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CROSS SECTION BALANCE IN THE $^{14}N + ^{159}Tb$ REACTION AND THE ORIGIN OF FAST ALPHA PARTICLES

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Exclusive cross sections have been obtained from particle–K X-ray coincidence data measured at 236 MeV for ejectiles ranging from ^4He to ^{15}N. Production cross sections for primary fragments and alpha particle multiplicities associated with different channels have been deduced. The major fraction of the alpha particles appears to originate from inelastic (damped) processes in which only light particles with $Z \leqslant 2$ are emitted.

An intriguing question in the study of heavy ion reactions at low and intermediate energies is the striking difference between reactions induced by light heavy ions on one hand and those induced by very massive nuclei. Whereas in the latter deep-inelastic processes appear to be the dominant reaction mode, quasi-elastic reactions in which ejectiles are emitted with approximately beam velocity are most prominent in reactions with light heavy ions. Other characteristics of reactions with light heavy ions are the strongly asymmetric mass flow from the projectile to the target and the large abundance of alpha particles at forward angles [1].

In this letter we report on results from particle–K X-ray coincidence measurements at 236 MeV that are part of a wider study of the $^{14}N + ^{159}Tb$ system in the energy range 115–310 MeV. The particle–K X-ray coincidence method has been shown to be a powerful tool to identify reaction channels [2]. From the present investigation we find that restrictions of the method in the determination of cross sections due to unknown K X-ray multiplicities are less severe for the system studied than was originally feared. We find that it is possible to account for all of the inclusive cross sections of projectile-like fragments (PLF's) ranging from alpha particles to ^{14}C. Furthermore, partial cross sections for alpha particles that are not in coincidence with a PLF can be deduced. By reconstructing cross sections for the emission of primary fragments we find the quasi-elastic channels to be the dominant ones for PLF's with $Z > 2$, while for the bulk of the alpha particles a different (more inelastic) reaction mode appears to be responsible.

The experimental method that involves the measurement of coincidences between PLF's and characteristic K X-rays from the target-like residual nuclei has been discussed extensively before. [2–4] A metallic ^{159}Tb target of 2.9 mg/cm^2 thickness was bombarded with a ^{14}N beam from the KVI cyclotron. PLF's were detected with solid state detector telescopes placed at 20°, 30° and 150°. Three Ge X-ray detectors of 10, 16, and 16 mm diameter were positioned at the

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flat, thin-windowed side of a "half-moon" chamber 6 cm from the target. The resolution for the K X-rays of interest was approximately 500 eV and the absolute detection efficiency 0.2%. For the measurement of γ-ray multiplicities [4] 3 large (12 cm ⌀) NaI detectors were placed in the reaction plane outside the scattering chamber. Absolute cross sections were obtained by normalizing to elastic scattering at forward angles.

From the K X-ray coincidence measurements partial yields of different ejectile–residual nucleus (Z_{res}) combinations are obtained, and with a knowledge of the K X-ray multiplicities the partial cross sections. The raw coincidence data, corrected for coincidence efficiencies, exhibit a pronounced odd–even staggering dependent on Z_{res}. Such odd–even staggerings of about a factor of two have been observed previously [5–8] in average K X-ray multiplicities. With K X-ray multiplicities of 0.6 for Z_{res} = even and 1.2 for Z_{res} = odd, in qualitative agreement with average multiplicities independently deduced for this mass region [7,8], we find that we can consistently describe the data measured at different energies.

In fig. 1 partial differential cross sections for selected channels at $E_{lab} = 236$ MeV are plotted against the atomic number of the residual nuclei (Z_{res}). The rightmost bars present the (incomplete fusion) cross sections in which in a binary reaction the ejectile is emitted in a particle stable state (missing charge zero). The striking observation is the large contribution from "non-binary" channels, i.e. channels with "missing charges"

$$dZ = Z_{targ} + Z_{proj} - Z_{res} - Z_{PLF} > 0.$$

From the measurements at the other incident energies (not shown) it is found that the relative importance of these channels increases strongly with bombarding energy. They also become increasingly more important and even dominant as the PLF is further removed in mass and charge from the projectile. As was discussed in a previous publication [3] these "non-binary" channels can be attributed largely to (sequential) decays of primary PLF's. Charged particle decays of the target-like fragments were deduced from the back-angle decay yields of protons and alpha particles to be relatively unimportant. Assuming isotropic angular distributions multiplicities of evaporative protons and alpha particles related to the inclusive HI cross sections are less than 5%. Contributions from evaporative alpha particles to the exclusive alpha-particle cross sections at 20° also are smaller than 5%.

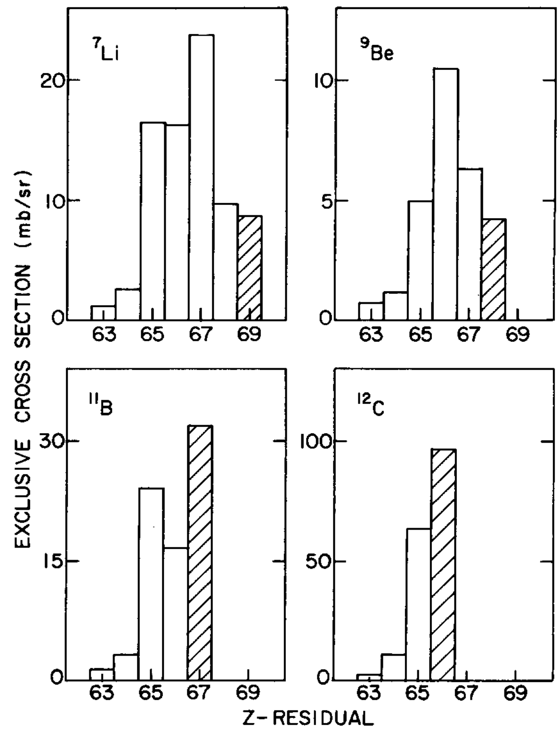

Fig. 1. Exclusive cross sections for selected projectile-like fragments from the $^{14}N + ^{159}Tb$ reaction at 236 MeV detected at 20°. The cross sections are plotted versus the atomic numbers of the residual target-like fragments. The rightmost (shaded) bars correspond to the $\Delta Z = 0$ channels.

In table 1 we list the matrix of partial cross sections measured at 20°. The columns in the matrix are ordered according to the atomic numbers of the residual nuclei ($Z = 65$ is terbium) and the rows indicate the detected fragment. Since the present method does not identify neutron decays of either the PLF or the TLF, cross sections for PLF's with the same atomic number have been combined except for ^{4}He. Adding the cross sections of table 1 in one row should yield the independently measured inclusive cross sections which, for comparison, are listed in the last column. We indeed find that we obtain with the

Table 1
Cross section matrix of combined isotopic yields at 20° [a].

PLF	Z_{res} 64	65	66	67	68	69	70	$\Sigma\sigma_{excl}$	σ_{incl}
α	71	215	290	220	185	140	7	1128	1057
Li	9	23	24	40	15	16		127	110
Be	2	7	20	12	8			49	60
B	6	46	25	57				134	135
C	18	105	158					281	300
N	11	232						243	(375)

[a] Cross sections in mb/sr. Estimated errors 20%.

K X-ray multiplicities mentioned earlier in this paper, the inclusive cross sections within about 20% for all ejectiles except nitrogen. The discrepancies for nitrogen can be understood in view of experimental difficulties in separating out the very intense elastic component from the inclusive data.

Conversely, if one assumes that the cross sections for different PLF's listed in the same column originate from the decay of the (excited) primary fragments for which the missing charge is zero (listed on the diagonal of the matrix) the production cross sections for the primary fragments emitted in a particle stable or unstable state can be obtained. These are shown as bargraphs in fig. 2a together with the measured inclusive cross sections. To avoid double counting only the cross sections for PLF's with $Z > 2$ have been added. As expected for a (direct) quasi-elastic process, the primary cross sections drop off rapidly as the PLF is further removed from the projectile (fig. 2a). Though the correct procedure to obtain the primary cross sections for the PLF's would have been to add angle integrated rather than differential cross sections, estimates of the kinematic effects on the sequential decays indicate that our conclusions are not grossly affected by these.

If it is further assumed that the missing charge in the sequential decays of the PLF's is carried away by protons and alpha particles only, and that decay via an alpha particle is favoured over two-proton decays, differential cross sections of alpha particles that are not associated with a PLF with $Z > 2$ can be obtained from the cross section matrix. These, corrected for the respective alpha-

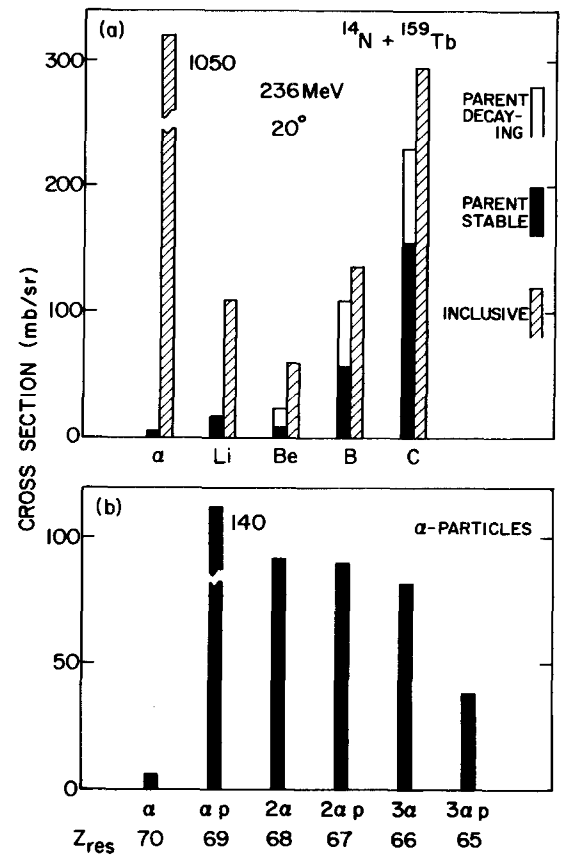

Fig. 2. (a) Cross sections of primary fragments emitted in a particle stable (black bars) or a particle unstable (open bars) state. For Li the particle unstable fraction could not be determined reliably. In addition also the inclusive differential cross sections (shaded bars) measured at the same angle (20°) are shown. In the bottom (b) alpha particle cross sections, corrected for multiplicities, are shown for the different channels.

particle multiplicities are plotted in fig. 2b. The very small cross section for incomplete fusion with one alpha particle emitted should be noted, though some of this strength will be missing due to charged particle evaporation and fission.

In striking contrast to the steep fall off of the cross sections of fig. 2a for primary PLF's with $Z > 2$ the alpha-particle cross sections of fig. 2b have a much broader distribution as a function of Z_{res}. This observation strongly suggests that most of these alpha particles do not originate from the same quasi-elastic process but are produced in more dissipative reactions instead, for which the mass distributions are known to be wider. The assumption of a dissipative process as the source of the alpha particles is further supported by the γ-ray multiplicities measured simultaneously in this experiment. The γ-ray multiplicities and thus the energy dissipated in the TLF are found to increase strongly with missing charge for the same residual nucleus. For $Z_{res} = 65$ (Tb) for which the effect is most dramatic we e.g. find multiplicities of 2.3(0.2), 3(0.5), 5(1.0), 6.5(3.5), 7.5(1.8) and 11(2.6) for N, C, B, Be, Li and alpha particles, respectively. The γ-ray multiplicities also increase with charge transfer, i.e. Z_{res}. The large γ-ray multiplicity for alpha particles and $Z_{res} = 65$ (no charge transfer to the target) is most remarkable. It clearly excludes quasi-elastic processes followed by sequential decay as the primary source of these alpha particles. We also refer to particle–particle correlation studies in which the contribution of "non-sequential" alpha particles is found to increase with inelasticity [9–11] and to a neutron multiplicity measurement [12] in which non-equilibrium alpha particles were found to be associated with large neutron multiplicities.

From the above features it is tempting to associate those alpha particles that are not accompanied by PLF's with $Z > 2$ with deep-inelastic processes. Such a mechanism could readily explain the large cross sections for alpha particles and their wide distribution in Z_{res}. On the other hand, the energy spectra of the alpha particles show that they do not originate from a totally energy-damped process. This might indicate that the alpha particles and nucleons are produced already in the initial stage of energy dissipation before full relaxation has been reached. We leave the question open, whether the alpha particles and nucleons are emitted spontaneously during the relaxation process, or whether they are the products of a sequential decay chain. It is of further interest to explore whether or not there is a relation to the fragmentation-like processes recently observed at GANIL [13–15] that are characterized by a wide mass distribution (in contrast to the quasi-elastic processes simultaneously seen) and some energy damping.

In summary an extensive set of exclusive cross section data has been obtained for the $^{14}N + ^{159}Tb$ reaction at 236 MeV from which production cross sections of particle stable as well as particle unstable primary fragments have been deduced. For the observed PLF's with $Z > 2$ a quasi-elastic process seems to be the main source of ejectiles, whereas the major fraction of alpha particles appears to originate from more damped reactions involving strong excitation of both target and projectile.

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