NEAR–SCISSION ALPHA PARTICLES IN FUSION–FISSION REACTION*

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There is strong experimental evidence that low energy fusion-fission reactions are accompanied by an emission of alpha particles whose characteristics cannot be explained by statistical pre-scission emission from the compound system nor by post-scission emission from the accelerated fission fragments. These particles are found at angles close to 90 degrees (with respect to the fission axis). They seem to originate from the neck area of the system and be emitted near scission. We discuss possible mechanisms responsible for their emission and present a dynamical study of their motion in the Coulomb and nuclear fields of the separating fission fragments.

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1. The nature of near scission emission

It is very unlikely that NSE (near scission emitted) alpha particles are emitted by the compound system on its way from saddle to scission. In this case the

Coulomb field of the compound system would accelerate NSE alpha particles to kinetic energies much higher than those observed. The angular distribution of the alpha particles is peaked nearly perpendicular to the direction of the fragments. So, the alpha particle must separate close to the moment of scission when the Coulomb field of the nascent fragments still has a focusing character. For a review of experimental data see Ref. [1]. A review of Theobald *et al.* [2] offers a discussion of some of the approaches

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to the production mechanism of NSE alpha particles. Some of the models are based on an idea of a sudden double neck rupture [3] governed by saddle to scission dynamics. Within this model, after the first rupture there is a statistical exchange of nucleons between the second main fragment and the rest of the neutron rich neck, which leads to a formation of light particles that re-separate in the rupture. The model then predicts the experimentally observed dependence of multiplicity of near scission alpha particles on mass number. It gives the correct order of multiplicities but it does not predict the experimentally observed dependence of multiplicity on excitation energy. The idea of a double neck rupture has been supported by TDHF calculations [4]. The idea of fast changing shape of the fissioning system was used by Tanimura *et al.* [5]. They considered an alpha decay process with a time dependent potential. Some characteristics of NSE alpha particles, such as their average energy, which is close to the value of the Coulomb barrier for fission fragments increased by fragments temperature, the shape of the energy spectra, the scaling down of the multiplicities with excitation energy (and post-scission multiplicities), show that NSE alpha particles might come from statistical evaporation [6–12]. This evaporation can occur either just before scission from the well developed neck or from a post neck region of one of the fission fragments, shortly after scission. This emission could be enhanced by higher than equilibrium temperature in the neck region. Some authors consider the possibility of statistical evaporation from a fission fragment close to scission, to be modulated by the interaction with a third body, the second fission fragment. It leads to a lowering of the Coulomb barrier for a range of emission angles [8, 9].

2. Trajectory calculations

To simulate a physical configuration of an alpha particle in one of the possible processes considered above, we start with two ellipsoidally deformed touching fission fragments. For simplicity we take them identical. In order to choose their deformation we run a two-body fragment-fragment dynamical trajectory calculation and require that the asymptotic value of the kinetic energy of the relative motion agrees with the experiment. The trajectory calculation for NSE alpha particles starts when the center to center distance between two fragments is approximately equal to twice the radius of the barrier for alpha particle emission from an individual fragment. The initial position of the alpha particle is chosen midway between the fragments, with its center on the symmetry axis (see Fig. 1). The results for kinetic energy and angular distribution of NSE alpha particles are not very sensitive to the exact choice of the initial location. The initial speed of the NSE alpha particle is assumed to have Maxwellian distribution with temperature

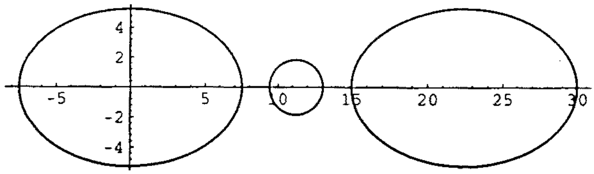

Fig. 1. Schematic diagram of initial conditions for the trajectory calculations. An α-particle originates from the neck region.

being a free parameter. The Coulomb interaction between two deformed fragments includes all terms up to quadrupole-quadrupole and monopole-hexadecapole [13]. For the nuclear interaction we use the proximity formalism [14]. For the Coulomb interaction between an alpha particle and a fission fragment we took monopole-monopole, monopole-quadrupole and monopole-hexadecapole contributions. The nuclear interaction in this case has a Woods-Saxon form [15]. We have performed a full three-dimensional, three body dynamical trajectory calculation which includes the rotational degrees of freedom of the fragments. For rotational motion, the rigid body moments of inertia were used. For chosen fragments masses, angular momentum of relative motion, and values of nuclear temperature, we can now calculate the average value and the dispersion in NSE alpha particle energy, the average angle of emission with respect to the symmetry axis of the fissioning system and the width of the angular distribution.

3. Results and discussion

In Table I we present the results of the trajectory calculations for the reaction ^{28}Si $+^{164}$Er at l=3D 50 $\hbar$. Column 1 gives the nuclear temperature T, column 2 the average kinetic energy $\bar{E}$ of NSE alpha particles, column 3 the width, σ_E, of the energy distribution. In columns 4 and 5 we show the average angle of emission $\bar{\phi}$ with respect to the direction perpendicular to the fission axis, and the width σ_ϕ of the angular distribution. The values of nuclear temperatures used in the calculation are close to fragments temperature parameter used in statistical code Joanne in Ref. [10]. The results are in very good agreement with the experimental data as can be seen in Fig. 2. In Ref. [10] the fragment temperature parameter was about 1.5 MeV. It did not show any significant dependence on the beam energy. We have not observed any significant dependence of our results on the isotope mass of the Er target. Similarly the dependence of the results on angular momentum is weak.

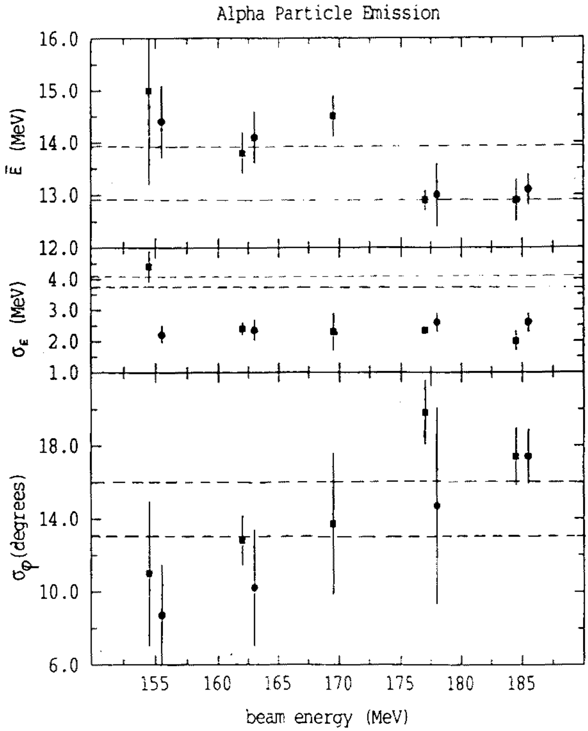

Fig. 2. Average energy, $\bar{E}$, of NSE alpha particles, the values of σ_E and σ_ϕ for ^{28}Si $+^{164}$Er and ^{28}Si + ^{170}Er. The experimental values are from Ref. [10]. The calculated range of $\bar{E}$, σ_E and σ_ϕ corresponds to the temperature $1.4 < T < 1.8$ MeV and is shown by the dashed lines.

TABLE I

Dependence of $\bar{E}$, σ_E and σ_ϕ for NSE alpha particles on temperature for ^{28}Si + ^{164}Er.

T (MeV)	$\bar{E}$ (MeV)	σ_E (MeV)	$\bar{\phi}$ (degree s)	σ_ϕ (degrees)
1.000	11.460	3.30	0	10.70
1.250	12.344	3.62	0	12.26
1.375	12.735	3.75	0	12.93
1.500	13.096	3.86	0	13.52
1.750	13.731	4.03	0	14.52

If the nature of NSE is statistical evaporation, the multiplicities depend on the barrier, temperature, separation energy and emission time. The barrier height can be found by looking at the maximum of the sum of Coulomb and nuclear interactions. Both of them depend on the distance between the interacting nuclei, so we get different barrier heights, V_b, and radii, R_b, depending on the nuclear shape. For the case of Si + Er, where the ratio of the semi-axes, ϵ, is around 0.6, the barrier height is between 9 and 11.3 MeV with the radius between 12.6 and 8.4 fm as one goes from the direction along the long semi-axis to the short one. In order to have some idea about the time scale of the ^{28}Si+^{164}Er reaction at $E_{\rm lab}$ =3D 170 MeV, we use the code HICOL [16]. If we assume that NSE alpha particles are emitted just before scission when the neck is well developed, or just after scission when the fragments are still in close proximity, we can get an estimate for the pre-scission time to be of the order of 1×10^{-21} s. The post-scission time can be easily evaluated by running a two-body fragment-fragment trajectory calculation and is of the order of 1×10^{-21} s. The knowledge of emission barriers, separation energy, temperature and near-scission time allows us to estimate the multiplicities of NSE alpha particles. We will use the approximate formalism of Ho *et al.* [6]. The observed multiplicity is given by

$$M = 3DfP(T)\tau\,, \tag{1}$$

where $P(T)$ is a temperature dependent emission rate, τ is the emission time and f is the fraction of total nuclear surface from which the particle emission occurs. The emission rate,

$$P(T) = \frac{1}{\pi\hbar^3} g\mu R_b^2 T^2 \exp\Big(-\frac{B+V_b}{T}\Big)\,. \tag{3}$$

Here, g is a degeneracy factor, μ is the reduced mass, B is the separation energy. For a case of ^{28}Si $+^{164}$Er, one of the possible emitters is ^{96}Nb for which, $B = 3.2$ MeV. If the barrier is $V_b = 9$ MeV with the radius $R_b = 12.6$ fm a nd $T = 1.5$ MeV $P(T) = 4.35 \times 10^{18}$/s. If f = neck area/ total area is taken to be 0.1 and the time $t = \tau_{\rm precision} + \tau_{\rm postscission} = 1 \times 10^{-2=1}$s+ 2×10^{-21}s =3×10^{-21}s, we get $M = 4.35 \times 10^{18}$ /s $\times 0.1 \times 3 \times 10^{-21}$s = $1.3 \times 1 = 0^{-3}$. M is a very sensitive function of T. If the temperature is 2 MeV (hotter area), $M = 1.77 \times 10^{-2}$. The multiplicities obtained in Ref. [10] for ^{28}Si $+^{164}$Er are between 1×10^{-3} and 6×10^{-3} for 155 MeV< $E_{\rm lab}$ <185 MeV.

We have shown that a simple dynamical three body trajectory calculation which assumes that alpha particles originate from the neck area or its neighborhood during the time when fragments are in close proximity, successfully describes the experimentally observed energy and angular distributions of NSE alpha particles. The observed multiplicities support the idea of statistical evaporation from the tips of the fragments where the emission barriers are significantly lower and the temperature might be slightly higher due to one-body dissipation and short time during which the fission fragments are close to each other.

REFERENCES

[1] A.K. Sinha, D.M. Nadkarni, G.K. Mehta, *Pramana J. Phys.* **33**, 85 (1989).
[2] J.P. Theobald, P. Heeg, M. Mutterer, *Nucl. Phys.* **A502**, 343c (1989).
[3] V.A. Rubchenya, S.G. Yavshits, *Z. Phys.* **A329**, 217 (1988).
[4] K.T.R. Davies, K.R.S. Devi, S.E. Koonin, M.R. Strayer, Treatise on Heavy Ion Physics, vol. 3, edited by D.A. Bromley, p. 3. UWAGA!!!! Wydawca, rok wydania?!!!!!!!!!!!
[5] O. Tanimura, T. Fliessbach, *Z. Phys.* **A328**, 475 (1987).
[6] H. Ho, R. Albrecht, W. Dunnweber, G. Graw, S.G. Steadman, J.P. Wurm, D. Disdier, V. Ranch and F. Scheibling, *Z. Phys.* **A283**, 235 (1977).
[7] M. Sowiński, M. Lewitowicz, R. Kupczak, A. Jankowski, N.K. Skobelew, S. Chojnacki, *Z. Phys.* **A324**, 87 (1986).
[8] A. Brucker, B. Lindl, M. Bantel, H. Ho, R. Muffler, L. Schod, M.G. Tranth, J.P. Wurm, *Phys. Lett.* **186B**, 20 (1987).
[9] B. Lindl , A. Brucker, M. Bantel, H. Ho, R. Muffler, L. Schod, M.G. Tranth, J.P. Wurm, *Z. Phys.* **A328**, 277 (1993).
[10] J.P. Lestone, J.R. Leigh, J.O. Newton, D. J. Hinde, J.X. Wei, J.X. Chen, S. Elstrom, M. Zielińska-Pfabe, *Nucl. Phys.* **A559**, 277 (1993).
[11] K. Siwek-Wilczyńska, J. Wilczyński, H.K.W. Leegte, R.H. Siemssen, H.W. Wilschut, K. Grotowski, A. Panasiewicz, Z. Sosin, A. Wieloch, *Phys. Rev.* **C48**, 228 (1993).
[12] V.P. Aleshin, *J. Phys. G: Nucl. Part. Phys.*, **19**, 307 (1993).
[13] R. Hasse, W. Myers, *Geometrical Relationships of Macroscopic Nuclear Physic*, Springer-Verlag, Berlin-New York 1988.
[14] J. Randrup, *Ann. Phys.* NY, **112**, 356 (1978).
[15] J. Huizenga, G. Igo, *Nucl. Phys.* **29**, 40 (1962).
[16] H. Feldmeier, *Rep. Prog. Phys.* **50**, 915 (1987).