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Effects of the fission fragments on the angular distribution of scission particles

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Abstract

We investigate the angular distribution of scission particles taking account of the effects of fission fragments. The time evolution of the wave function of the scission particle is obtained by integrating the time-dependent Schrödinger equation. The effects of the fission fragments are taken into account by means of the optical potentials. The angular distribution is strongly modified by the presence of the fragments. The attractive nuclear potential enhances the yield along the fragment axis for both neutrons and protons. For scission protons, the focusing effect due to the repulsive Coulomb field of the fragments is demonstrated. In the case of asymmetric fission, it is found that the heavy fragment has stronger effects.

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1. Introduction

In studying the dynamics of nuclear fission, the knowledge on how scission occurs is very important. The kinetic energy of the fragments strongly depends on the scission configuration because it is essentially determined by the Coulomb repulsion between the fragments. The mass/charge distribution of the fragments also depends on the way how the neck breaks. Because of the large collective mass and the strong dissipation, the fission is normally

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supposed to be a slow process. After passing the saddle point, the nucleus develops its shape toward scission. At the moment of scission, the neck that has connected the two fission fragments ruptures. This neck rupture can be very quick because the number of nucleons involved in the neck region is relatively small. After the scission, the neck disappears being absorbed by the fragments leaving some nucleons behind in the neck region and these nucleons are observed as particle emission. The number of scission particles carries the information on the scission process. There are two main components of the particles which are emitted in coincidence with fission; one component is the scission particles and the other one is the post-scission particles that are emitted from accelerated fragments. Attempts have been made to separate the yield of scission neutrons in low energy fission (Franklyn, 1978, Kornilov, 2001), they reported that 10-20% of the total neutron yield could be scission neutrons. It is also attempted to estimate the number of scission neutrons theoretically (Carjan, 2007, Carjan, 2010). The results depend on the nuclear shape such as the neck radius before scission. If we extract the reliable number of scission neutrons from experiments, we can get information on the nuclear shape at the time of scission.

In measuring the scission particles (neutrons or protons) experimentally, the information on their angular distribution is essential. The scission particles are emitted from the neck region and the emission is normally supposed to be isotropic in the rest frame of the mother nucleus in the lowest order approximation. However, since they are emitted in the close vicinity of the fission fragments, the final angular distribution of the scission particles is disturbed with the re-absorption and scattering by the fragments. At Theory-2 workshop, we proposed a framework to calculate the angular distribution of scission particles by solving a time-dependent Schrödinger equation (Wada, 2013). It was shown that the angular distribution of the scission neutron is strongly modified by the presence of the fragments, namely, the attractive nuclear potential enhances the yields around 0 and 180 degrees, while the absorptive potential diminishes them. However, the calculation was limited to the symmetric fission and only scission neutrons were considered. In this paper, we present new results on the asymmetric fission and on the scission protons. When we consider the emission of charged particles, it is necessary to take account of the effects of the Coulomb field of the fragments. We expect that the repulsive Coulomb field brings a focusing effect on the emitted particles toward the perpendicular direction to the fragment axis. In the next section, the formulation to calculate the angular distribution of the scission particles is revisited. Results are presented for the case of an asymmetric fission of ^{236}U, comparing them with the case of the symmetric fission. Comparison of the results of the neutrons and protons is given. The focusing of a charged particle due to the Coulomb field of the fission fragments is examined. The effect of the Coulomb field is compared with that of the nuclear interaction. Finally, a summary is given.

2. Framework

We start with a time-dependent Schrödinger equation (TDSE),

$$i\frac{\partial \psi}{\partial t} = H\psi \ , \quad H = -\frac{1}{2m}\nabla^2 + U \ , \quad \hbar = 1, \tag{1}$$

where ψ denotes the wave function of the emitted particle, H is the Hamiltonian, and U is the potential that represents the effect of the fission fragments. The time development is obtained with the use of the mid-point integration,

$$\psi(t+\Delta t) = \psi(t) - i\Delta t\, H\psi(t+\Delta t/2)\ . \tag{2}$$

By decomposing ψ into the real and the imaginary part, $\psi = R + iI$, the numerical solution is obtained using the following formula (the leapfrog method),

$$\begin{cases} I(t+\Delta t/2) = I(t-\Delta t/2) + \Delta t\, HR(t) \\ \quad R(t+\Delta t) = R(t) - \Delta t\, HI(t+\Delta t/2). \end{cases} \tag{3}$$

Some modification is necessary when we introduce an imaginary potential in H,