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Neutron emission and energy partition in the inelastic reactions of 154 MeV ^{32}S on ^{100}Mo

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Neutrons emitted by targetlike fragments after the inelastic reactions of 154 MeV ^{32}S on ^{100}Mo have been measured. Neutron energy spectra and multiplicities have been derived as a function of the dissipated energy for targetlike fragment mass bins $A_{\rm TLF}$=96–98, 101–103, and 104–106 and have been compared with the results of a Monte Carlo simulation which performs statistical model calculations of the targetlike fragment decay, with different assumptions on the partition of the excitation energy between the reaction partners. The partition following an equal temperature hypothesis better describes the experimental data but a sizable influence of the exit channel is found on the experimental neutron multiplicity.

The partition of the excitation energy between the reaction partners in a dissipative heavy ion collision is a fundamental test of the ability of current theoretical models in describing reaction mechanisms.[1] Earlier measurements of neutron spectra and multiplicities emitted from light and heavy fragments suggested that the dinuclear system is thermalized not only when all of the kinetic energy has been dissipated but also for incompletely relaxed events, corresponding to short interaction times.[2] On the other hand, more recent data based on different techniques[3–5] and a new interpretation of neutron data[6,7] show the tendency to an equal sharing of the excitation energy between the fragments at small energy losses and the evolution towards a thermal equilibrium regime at large energy losses, as expected from dynamical transport theories.[8] In addition, evidence was found for the dependence of the excitation energy partition on the exit channel in quasielastic reactions.[9] In the last few years, a number of experiments performed to study the transition between the two extreme assumptions on the excitation energy sharing found a complex dependence of the partition function on the energy loss as well as on the exit channel.[10,11]

We report here on a measurement of neutrons emitted from the exit channel fragments after the inelastic collisions of ^{32}S on ^{100}Mo at 154 MeV, with the aim of studying the excitation energy partition in an asymmetric system and for energy losses up to 50 MeV. These conditions involve a large difference in the excitation energy ratio of the exit channel fragments, in the two limiting cases of equal temperature or equal excitation energy assumptions. This particular reaction was chosen because (i) it was studied in the past with inclusive measurements,[12] (ii) the kinematics of this system helps in separating the products of the sequential decay from the light (fast) and heavy (very slow) fragments, and (iii) statistical model calculations of the decay of such neutron rich targetlike fragments (TLF) are reliable.

The experiment was performed at the upgraded MP Tandem of the Laboratori Nazionali del Sud in Catania, Italy. A ^{32}S beam was focused onto a 0.45 mg/cm^2 self-supporting target of ^{100}Mo, 97% enriched. The target was located in a thin-walled (3 mm) spherical aluminum scattering chamber, 100 cm in diameter.

Projectilelike fragments (PLF) were detected by a time of flight (TOF) telescope consisting of a 5×4 cm^2 parallel plate avalanche counter (PPAC) as a start and a large area (25×20 cm^2) position sensitive PPAC as a stop detector. The shortest flight path was 40 cm. The TOF telescope was operated in conjunction with a second large area (25×20 cm^2) position-sensitive PPAC used to detect TLF. Mass and energy of the fragments were derived by two-body kinematics from the measured PLF velocity and PLF and TLF detection angles. The PLF detector covered the angular range $\theta_{\rm c.m.}=30°-65°$ near the grazing angle for the reaction ($\theta_{\rm c.m.\,gr}=70°$). The experimental resolutions were $\delta t=700$ ps full width at half maximum (FWHM) for the PLF TOF and $\delta\theta=0.5°$ for PLF and TLF emission angles, the latter determined by wire spacing. The overall Q value and mass resolutions, mainly determined by the multiple scattering of TLF in the target, were $\delta Q=11$ MeV and $\delta M=2.3$ mass units FWHM on the elastic peak. The quoted resolutions are the worst because of the detection of the fastest PLF and the slowest TLF, the latter being affected by an angular broadening of $\sim6°$. With increasing energy loss, the TLF recoiling energy increases, causing a reduction of their angular spread. Overall resolutions are therefore expected to improve with the energy loss. The target thickness was chosen as a compromise between the statistical significance of the measurements and the resolution.

Neutrons were detected by a TOF of four NE213 liquid scintillators (12.8 cm diam, 5 cm thick) against the same PPAC start detector as above with pulse shape discrimination to reduce the γ ray background. Neutron flight paths were about 1 m. The neutron TOF resolution was 1.2 ns FWHM.

Neutron yields were corrected for the detector efficiencies obtained by Monte Carlo calculations, tuned on the results of detection efficiency measurements at 2.4 and 13.9 MeV. Less than 5% uncertainty can be attribut-

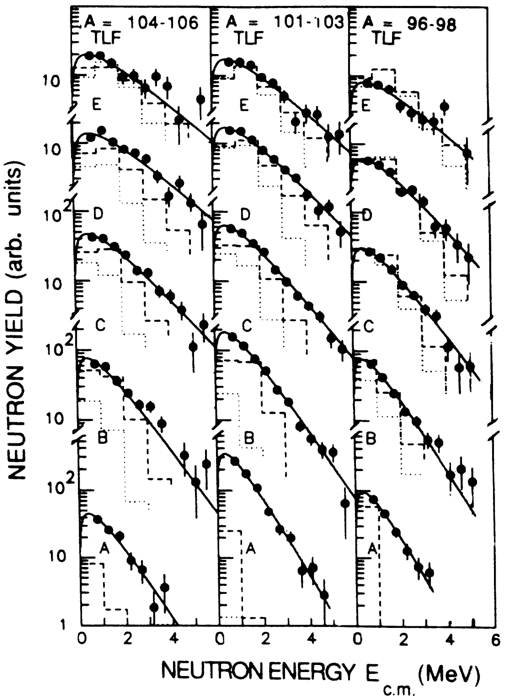

FIG. 1. Neutron energy spectra for different mass and E_{loss} gates (A = 0–10 MeV, B = 10–20 MeV, C = 20–30 MeV, D = 30–40 MeV, and E = 40–50 MeV). Solid lines are Maxwellian fits to the experimental spectra. Results from Monte Carlo simulations are also shown assuming a partition of the excitation energy proportional to the mass ratio (dashed line) or equipartition (dotted line).

ed to the employed detection efficiency values up to 5 MeV.[13] Three detectors were positioned at $\theta_{\text{lab}} = 40°$, 60°, and 80° on the same side of the TLF counter with respect to the beam direction. The fourth was set at $\theta_{\text{lab}} = 40°$ behind the PLF TOF system. The neutron detection angles were chosen to optimize the discrimination between PLF and TLF sequential decay products. PLF-TLF and PLF-TLF-neutron coincidences were recorded.

A complete description of this experiment will be published elsewhere. We show here the main results obtained.

Neutron energy spectra were obtained for each neutron detector, and for the mass gates A_{TLF} = 96–98, 101–103, and 104–106, as a function of the reconstructed energy loss E_{loss} (including Q_{gg} corrections) with the assumption of a two-body reaction. As expected, the spectra corresponding to the three detectors on the TLF side are identical after an event-by-event conversion to the frame of the recoiling TLF, proof that the TLF is the unique source of neutrons at these angles. Energy spectra were obtained for 10-MeV E_{loss} bins by summing properly over the three detectors. Angle integration of the cross section allows for the derivation of the corresponding neutron multiplicities. These are affected by ~10% systematic uncertainties due to neutron detector efficiency corrections and angle integration procedure.

Neutron energy spectra and multiplicities are shown in Figs. 1 and 2, respectively. The general trend of the data is the increase of neutron multiplicity and average energy of the neutron spectra with the energy loss. A strong dependence of experimental neutron multiplicity on the mass bin is in evidence, apart from very low energy losses.

To obtain information about the excitation energy partition we have compared the experimental data with a Monte Carlo simulation of the TLF deexcitation. The calculations started from a sample of the TLF-PLF experimental coincidence data. We made the assumption that these data are unaffected on the average by the sequential decay of the fragments, i.e., the measured mass and energy losses are representative of the corresponding quantities of the primary fragments. This assumption was validated by a Monte Carlo simulation of the different contributions to the overall experimental resolutions (instrumental resolutions, target thickness effects, approximation in the derivation of Q and A, and sequential evaporation of neutrons). For a given measured event (A_{TLF}, A_{PLF}, E_{loss}) fragment charges were chosen randomly from Gaussian element distributions with variances depending on the energy loss. The parameters of these Z distributions were obtained following Ref. 14 and checked with known experimental element distributions.[12] For each event (A_{PLF}, Z_{PLF}, A_{TLF}, Z_{TLF}, and E_{loss}) the Q_{gg} was

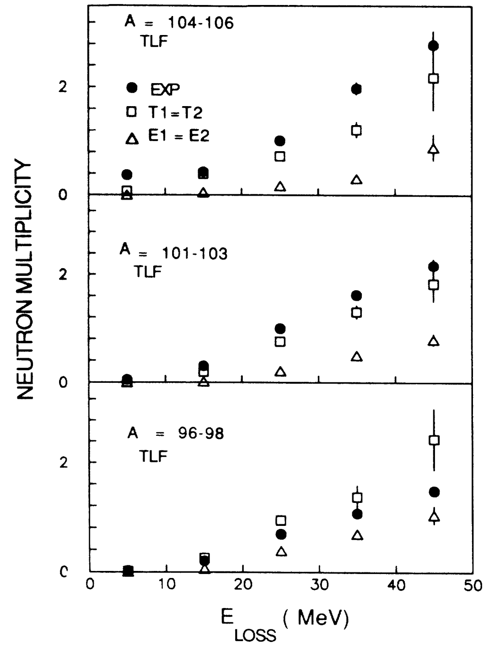

FIG. 2. Neutron multiplicity as a function of the energy loss and for different mass gates. Only statistical errors are shown. $T1 = T2$ and $E1 = E2$ label Monte Carlo simulation results assuming a partition of the excitation energy proportional to the mass ratio or equipartition, respectively. The error bars signal that fewer Monte Carlo stories preserve a physical significance after the thermal excitation energy partition, because of experimental resolutions on the starting events. All the calculations take into account excitation energy and mean spin fluctuations as well as a Gaussian distribution assumption for fragment charges.

subtracted from the measured $E_{\rm loss}$ yielding the total excitation energy to be shared between the reaction partners. The total spin carried by the fragments at scission was evaluated as the sticking limit at $E_{\rm loss} > 30$ MeV, corresponding to fragments with only Coulomb repulsion energies, with a linear dependence to total spin zero for $E_{\rm loss} = 0$. In any case, total spin was shared between the reaction partners proportionally to their masses. Instead, excitation energy was supposed to be shared either equally or proportionally to fragment masses, the limiting cases describing equal excitation energy and equal temperature. Fluctuations around mean spin and excitation energy values were accounted for, with the methods of Refs. 15 and 16. For any TLF event (defined as $A_{\rm TLF}$, $Z_{\rm TLF}$, $J_{\rm TLF}$, and $E^*_{\rm TLF}$), a statistical model calculation was performed using the code PACE2.[17] This particular code was chosen because of the Monte Carlo method that was employed. In fact, 100 evaporation calculations were performed, for any TLF event obtaining neutron events in the TLF center of mass frame. Neutrons produced in PACE2 calculations were stored by energy in arrays to yield neutron energy spectra for $A_{\rm TLF}$ and $E_{\rm loss}$ bins.

The results of the statistical model simulations are shown in Figs. 1 and 2 and compared with the experimental data. Since the interpretation of the experimental data relies on the Monte Carlo simulation, tests were performed to verify the influence on the results of the assumptions made. The combined effects of the fluctuations in energy loss and spin introduces an average 15% increase of the neutron multiplicity values calculated ignoring the same. The assignment of a mean fragment charge uniquely correlated to the mass produces neutron multiplicity values $\sim 30\%$ higher than the ones obtained assigning randomly distributed $Z_{\rm PLF}$ and $Z_{\rm TLF}$. All the above assumptions produce the same shape of the simulated neutron energy spectra shown in Fig. 1. The percent increase in calculated neutron multiplicity obtained in the extreme case of ignoring the fluctuations in primary fragment distributions is almost independent on the mass gate and $E_{\rm loss}$ and does not affect the conclusions drawn below.

The calculations assuming an excitation energy sharing proportional to the masses of the two reaction partners describe the experimental data better than the ones relative to the hypothesis of equal excitation energies. Furthermore, it is evident that the quality of the agreement between calculations and experiment depends on the mass bin. Some experimental overestimation of the neutron yields is observed for the heavier TLF, while for the lighter ones slight evidence exists near $E_{\rm loss} = 20$ MeV of an excitation energy partition intermediate between the two extreme cases evaluated here.

We emphasize here that the thermal equilibrium hypothesis has been originally formulated[2,3] for events characterized by a complete relaxation of the degrees of freedom. If the two fragments in contact have high excitation energies so that their level densities can be described by the Fermi gas approximation, then thermal equilibrium implies excitation energies proportional to the masses. In the present experiment, the total kinetic energy available in the entrance channel is quite small, being the Coulomb barrier at $E_{\rm loss} = 30$ MeV, and, moreover, it is difficult to separate incompletely from totally relaxed events because of the limited Q-value experimental resolution. Nevertheless, a requirement of excitation energies ratio ($E^*_{\rm TLF}/E^*_{\rm PLF}$) greater than the mass ratio appears clearly also for totally relaxed events. At thermal equilibrium the light mass PLF is certainly at a low excitation energy, so that shell effects in the level density are not yet washed out. For the present case, this means that thermal equilibrium does not simply mean a partition following the mass ratio, independently from the exit channel.

In conclusion, we can state that the present experiment offers evidence for a partition of the excitation energy roughly proportional to the mass ratio but with additional exit channel effects. This effect might be related, in our opinion, to the PLF level density at low excitation, not described by the Fermi gas approximation. The same conclusion was drawn by Sohlbach *et al.*[18] for quasielastic reactions in heavier systems.

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