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GENERATION AND DIVISION OF EXCITATION ENERGY IN HEAVY-ION COLLISIONS STUDIED BY MEASURING CHARGED-PARTICLE SURVIVAL FRACTIONS

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Charged-particle survival fractions of primary projectile-like fragments from the ^{40}Ar+^{197}Au reaction at 450 MeV were measured by using a large array of 32 phoswich detectors operating in coincidence with a detector of projectile-like fragments. Differential survival fractions of the primary pickup and stripping reaction products indicate a dependence of the average excitation energy generated in the primary fragments on the direction of the mass transfer.

The question of the partition of excitation energy in heavy-ion reactions has attracted much interest because of its connection with the mechanism of energy dissipation. For example, the transport model of Randrup [1] based on the wall-plus-window dissipation mechanism [2] predicts for collisions of complex nuclei an approximately equal division of excitation energy in peripheral (quasi-elastic) collisions. with increasing total kinetic energy loss the division is predicted to change gradually, approaching the fully-relaxed (equal-temperature) limit for deep-inelastic reactions. Since the observation by Awes et al. [3] and Vandenbosch et al. [4] of sharing of the excitation energy different from the equal-temperature assumption, the description by Randrup [1] has met with increasing experimental confirmation.

For very asymmetric systems involving relatively light projectiles of $A=10$–20, the energy losses corresponding to quasi-elastic collisions can be well reproduced by the model of Siemens et al. [5], assuming the minimum nucleon transfer necessary to produce the observed reaction products. This demonstrates that for most events the *net* (i.e., observed) transfer of nucleons is *not accompanied* by an additional bi-directional exchange of nucleons between target and projectile, contrary to the suggestion of transport models for heavier systems.

Siwek-Wilczynska et al. [6] proposed that the participant–spectator scheme [7] underlying the model of Siemens et al. [5] implies an allocation of the excitation energy in the receptor nucleus. Thus one can expect to observe a dependence of the division of excitation energy on the direction of the transfer of mass, at least for quasi-elastic reactions induced by light projectiles and dominated by the *net* transfer of nucleons. Evidence of such a dependence has been reported in refs. [6,8] and there are indications that also in heavy systems the partition of excitation energy depends on the direction of nucleon flow (see ref. [9] and references therein).

In the present letter we report on a study of the ^{40}Ar+ ^{197}Au reaction aimed at a comparison of the charged-particle survival fractions of pickup and stripping reaction products as a function of the total amount of excitation energy generated in the colliding system. In such a way, quantitative information on the correlation between the direction of the mass flow and the allocation of the excitation energy could be obtained. The study has been done for a system that is intermediate in mass between heavy systems, which are well described by bi-directional nucleon exchange, and very asymmetric systems, for which

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quasi-elastic processes are dominated by the net transfer of nucleons.

In the experiment, a $^{40}\mathrm{Ar}^{(12+)}$ beam of 450 MeV from the KVI isosynchronous cyclotron bombarded a $^{197}\mathrm{Au}$ target of 2.3 mg/cm^2 thickness. Projectile-like fragments (PLF) were detected with a solid-state-detector telescope at an angle of 28°, i.e., slightly forward of the classical grazing angle for the studied reaction. Simultaneously, nearly all of the accompanying light charged particles (p, d, t, α) were detected with a "plastic wall" constructed from 32 fast/slow phoswich detectors [10] having a 1 m thick fast scintillator as ΔE detector. The wall covered an angular range of about 70° in the vertical (out of plane) direction and about 100° in the horizontal direction (60° on the side of the PLF detector and 40° on the opposite side of the beam). A solid angle of about 50 msr around the beam axis was not covered by the plastic wall.

Only "fast" (non-compound) light charged particles were recorded with the phoswich detectors. Thus, for example, the energy threshold for α-particles was about 29 MeV. At a beam energy of 11 MeV/nucleon, this energy threshold did not significantly limit the detection efficiency for light charged particles originating from the decay of unbound states of the primary PLF's. For these particles the measured coincidence yields fell practically to zero for the most peripheral elements of the plastic wall, thus showing almost 100% detection efficiency of the plastic wall (due to the kinematical focussing), except for the gap in the beam direction.

Fig. 1 shows the multiplicity distribution of light charged particles ($Z=1, 2$) accompanying the projectile-like fragments. The $M=0$ events represent the charge-binary reactions in which the observed PLF does not decay by emission of charged particles, such as p, d, t or α. One can see from fig. 1 that the charge-binary reactions dominate over charge-ternary reactions ($M=1$) and some more complicated processes with a larger number of charged particles in the final state ($M>1$). However, the contribution of non-binary reactions is not negligible even at such a relatively low beam energy. Some events of multiple fragmentation (up to $M=6$) evidently are present.

From the measured coincidence ($M\geqslant 1$) and anticoincidence ($M=0$) events the kinetic-energy spectra of the primary fragments have been reconstructed. The reconstructions have been performed under two simplifying assumptions: (i) All the observed light charged particles originate from sequential decay of the primary PLF's; (ii) The kinetic energy of the primary PLF scales as the kinetic energy of the observed (residual) PLF with a factor proportional to the combined mass of all the observed decay products, i.e. the average velocity is not affected by the sequential decay.

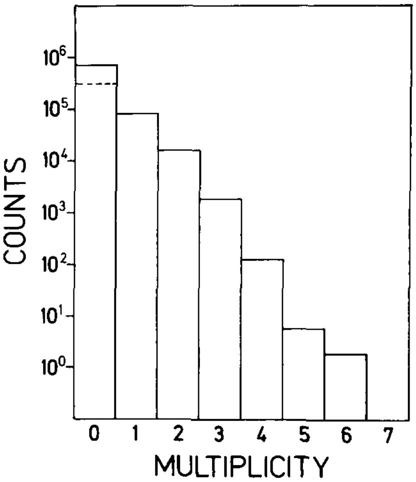

Fig. 1. Multiplicity distribution of light charged particles ($Z=1, 2$) accompanying the projectile-like fragments detected at an angle of 28°. The dashed line for $M=0$ corresponds to the number of PLF's with elastic-scattering events subtracted.

The energy spectra of some of the reconstructed primary fragments are shown in fig. 2. There is a distinct separation of the quasi-elastic and deep-inelastic components. However, for the lightest ejectiles ($Z<13$, not shown) the quasi-elastic component vanishes, and consequently only the deep-inelastic maximum is present. It can be seen from fig. 2 that the quasi-elastic peaks are located at kinetic energies significantly lower than predicted by the optimum Q-value model of Siemens et al. [5]. The shift in energy ranges from 15 MeV to more than 50 MeV, depending on the transferred charge and mass. It seems therefore that for $^{40}\mathrm{Ar}$ as a projectile, the most probable processes at the quasi-elastic peaks no longer are limited to the net transfer of nucleons (as is the case for very asymmetric systems), and an additional exchange of nucleons takes place. One can estimate on the grounds of the optimum Q-value model [5] that the exchange of 1–5 additional pairs of nucleons can

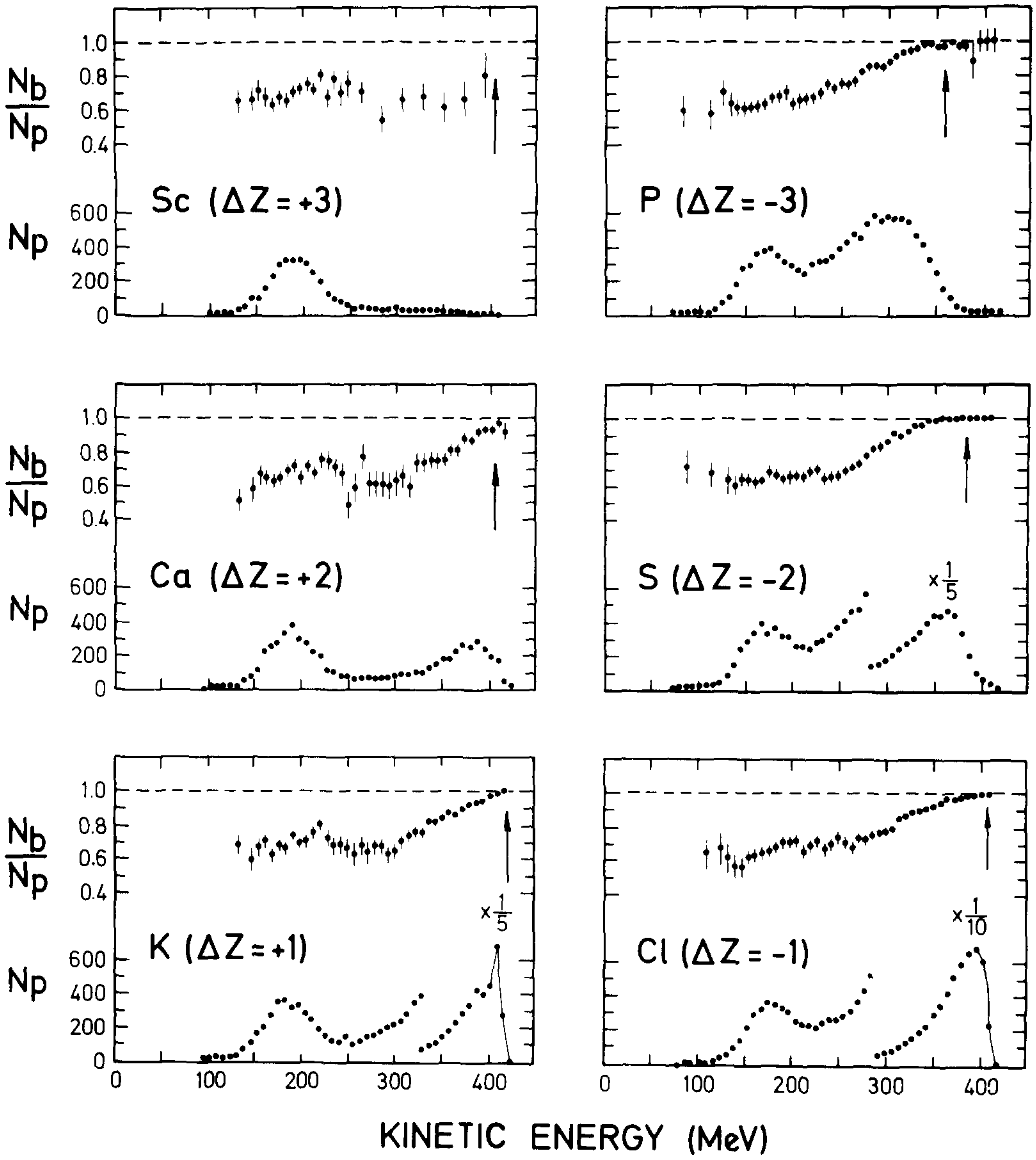

Fig. 2. Energy spectra of primary projectile-like fragments (N_p) and the energy dependence of the charged-particle survival fraction (N_b/N_p) for selected primary products of pickup (left) and stripping reactions (right). The arrows indicate the kinetic energies corresponding to the optimum Q-values [5] calculated for the assumed primary fragments: ^{45}Sc, ^{44}Ca, ^{41}K, ^{39}Cl, ^{36}S and ^{33}P.

produce the observed displacements of the peaks. Thus the observed reactions in the ^{40}Ar+^{197}Au system may be viewed as a link between the net-transfer reactions for very asymmetric systems and multiple bi-directional exchange processes believed to dominate in collisions of two heavy nuclei.

In the present work we were able to determine differential distributions of the charged-particle survival fraction (CPSF) for all the primary PLF's as a function of the kinetic energy of the primary fragment. The CPSF was defined as the ratio of the number of primary PLF's that had survived the charged-particle decay, N_b, (no light charged particles accompanying the PLF) to the total number of primary fragments, N_p. The value of CPSF for a given excitation energy of the primary PLF can be *calculated* with standard statistical-decay codes, so this quantity provides important information about the primary excitations.

The energy dependence of the CPSF for some of the reconstructed primary fragments is shown in fig.2. The survival fractions are displayed together with the energy spectra of the primary fragments. For all ejectiles, the survival fraction systematically decreases with decreasing kinetic energy. (This means that the average excitation energy of the primary fragment increases at the same time.) For the highest kinetic energies, corresponding to low excitation energies generated in the reaction, the survival fractions approach the bound-state limit, CPSF = 1.

For lower kinetic energies the survival fractions have smaller values, stabilizing at about 0.7 in the region of the deep-inelastic maxima. Statistical calculations with the program CASCADE [11] show that such a nearly constant value of the CPSF for the deep-inelastic maxima is consistent with the equal-temperature division of the excitation energy (i.e., proportionally to mass numbers) and with almost complete equilibration of the N/Z ratio of the fragments. For example, the CPSF of about 0.7 would correspond to the equal-temperature division of the composite system by emission of primary PLF's such as ^{49,50}Sc, ^{46}Ca, ..., ^{26,27}Mg, ^{22}Ne, etc. In considering the CPSF it must be remembered that for excited neutron-rich primary PLF's the particle decay is dominated by neutron emission.

For the non-relaxed parts of the energy spectra, the measured charged-particle survival fractions indicate a dependence of the average excitation energy generated in the primary fragments on the direction of the mass transfer. This effect had already been suggested by Siwek-Wilczynska et al. [6], and later in refs. [7,8], on the grounds of the participant–spectator approximation underlying the optimum Q-value model of Siemens et al. [5]. The basic ingredient of this mechanism is that only the transferred fragment and the nucleus that absorbs the transferred mass are participants in the reaction, whereas the rest of the donor nucleus is only a spectator and thus remains "cold" in the reaction.

Fig. 2 presents a comparison of the survival fractions for pickup and stripping of comparable groups of nucleons, $\Delta Z = +3$, $+2$, $+1$ and -3, -2, -1, respectively. For the pickup reactions (on the left-hand side of fig. 2) one can see that the survival fractions deviate from the CPSF = 1 limit faster than for the stripping reactions. The effect is unquestionable, though due to the important role of neutron decay the differences in the CPSF values are limited to the range from 0.8 to 1.0. We will concentrate the discussion on the regions of the energy spectra corresponding to the optimum Q-values calculated according to the model of Siemens et al. [5] and indicated in fig. 2 by arrows. As discussed before, for these kinetic energies one can assume *only* the *net transfer* of nucleons (i.e., without an additional exchange), so that it is easier to check to what extent the partition of excitation energy is governed by the participant–spectator mechanism. One can see from fig. 2 that at the optimum Q-values only the $\Delta Z = +3$ and $\Delta Z = +2$ primary PLF's are excited sufficiently to result in CPSF values significantly lower than 1. For Sc primary fragments ($\Delta Z = +3$) CPSF $\cong$ 0.7–0.8 and for Ca ($\Delta Z = +2$) CPSF = 0.94. For the ejectiles corresponding to pickup of one charge unit ($\Delta Z = +1$) and all stripping reactions ($\Delta Z = -3$, -2, -1) the CPSF at the optimum Q-value is 1.00. These results are consistent with the hypothesis that the *receptor* nuclei take the main part of the excitation energy. Specifically, assigning the mass numbers of the primary fragments as listed in the caption of fig. 2, and assuming that the *entire* excitation energy corresponding to the calculated optimum Q-value is allocated in the receptor nucleus, we have obtained with the code CASCADE [11] the following values of the CPSF: 1.00 for ^{33}P, ^{36}S, ^{39}Cl and ^{41}K, 0.88 for ^{44}Ca and 0.68 for ^{45}Sc. The listed PLF's are the most probable (i.e. Z/N near the projectile, cf. ref. [12]). However, the consistency is independent of the precise mass numbers: The calculated optimum Q-values for pickup ($\Delta Z > 0$) correspond to lower energies than indicated in fig. 2, 6 MeV for each extra neutron picked up. The excitation energy of the PLF will be correspondingly larger. Due to higher N/Z ratio the predicted CPSF decreases only slightly, following the experimental data. For $\Delta Z < 0$ the only effect is that the calculated optimum Q-value corresponds to higher kinetic energies if less neutrons are stripped.

As was mentioned before, we suppose that at kinetic energies lower than predicted by the optimum Q-value model [5] the reactions involve an exchange of nucleons in addition to the observed net transfer.

The picture of the predominant excitation of the receptor nuclei points towards an approximately equal division of the excess of the excitation energy above the amount generated by the net transfer. One can therefore expect that the CPSF of the primary PLF's will decrease systematically with increasing total excitation energy, not only for pickup reactions but also for stripping channels. This effect is clearly seen in fig. 2.

In summary, we were able to reconstruct the primary reaction products from the ^{40}Ar+^{197}Au reaction at 450 MeV. The dominant part of the observed projectile-like fragments originated from charge-binary reactions. Charged-particle survival fractions have been determined as a function of the kinetic energy of the primary PLF's. The CPSF values for the deep-inelastic components in the energy spectra are consistent with the equal-temperature division of the excitation energy and with almost complete equilibration of the N/Z ratio of the fragments. The quasi-elastic parts of the spectra show significant displacements in the most probable energy loss as compared with predictions of the optimum Q-value model of Siemens et al. This effect is interpreted as a consequence of bi-directional exchange of nucleons taking place in addition to the observed net transfer. The CPSF's measured for the quasi-elastic parts of the energy spectra show a dependence of the average excitation energy generated in the primary fragments on the direction of the mass transfer. Statistical-model calculations indicate that the partition of the excitation energy in these quasi-elastic reactions follows the picture of nucleon transfer and exchange as the main dissipative mechanism, with the excitation energy generated mostly in the nucleus that absorbs the transferred mass.

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References

[1] J. Randrup. Nucl. Phys. A 383 (1982) 468.
[2] W.J. Swiatecki, Semical descriptions of atomic and nuclear collisions, eds. J. Bang and J. de Boer (Elsevier, Amsterdam, 1985) p. 281, and references therein.
[3] T.C. Awes et al., Phys. Rev. Lett. 52 (1984) 251.
[4] R. Vandenbosch et al., Phys. Rev. Lett. 52 (1984) 1964.
[5] P.J. Siemens et al., Phys. Lett. B 36 (1971) 24.
[6] K. Siwek-Wilczynska et al., Phys. Rev. C 32 (1985) 1450.
[7] J. Wilczynski, Proc. Intern. Symp. on Heavy-ion physics and nuclear astrophysical problems (Tokyo, 1988) (World Scientific, Singapore), to be published.
[8] H.R. Schmidt et al., Phys. Lett. B 180 (1986) 9.
[9] V.E. Viola et al., Proc. XX Intern. Summer School on Nuclear physics (Mikolajki, 1988) (IOP, Bristol), to be published.
[10] E.E. Koldenhof and H.W. Wilschut, Annual Report KVI Groningen (1985) p. 109.
[11] F. Pühlhofer, Nucl. Phys. A 280 (1977) 267.
[12] H. Breuer et al., Phys. Rev. C 28 (1983)1080.