d}M_n$ at $L = 85\hbar$ is always larger than the one at $L = 80\hbar$ for various energy and it is also larger than that at a higher angular momentum $90\hbar$ for $E^* < 180$ MeV and $95\hbar$ for $E^* < 260$ MeV. Besides, it can be seen that $\mathrm{d}M_n$ at $L = 95\hbar$ is somewhat larger than $\mathrm{d}M_n$ at $L = 80\hbar$ after $E^* >$

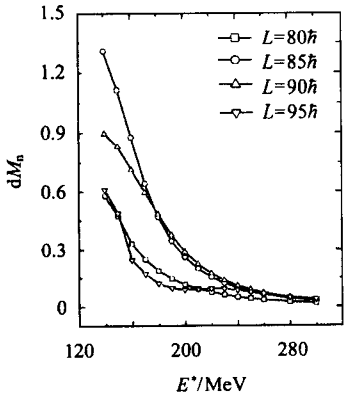

Fig.4. The differences of pre-scission neutron multiplicity of the ^{132}Sn nucleus with and without shell correction at four angular momenta $L = 80\hbar$(□), $85\hbar$(○), $90\hbar$(△) and $95\hbar$(▽), and at viscosity coefficient $\beta = 5\times10^{21}\,\mathrm{s}^{-1}$ as a function of excitation energy. The lines are for guiding eyes.

210 MeV. These results indicate that shell effects on neutron multiplicity depend on both the angular momentum and excitation energy. This is because dM_n in this work is defined as a difference of neutron multiplicity with and without shell correction, so how neutron emission containing shell correction changes with E^* and L is a key to understanding the behavior of dM_n at different excitation energies and angular momenta. Since a larger M_n makes shell effects evident, this demands a high excitation energy and/or a small angular momentum. However the emission of neutron is also closely connected with fission barrier. A higher fission barrier suppresses fission and enhances neutron multiplicity. Considering that the shell correction dependent fission barrier is related to the temperature of a compound system. These two reasons imply that a high angular momentum and/or a low excitation energy is desirable for enhancing the shell effect. Therefore the complicated roles played by excitation energy and angular momentum in affecting the shell-correction barrier and neutron evaporation produce some variations of dM_n with energy and nuclear spin. Moreover, in comparison with dM_n at $L = 85\hbar, 90\hbar$ and $95\hbar$ we can see that with increasing L, dM_n decreases. This means that shell effects are the weakest at $L = 95\hbar$. Although a high angular momentum increases the contribution of shell to fission barrier and enhance the shell effects, it also greatly decreases pre-scission particle multiplicity. As a competing result of the two factors, the shell effect at $L = 95\hbar$ is smaller than that at lower angular momenta $85\hbar$ and $90\hbar$.

4 Summary

In conclusion, within the framework of the Smoluchowski equation we studied the influence of angular momentum on the shell effects of particle emission for the light shell closed nucleus ^{132}Sn and found the shell effects of pre-scission neutrons depend on the angular momentum in a complex way.

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角动量对断前粒子发射壳效应的影响*

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摘要　用 Smoluchowski 方程研究了角动量对一个轻的闭壳核^{132}Sn 裂变前粒子蒸发壳效应的影响,发现壳对断前粒子发射的影响敏感地依赖于这个裂变系统的角动量. 对可能的原因进行了讨论.

关键词　断前粒子发射的壳效应　角动量　双幻核^{132}Sn　裂变扩散模型

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