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Neutron multiplicities and energy sharing in the inelastic collisions of ^{32}S on ^{64}Ni at $E/A = 4.9$ MeV

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The neutron emission from the targetlike fragments (TLF) of the inelastic reactions of 157 MeV ^{32}S on ^{64}Ni has been measured. Neutron energy spectra and multiplicities have been extracted as a function of the dissipated energy for six targetlike fragments mass gates between $A = 56$ and $A = 70$. The comparison between the data and the results of a Monte Carlo simulation based on statistical model calculations with different assumptions on the excitation energy sharing between the reaction partners evidences a dependence from the net mass flow of the evolution of the excitation energy ratios with the energy loss.

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The conversion of varying fractions of the entrance channel kinetic energy into excitation energy of the reaction partners, followed by particle evaporation, is one of the most prominent features of damped nuclear collisions [1]. When experimental information about the partition of the total excitation energy between the exit channel products is lacking, ambiguous considerations can be made about particle evaporation from the primary reaction fragments. Consequently many different experiments [1] have been aimed at measuring the excitation energy fractions found in the main fragments of damped nuclear reactions.

The main experimental evidences have been successfully reproduced in the framework of the one-body nucleon exchange model (NEM) by Randrup and collaborators [2], which describes the evolution of the excitation energy division with the energy loss as going from equal fractions in the early stage of the reaction toward fractions proportional to fragment masses (equal temperature) at complete damping.

Unfortunately the NEM fails to account for some experimental correlations between mass and energy flow and donor-acceptor effects in the net number of exchanged nucleons [3]. In fact, while it can explain a significantly more excited acceptor fragment in the early phases of a peripheral collision [4], it is not able to account for acceptor fragments always strongly favored in the total excitation energy division, over a large range of energy losses.

More experimental evidences are thus needed to provide support for the model refinements required. Within this picture some contribution can be given by the present work.

We report here on a measurement of neutrons emitted from the fragments in the exit channel of the inelastic reactions of 157 MeV ^{32}S on ^{64}Ni to study the excitation energy division between the reaction partners for energy losses up to 50 MeV. This measurement followed a first one on the system 154 MeV ^{32}S on ^{100}Mo, from the report of which [5] some details of the experimental apparatus and procedures can be taken.

The asymmetry of the new system was yet in favor of a good separation of the cases of equipartition and thermal equilibrium partition of the total excitation energy between the fragments, and the bombarding energy assured a sufficiently large range of energy losses for the inelastic reactions.

The experiment was performed at the upgraded MP Tandem of the Laboratori Nazionali del Sud in Catania, with a 360 μg/cm^2 self-supporting target of ^{64}Ni 97% enriched and a position sensitive (15×15 cm^2) parallel plate avalanche counter (PPAC) as the projectile-like fragment (PLF) detector, covering the angular range $\theta_{\rm lab} = 23°-37°$, with overlap of the grazing angle for the reaction ($\theta_{\rm gr,lab} = 32°$). The PLF detector was operated as a stop detector against a small PPAC start detector placed near the target, to measure the PLF velocity vector, in coincidence with a second large area (25×20 cm^2) position-sensitive PPAC to detect TLF angles. The overall mass and energy resolutions were measured on the elastic scattering peak as $\delta A = 1.8$ FWHM and $\delta E = 8$ MeV FWHM, expected to improve with the energy loss as TLF recoiling energy increases and multiple scattering angular spread is reduced.

Neutrons were detected by four NE213 liquid scintillator cells, 12.8 cm in diameter and 5 cm thick, measuring their TOF against the same start detector as above on a flight base of about 1 m with a time resolution of 1.2 ns FWHM. A pulse shape γ-ray discrimination greatly reduced the uncorrelated background. Neutron counts were corrected for the detector efficiencies evaluated within 5% uncertainty by means of experimentally tuned Monte Carlo calculations [6]. Three detectors were placed at $\theta_{\rm lab} = 40°$, $60°$, and $80°$ in the reaction plane on the same side of the TLF counter, while the fourth was located at $\theta_{\rm lab} = 28°$, behind the PLF TOF arm.

In Fig. 1 the measured diffusion plots are shown for PLF-TLF and PLF-TLF-n coincidences. A strong contribution of the elastic scattering peak is observed (which presents enough tails and random coincidences with neutrons to suggest discarding any results near $A_{\rm PLF} = 32$) and a well-defined deep inelastic component appears, more evident in the threefold coincidence scatter plot.

Neutron energy spectra were sorted for each neutron detector and for two units wide mass gates centered at $A_{\rm TLF} = 70$, 68, 62, 60, 58 and 56 as a function of the energy loss $E_{\rm loss}$ reconstructed in the framework of a binary collision dynamics, including Q_{gg} corrections after choosing Z values randomly from Gaussian distributions around the minima of the β stability valley. The chosen mass gates present no contamination from the elastic peak.

After the assumption that the TLF is the only source of the neutrons detected on the same side of the TLF detector and an event-by-event conversion to the frame of the recoiling TLF, the spectra of the three neutron detectors in interest appear identical in shape, a proof that the assumption of the TLF being the only neutron source for that angular region is correct.

Neutron energy spectra were obtained for bins of 10 MeV in $E_{\rm loss}$, up to an $E_{\rm loss}$ value of 50 MeV, by summing properly over the three detectors, and are shown in Fig. 2. Neutron detection efficiency corrections and angle integration procedure affect the spectra with a 10% systematic uncertainty. Mean neutron multiplicities versus $E_{\rm loss}$ for the different mass gates chosen are shown in Fig. 3.

The general trend of the data is the increase of neutron multiplicity and average energy of the neutron spectra with the energy loss, a behavior similar to the one of the data in Ref. [5]. However neutron multiplicity values are here generally lower than in the previously reported case. An overall lower neutron multiplicity range is associated to larger uncertainties in discriminating the fractions of the total excitation energy deposited in the fragments, but the wider mass range of the present data allows some interesting considerations.

Following the methods described in Ref. [5], Monte Carlo statistical model (PACE2 code) simulations have

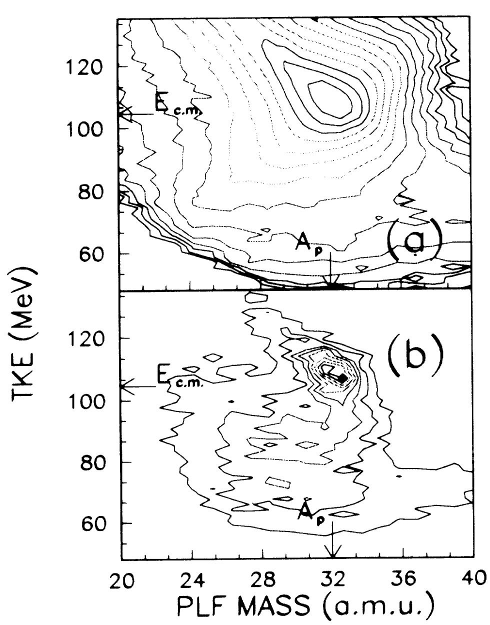

FIG. 1. Diffusion plots for PLF-TLF (a) and PLF-TLF-n (b) coincidences. The arrows mark the c.m. energy and the PLF mass. Isolevel curves are logarithmic in (a) and linear in (b).

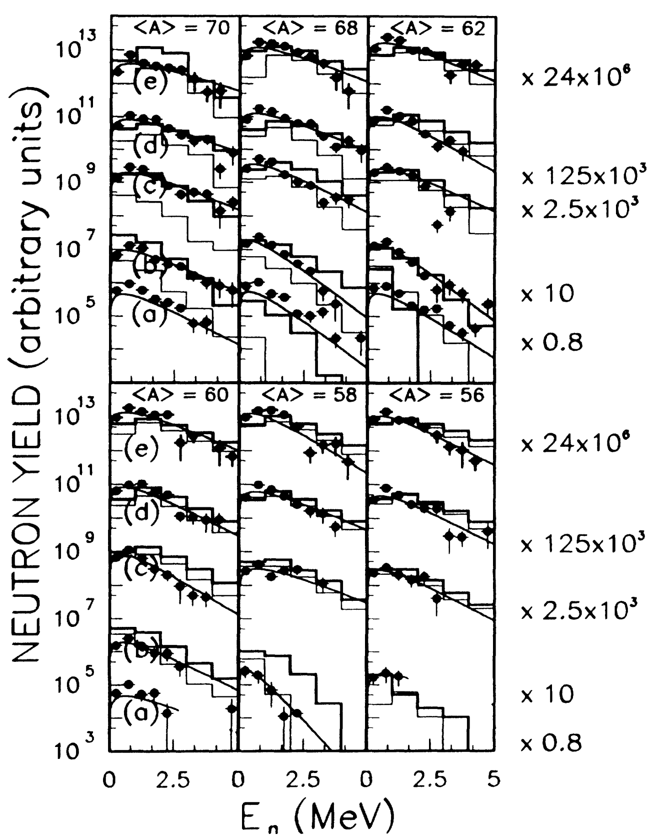

FIG. 2. Neutron energy spectra for different TLF mass and $E_{\rm loss}$ gates [(a) = 0–10 MeV, (b) = 10–20 MeV, (c) = 20–30 MeV, (d) = 30–40 MeV, (e) = 40–50 MeV]. Solid curves on data are only to guide the eye. The results from Monte Carlo simulations are also shown which adopt a partition of the excitation energy proportional to the masses (bold bins) or equipartition (thin bins).

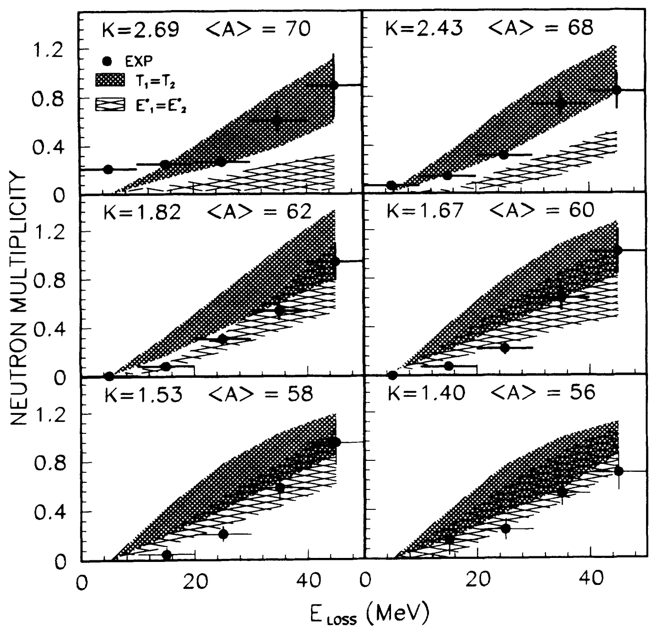

FIG. 3. Mean neutron multiplicity as a function of E_{loss} for different mass gates (two mass units around the shown mean value). The hatched areas show the envelope of the results of Monte Carlo simulation assuming a partition of the excitation energy proportional to the masses and equipartition with various model assumptions (see text). K gives the values of the ratio A_{TLF}/A_{PLF}, and the errors on the experimental data are only statistical.

been performed on the TLF deexcitation, in the two hypotheses of equal ($E_1^* = E_2^*$) or mass proportional ($T_1 = T_2$) sharing of the total excitation energy between the fragments. The results are shown in Figs. 2 and 3 as compared with the experimental data.

In particular, the thin and bold bins drawn in Fig. 2 refer to the calculations for the two cases $E_1^* = E_2^*$ and $T_1 = T_2$, respectively, adopting Z values for the fragments randomly correlated to their masses within a Gaussian distribution centered at the β stability value and fluctuations around mean spin and excitation energy (see Ref. [5]). The hatched areas in Fig. 3 represent the envelope of the results for the same cases, obtained with or without the adoption of the fluctuations around mean spin and excitation energy and of the distribution of the fragment charge around the β stability value. This distribution covers the Z value corresponding to constant N/Z of the compound nucleus, very near for the present system to the β stability value. The hatched areas show the maximum incertitude of the simulated neutron multiplicity values.

The exit channel mass ratios here investigated extend from 2.69 to 1.40 while the net number of nucleons transferred to or from the TLF is between +6 and −8. In Ref. [5] the mass ratios extended from 3.89 to 2.77, while the net number of nucleons transferred to or from the TLF was between +5 and −3. It is to be observed that while we have extended the investigated mass ratio, we have a partial overlap in the net number of exchanged nucleons. Furthermore for the reactions here studied the amount of excitation energy left at thermal equilibrium into the PLF is always greater than in the previous study [5], so that the shell effects in the level density which can influence a partition of the excitation energy in proportion to masses are to play a minor role.

The comparison of the multiplicity data of Fig. 3 with the results of the Monte Carlo statistical model calculations indicates that for the two heavier TLF ($A = 70$ and 68) the excitation energy partition is compatible with mass proportion at almost any energy loss, while for the two lighter ones with $A = 62$ and 60 an evolution is observed from equipartition at low energy losses to mass proportion at the highest energy losses. For the remaining lighter TLF ($A = 58$ and 56) the difference in the excitation energy correlated to equipartition or mass proportional partition is only 17%, smaller than the calculation uncertainties. However the data seem to indicate that a partition proportional to the masses is never reached.

Recalling the experimental results from Ref. [5], an overall experimental trend seems to emerge: acceptor TLF take a larger fraction of the total excitation energy than expected from the NEM at all the energy losses. Slightly donor TLF seem to be excited with increasing energy losses similarly to the general predictions of the NEM, describing an evolution from excitation energy equipartition at low energy loss to mass proportional partition at the highest energy losses. Lightest donor TLF seem to be excited at almost all energy losses accordingly to equipartition.

The trend of the above seems to depend only on the net number of nucleons exchanged: in fact, a few nucleons lost from the TLF seem to be in favor of an excitation energy partition agreeing with NEM general predictions, almost independently on the different mass asymmetry values of both the present and previous study [5]. On the contrary, nucleons gained by the TLF single out extra excitation energy taken by the acceptor fragment, while more nucleons lost by the TLF seem to favor excitation energy equipartition, in both cases at all energy losses. A dependence on the mass asymmetry cannot be clearly established, because of the systematical error of the statistical model calculations.

The amount of uncertainty of the calculations does not allow to be more stringent in conclusions, but we feel that evidence has been provided for the existence of mass exchange effects similar to the ones previously observed by K. Kwiatkowski *et al.* (3). These effects cannot be easily explained, for the reactions of interest here, with only the limitations of the applicability of the Fermi gas model approximation to the PLF level density at low excitation.

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