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Neutron Emission from the Strongly Damped Reaction $^{165}Ho+^{56}Fe$ at 8.5 MeV/A

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ABSTRACT

Neutron and α-particle emission from the $^{165}Ho+^{56}Fe$ reaction at 8.5 MeV/A has been studied for damped and fusion-fission events. It is shown, that the measured multiplicities, energy spectra and angular distributions of neutrons are consistent with a full equilibration of the excitation energy and the N/Z degree of freedom during the reaction time.

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1. Introduction

In strongly damped reactions between heavy ions, a large fraction of the available kinetic energy in the entrance channel is converted into intrinsic-excitation energy within the short (10^{-21} - 10^{-22} sec) interaction time of the ions. The highly excited nuclei de-excite mostly via emission of particles such as neutrons, protons and alphas. Although these are secondary processes, they can reveal important information about strongly damped reactions, such as the timescales for energy and N/Z equilibration. Particles emitted from the rotating double-nucleus complex are expected to show angular distributions and energy spectra characteristic of fast pre-equilibrium processes and are, thus, rather different from particles evaporated from the separated and by their mutual Coulomb repulsion accelerated final fragments. In the latter case, which is realized in the reaction under study, the scattering angles and the velocities of the fragments determine the observed particle spectra and angular distributions.

2. Experimental Procedure

The experimental setup is shown in Fig. 1. Neutrons and α-particles emitted from the reaction $^{165}Ho+^{56}Fe$ at a bombarding energy of 8.5 MeV/A are measured in coincidence with Fe-like fragments detected with a ΔE-E telescope, which provided Z-identification of the reaction products at laboratory angles of Θ_T = 16, 20 and 25°. The neutrons were detected with six NE213 liquid scintillators employing n-γ discrimination units.+ The neutron energy was determined from the measured time of flight for a 70 cm flight path. The α -particles were measured using a triple-element solid-state detector telescope.

3. Results and Discussion

Fig. 2 shows the angular distribution of all coincident neutrons in

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the laboratory system. It is strongly peaked at the detection angle Θ_T of the fast moving, Fe-like fragments indicating that the neutrons originate mainly from fully accelerated fragments. The laboratory neutron energy spectrum is found to be consistent with this picture. Fig. 3 shows a contour plot of the neutron cross section as a function of laboratory energy and angle. It clearly demonstrates the strong focussing of neutrons emitted from the fast Fe-like fragment and a weak focussing of those emitted by the heavy, slow-moving fragments (broken lines). Using an iterative method, the multiplicities and energy spectra of the neutrons in the restframes of the heavy and light fragments were determined. Due to the focussing effect mentioned above convergence was reached very quickly. The resulting neutron energy spectra are shown in Fig. 4. (In the following plots, the heavy and the light fragments are referred to by filled squares and open circles, respectively). The solid curves in Fig. 4 represent an evaporation spectrum of the Watt[2] type ($dN/dE \sim E^{1/2} \exp(-E/T)$) with a temperature $T = 2$ MeV fitting the data rather well. On the basis of the good agreement with the data for both the heavy and the light fragments, we conclude, that both fragments have attained the same temperature. This implies, that the excitation energy was equilibrated in the very short interaction time of the two heavy ions. Then, assuming the level density parameters a to be proportional to the masses of the nuclei, the excitation energy obtained by the fragment is proportional to its mass:

$$E_H^* : E_L^* = a_L T^2 : a_H T^2 = A_L : A_H,$$

where the H and L denote the heavy and the light fragment, respectively. An analysis of the fragment temperature as a function of the observed TKE loss confirmed, that the excitation energy is indeed proportional to the square of the measured temperature. The data provide no evidence for the occurence of fast, pre-equilibrium neutrons. This is true also for the spectra taken with a neutron detector located at a forward laboratory angle (10°), where the probability for the detection of fast neutrons generated by 'Fermi jets' would be highest (Fig.5).

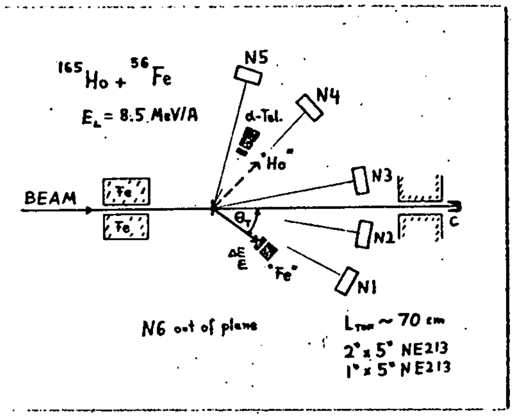

Fig. 1

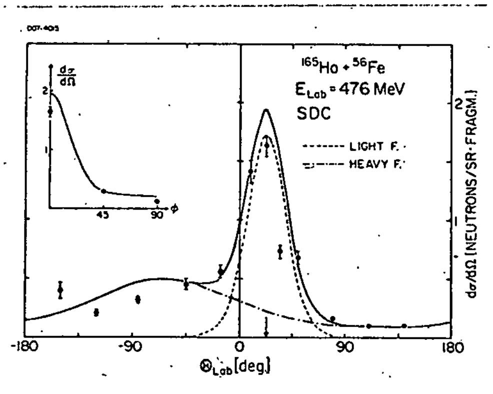

Fig. 2

An investigation of the neutron multiplicities provides further evidence for a distribution of the excitation energy proportional to the fragment masses. In Fig. 6, the ratio of the multiplicities for the heavy and the light fragment is shown as a function of the light-fragment Z. The solid line indicates the mass ratio of the fragments, assuming complete N/Z equilibrations (N/Z = 129/93). Evidence for applicability of this assumption and the detailed relationship between multiplicity and excitation energy will be discussed later. It is already obvious, however, that the multiplicity ratio follows the mass ratio rather closely. The lower part of Fig. 6 shows the neutron multiplicity as a function of the charge of the detected light fragment (open circles) and of the correlated heavy

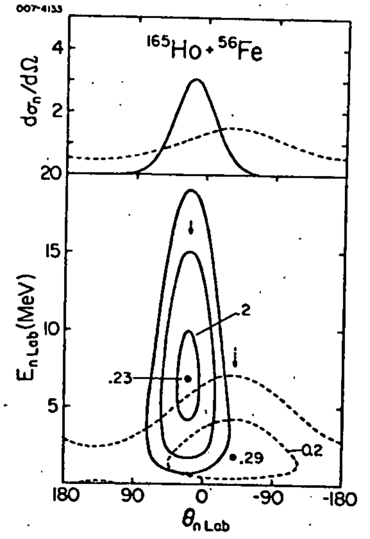

Fig. 3

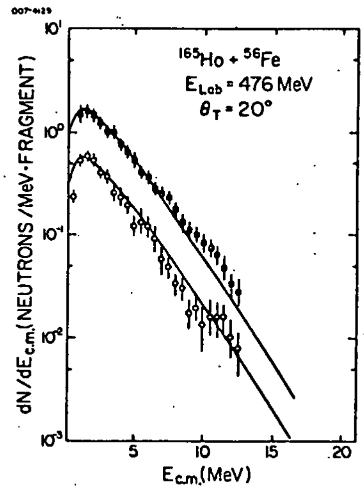

Fig. 4

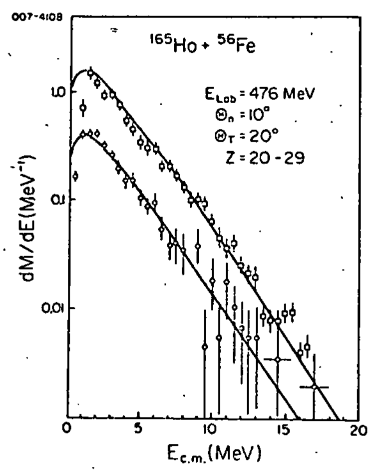

Fig. 5

fragments (filled squares). The charge of the latter was calculated from $Z_H = Z_T + Z_P - Z_L$, the evaporation of charged particles not being taken into account. Preliminary calculations with an evaporation code[3)] show, however, that on the average 2-3 charge units are evaporated for $Z > 40$. Including this effect, the two multiplicity distributions would join smoothly for the fusion-fission events (broken arrow). The measured neutron multiplicities are well reproduced by the calculations. They are shown in Fig. 7c as a function of TKE loss. It is seen that they increase approximately linearly with excitation energy for not too high energy losses, in good agreement with an approximate formula[4)] for spin-zero particles (solid lines). The dashed lines represent calculations with the evaporation code. For very high energy losses, the multiplicities saturate for the light fragment and even decrease for the heavy fragment. This may be partially due to the onset of charged particle evaporation, which is favored by high excitation energies and spins. Preliminary analysis of the α-data shows, that the α-yield increases markedly with high TKE losses. Fig. 7b shows the ratio of the neutron multiplicities for the two fragments. This quantity is a sensitive measure for the degree of N/Z equilibration. Neglecting γ-ray emission, the ratio M_H/M_L can be expressed as:

$$\frac{M_H}{M_L} = \frac{E_H^*}{E_L^*} \cdot \frac{\langle B_{nL} + 2T_L \rangle}{\langle B_{nH} + 2T_H \rangle} \cdot \frac{(\Gamma_p/\Gamma_n + \Gamma_\alpha/\Gamma_n + 1)_L}{(\Gamma_p/\Gamma_n + \Gamma_\alpha/\Gamma_n + 1)_H}$$

where the three factors represent the ratios of excitation energy, the average energy carried away by a neutron and the competition by charged particle emission, respectively. For thermal equilibration $T_L = T_H$ and $E_H^*/E_L^* = A_H/A_L$. The neutron binding energies B_n and the widths Γ_p, Γ_α depend sensitively on the N/Z ratio of the fragments. Assuming the same N/Z ratio for the heavy and the light fragments, i.e., complete N/Z equilibration- a value of 2.7 is obtained for the ratio M_H/M_L. The opposite assumption - that the light and the heavy reaction partners have the same N/Z ratio as ^{56}Fe and ^{165}Ho, respectively, would yield a value of $M_H/M_L = 5.5$. A comparison with Fig. 7b shows clearly, that the data are consistent with N/Z equilibration even for the lowest TKE loss bin of 50 MeV analyzed, corresponding to an interaction time of $5 \cdot 10^{-22}$ sec.

In Fig. 8, a schematic overview of the rele-

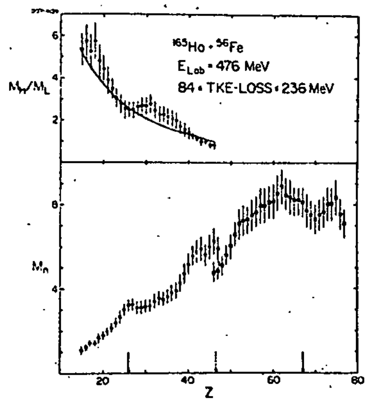

Fig. 6

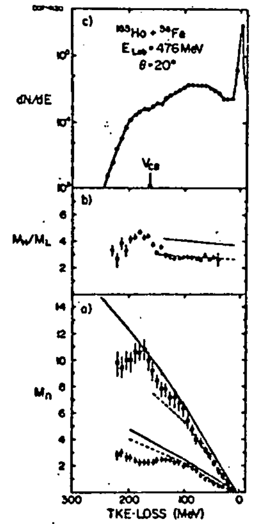

Fig. 7

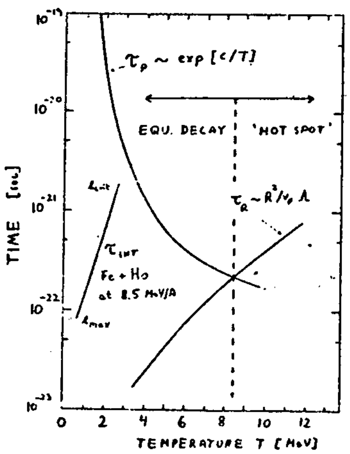

Fig. 8

vant time scales for this experiment is shown. τ_p is the time required for the evaporation of a particle from a nucleus of temperature T, as determined from a study of compound-nucleus decay widths[5].

τ_{int} is the nuclear interaction time for the reaction under study, as a function of the equilibrium temperature attained.

It is seen that for all ℓ-values not leading to fusion the interaction time is smaller than the time needed for particle evaporation. τ_R finally characterizes the time for the decay of a hot spot in a nucleus of temperature T[6]. It appears, that for the nuclear temperatures reached at this bombarding energy, even if a hot spot were formed on contact of the two ions, it would decay within a time short compared to the interaction time. However, the system would likely have to be heated up to temperatures of the order of 7-8 MeV, before the formation of a hot spot could be observed.

Hence, the results of this experiment are in concert with other observations[1] made for the energy-dissipation mechanism operating in damped reactions. According to these, kinetic energy is lost gradually and absorbed by the nucleus as a whole (one-body dissipation), as nucleons are exchanged. The long mean-free path of these low-energy nucleons effects a de-localization of the excitation energy deposited within the nucleus.

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