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ANGULAR MOMENTUM DEPENDENCE OF INCOMPLETE FUSION REACTIONS

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γ-ray multiplicities associated with various reaction channels have been measured for the $^{14}N + ^{197}Au$ system at E_{lab} = 115 and 168 MeV. Channel selection accomplished via charged ejectile–KX-ray coincidence measurements permitted distinction between reactions with two or more charged fragments in the final state. For the former type of reactions the angular momentum dependence expected for (binary) incomplete fusion reactions is observed. For the latter, the same angular momentum dependence is found if sequential decay of the primary light fragment is assumed.

Incomplete fusion reactions are processes in asymmetric nucleus–nucleus collisions in which only part of the (light) projectile is captured by the (heavy) target, while the remainder continues its flight with approximately beam velocity. Due to the localization of this process in *l*-space, there is a strong correlation expected between the captured mass on one hand, and the angular momentum and excitation energy of the heavy residue on the other. This prediction lay at the root of the angular momentum dependence of the incomplete fusion reactions as formulated by Siwek-Wilczyńska et al. [1] and incorporated into the "sum-rule" model of Wilczyński et al. [2]. In this letter we present results of γ-ray multiplicity measurements which give support to the predicted angular momentum dependence. In particular, attention is paid to the angular momentum balance in reactions in which there are more than two charged fragments in the exit channel. We have recently shown that there is an abundance of such processes in the $^{14}N + ^{197}Au$ reaction at 140 MeV [3]. We will demonstrate that the occurrence of these "non-binary" channels is consistent with the assumption that they are due to sequential charged particle emission from an excited light fragment following an incomplete fusion reaction.

The overall angular momentum dependence of deep inelastic and quasi-elastic (incomplete fusion) reactions has been known for some time from measurements of γ-ray multiplicities associated with various ejectiles [4–7]. For systems involving light ejectiles, the interpretation of these inclusive type experiments is difficult because of the abundance of the "non-binary" processes mentioned above. Exclusive experiments can be done by in addition measuring coincidence with discrete γ-lines from the residual nuclei [1,2,8]. With this method, however, only the strongest reaction channels could be studied. In the present investigation we used the more sensitive method [3] of measuring coincidences between the charged ejectiles and the characteristic X-ray of the residual nuclei. The method makes it possible to determine the charge balance of the reaction, i.e.

$$Z_P + Z_T = Z_R + Z_E + \Delta Z\,, \qquad (1)$$

where P and T denote projectile and target, respectively, Z_E is the atomic number of the detected ejectile and Z_R the atomic number of the heavy residue. ΔZ thus is the unobserved or missing charge in the reaction. If charged particle evaporation from the target-like fragment is not an important decay mode, the KX-ray coincidence method can be used to discriminate between the various reaction channels leading to the same ejectile. We have applied this method to the study of the $^{14}N + ^{197}Au$ reaction at 8.2 and 12 MeV/u. For the lower energy reaction channels with missing

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charge $\Delta Z = 0$ dominate, i.e. the reaction is mostly binary. At the higher energy we find a much larger contribution of reaction channels with $\Delta Z > 0$.

The experimental setup was similar to that described in ref. [3]. Two solid state detector telescopes were placed inside a "half moon" chamber, one close to the grazing angle for the measurement of heavy ion ejectiles and one placed at a backward angle for the identification of evaporated particles. For the measurement at 155 MeV an X-ray detector was positioned at 5 cm from the target at the flat side of the "half-moon" chamber. Three large NaI crystals (12 cm ϕ) were placed on top of the scattering chamber at approximately 17 cm from the target to serve as γ-ray-multiplicity detectors. In the experiment at 168 MeV two X-ray detectors and two NaI crystals were used. In addition, two 60 μm thick Si-detectors were mounted at backward angles to measure fission products. All events with up to 25 parameters were recorded on tape for later analysis.

The contribution to the $\Delta Z > 0$ channels due to the charged particle evaporation from heavy residues was estimated on the basis of the coincidence counting rates between the forward and backward detector and was found to be relatively unimportant for ejectiles with $Z_E > 2$; e.g. for ^{7}Li ejectiles we estimated this contribution to be less than 10%.

We will use the following nomenclature for binary reactions:

$$A_P + A_T \to A_{PLF} + A_{TLF}$$

$$= (A_P - n + m) + (A_T + n - m)\,, \qquad (2)$$

where PLF and TLF denote projectile-like fragment and target-like fragment, respectively. With n we denote the number of nucleons transferred from the projectile to the target and with m the number transferred in the opposite direction.

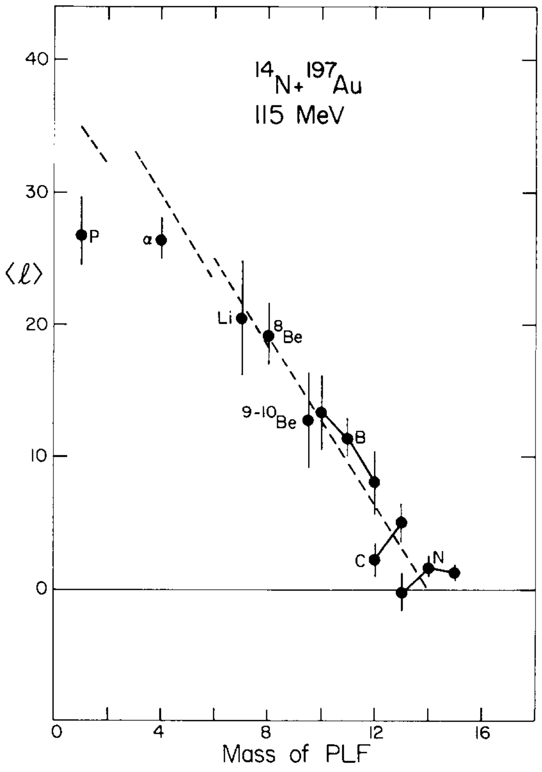

Fig. 1. The angular momentum of the residual nucleus as a function of the mass of the PLF (E_{lab} = 115 MeV). Only reactions that were binary in charge were included. The dashed lines are the sumrule model prediction obtained with the same parameters as in ref. [2]. The statistical errors are indicated.

The angular momentum, l, of the residues was deduced from the average γ-ray multiplicity, $\langle M \rangle$ via the relation $\langle l \rangle = 2(\langle M \rangle - 3)$ (cf. ref. [10]). We applied the fast converging method of Ockels [11] to determine $\langle M \rangle$ from the fold distributions. Figs. 1 and 2 show the average angular momentum of the residual nucleus as a function of the mass of the PLF, i.e. for reaction channels with missing charge $\Delta Z = 0$. In fig. 1 (115 MeV) the result for ^{8}Be is obtained from the reaction channel in which alpha-particles are coincident with KX-rays corresponding to a missing charge $\Delta Z = 2$. Statistical errors in $\langle M \rangle$ are usually below 10%. Some isotopes were combined to meet this requirement. Systematic errors in $\langle M \rangle$ due to the angular momentum alignment of the residue are estimated at about 20%. Additional errors in $\langle l \rangle$ are about 3–4$\hbar$, especially in view of the varying nuclear structure of the residues and for not explicitly correcting for neutron detection in the NaI-crystals. Both the alignment effect and the uncertainty due to nuclear structure will tend to bias $\langle l \rangle$ to lower values. The dashed lines indicate the prediction of the "sum-rule" model [2]. The observed particles have velocity spectra centered not far from the beam velocity. For such quasi-elastic reactions we may relate the entrance angular momentum l_i to the angular momentum l transferred to the

TLF in the following way (see e.g. [9]):

$$\langle l \rangle = (n/A_\mathrm{P} + m/A_\mathrm{T})\langle l_\mathrm{i} \rangle \approx (n/A_\mathrm{P})\langle l_\mathrm{i} \rangle . \qquad (3)$$

The approximately linear dependence for fragments heavier than α-particles can thus be taken as evidence that these reactions occur at about the same $\langle l_\mathrm{i} \rangle$. According to the "sum-rule" model one should find for these particles $\langle l_\mathrm{i} \rangle \approx l_\mathrm{max}$, which is the angular momentum associated with a distance that is the sum of the half-density radii of the colliding nuclei. For the lighter ejectiles $\langle l \rangle$ is determined by the critical angular momentum of the fusing subsystem $A_\mathrm{T} + n$. In figs. 1 and 2 several deviations from the "sumrule" model predictions are observed. For the heavy ejectiles the experimental values are systematically larger than the predicted ones. They also seem to be grouped according to the atomic number of the PLF. The first effect may occur because eq. (3) is valid only for purely quasi-elastic reactions, whereas more inelastic reactions lead to higher angular momenta in the TLF. Especially for ^{16}O at 168 MeV the inelastic component is relatively strong.

The systematic dependence of $\langle l \rangle$ on PLF and the apparent lack of such dependence on the mass for each Z_PLF is conspicuous. A similar behaviour was observed in ref. [6]. We can offer no explanation for these observations other than the sequential neutron emission from PLFs, which is difficult to assess quantitatively.

For protons and α-particles we find angular momenta that are too low compared to the model. From our particle fission coincidence data we estimate that at 168 MeV more than half of the binary reactions involving protons and alpha particles are not observed because of fission of the TLF. Therefore, it seems probable that due to the competition with fission or α-decay we observe only the residues which were populated with lower angular momenta.

So far we have only discussed binary data ($\Delta Z = 0$). In table 1 we also list γ-ray multiplicity values for reaction channels with missing charge $\Delta Z = 1$ and 2. It is evident, in spite of the relatively large scatter of the values, that $\langle M \rangle$ is associated with the atomic number of the primary fragment and not with that of the measured ejectile. We conclude from this observation that the reaction channels with missing charge are consistent with incomplete fusion reactions in which the excited PLF subsequently decays by particle emission.

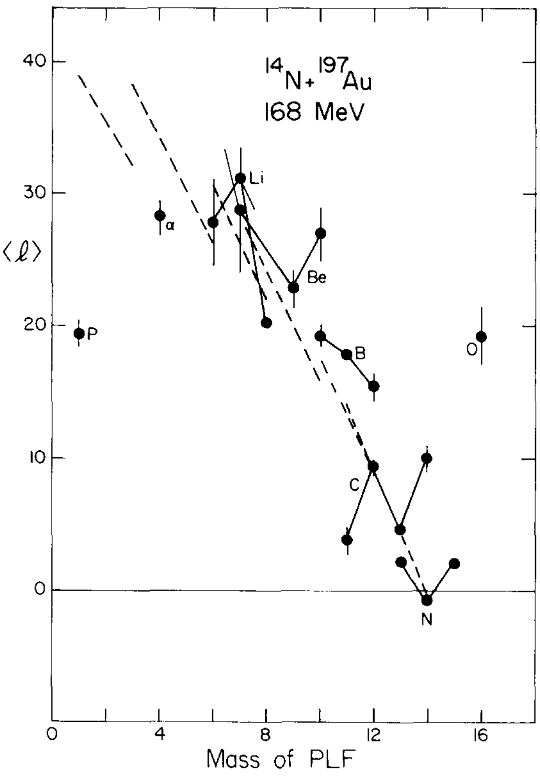

Fig. 2. As in fig. 1; E_lab = 168 MeV.

Such conclusions have also been reached with different techniques [12–14]. Note, however, that the present experiment cannot exclude a contribution from preequilibrium particle emission from TLFs.

Summarizing, we have carried out a set of exclusive measurements permitting determination of the dependence of the angular momentum transfer on the transferred mass. In view of the abundance of the sequential particle emission from the light ejectiles we find it imperative for the determination of the transferred mass to identify the atomic number of the heavy residue associated with each detected ejectile. We have accomplished this by recording the ejectiles in coincidence with the KX-rays characteristic for the heavy residues. We find the angular momentum dependence consistent with the predictions of the sum-rule model based on the assumed localization of the incomplete fusion reactions in l-space.

Table 1
Average γ-ray multiplicities $\langle M \rangle$ associated with various detected ejectiles tabulated according to the atomic number of the residues (E = 168 MeV). Statistical errors are $\Delta M \leqslant 1$. *n*-rules indicate insufficient counting statistics. .

detected ejectile	Z_{res}		
	79	80	81
^{15}N	4		
^{14}N	3		
^{13}N	4		
^{14}C	3	8	
^{13}C	7	5	
^{12}C	3	8	
^{11}C	–	5	
^{12}B	–	–	11
^{11}B	6	–	12
^{10}B	3	–	13
^{10}Be		9	–
^{9}Be		7	12
^{7}Be		7	13
^{8}Li			16
^{7}Li			14
^{6}Li			10
PLF (parent)	N	C	B

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References

[1] K. Siwek-Wilczyńska, E.H. du Marchie van Voorthuysen, J. van Popta, R.H. Siemssen and J. Wilczyński, Nucl. Phys. A330 (1979) 150.
[2] J. Wilczyński et al., Nucl. Phys. A373 (1982) 109.
[3] H.W. Wilschut et al., Phys. Lett. 123B (1983) 173.
[4] P. Glaessel et al., Phys. Rev. Lett. 38 (1977) 331.
[5] A. Olmi et al., Phys. Rev. Lett. 41 (1978) 688.
[6] M.L. Halbert et al., Phys. Scr. T5 (1983) 91.
[7] C. Gerschel, Nucl. Phys. A387 (1982) 297 and references therein.
[8] K.A. Geoffry, D.G. Sarantites, M.L. Halbert, D.C. Hensley, R.A. Dayras and J.H. Barker, Phys. Rev. Lett. 43 (1979) 1303.
[9] P.J. Siemens, J.P. Bondorf, D.H.E. Gross and F. Dickmann, Phys. Lett. 36B (1971) 24.
[10] D.G. Sarantites, L. Westenberg, M.L. Halbert, R.A. Dayras, D.C. Hensley and J.H. Barker, Phys. Rev. C18 (1978) 774.
[11] W. Ockels, Z. Phys. A286 (1978) 181.
[12] J. van Driel, S. Gonggrijp, R.V.F. Janssen, R.H. Siemssen, K. Siwek-Wilczyńska and J. Wilczyński, Phys. Lett. 98B (1981) 351.
[13] R.K. Bhowmik et al., Nucl. Phys. A390 (1982) 117 and references therein.
[14] U. Jahnke et al., Phys. Rev. Lett. 50 (1983) 1246.