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SEQUENTIAL EJECTILE DECAYS AND UNCORRELATED BREAKUP PROCESSES IN THE $^{14}\text{N} + ^{159}\text{Tb}$ REACTION

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From a study of particle-particle correlations, involving position-sensitive detector telescopes, conclusive evidence for sequential ejectile decay was found, and the relative importance of sequential decay and of breakup processes, which were observed to be uncorrelated in angle, could be determined.

Particle-particle correlations in energetic nucleus-nucleus collisions are a subject of much current interest [1-6]. Enhanced coincidence yields in the direction of the projectile-like fragment are suggestive of sequential ejectile decay [2,3,6]. Recent particle-particle coincidence data [4,5] which were found to be almost uncorrelated in angle point towards more complicated processes probably involving three-body final states. Open questions concern the relative importance of the various possible reaction modes, and the intermediate states that are involved.

We report here on a study of the $^{14}\text{N} + ^{159}\text{Tb}$ reaction in which we find conclusive evidence for sequential ejectile decay from the observation of sharp peaks, corresponding to the known α -decaying states of the ejectile in the c.m. energy spectrum of the two light fragments. A method is proposed to divide the double differential cross section into an uncorrelated part that very likely is due to inelastic projectile breakup [7], and a part resulting from sequential ejectile decays. Including the results from particle-gamma coincidence measurements of the incomplete fusion reaction we can account for most of the inclusive heavy-ion cross section.

Two sets of measurements were performed. In the

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first heavy-ion alpha correlations were measured in the reaction plane with two detector telescopes, consisting both of a $50\ \mu\text{m}$ ΔE and a $5\ \text{mm}$ E detector. Mass and charge resolution was possible for all ions with $2 \leq Z \leq 8$. In the second measurement, aimed specifically at studying the sequential ejectile decay, two *position-sensitive* detector telescopes were placed at 20° and 30.5° at distances of 173 and 113 mm, respectively. Each of these telescopes consisted of three solid state detectors of $50\ \mu\text{m}$, $500\ \mu\text{m}$ and $1500\ \mu\text{m}$ thickness of which the center detector was position-sensitive with an active area of $8 \times 10\ \text{mm}^2$. Targets consisted of metallic foils of ^{159}Tb of 1.4 and 3.1 mg/cm² thickness, respectively. To check and if necessary to correct for possible contributions from light contaminants measurements were also performed with a carbon target. These contributions to the α -Li, α -Be and α -B coincidence yields were found to be smaller than 15-20% (only upper limits could be determined), and therefore no corrections have been made. Absolute cross sections were obtained to $\pm 15\%$ by normalizing to elastic scattering.

In fig. 1 the results of the heavy-ion alpha correlation measurements at $E^{14}\text{N} = 112, 140$ and $168\ \text{MeV}$ are shown. Plotted are the double differential cross sections obtained with the heavy-ion detector at 20° and the alpha detector rotated in the reaction plane. The figure comprises the combined data (to improve on statistics) of $^6\text{-}^8\text{Li}$, $^7,9,10\text{Be}$ and $^{10}\text{-}^{12}\text{B}$ ions in

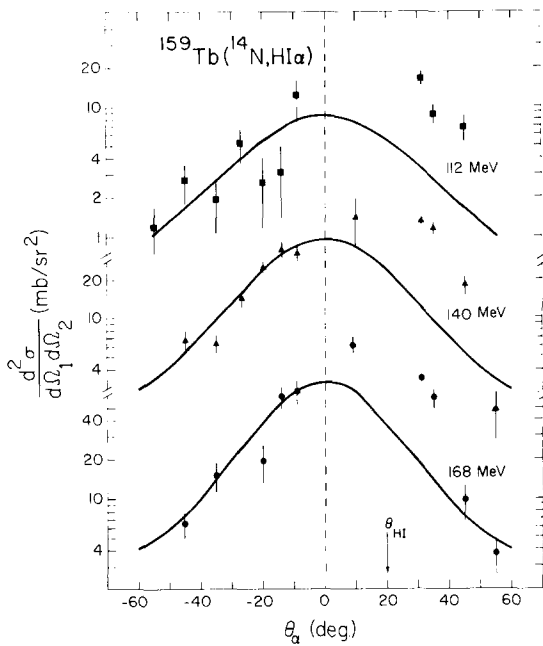


Fig. 1. Double differential cross sections for HI- α coincidences for three different bombarding energies measured with the heavy-ion detector at 20° , and the α -detector moved in the reaction plane. The data combine coincidences for Li, Be and B ions (HI = ${}^6\text{-}8\text{Li}$, ${}^7,9,10\text{Be}$ + ${}^{10-12}\text{B}$). Solid lines represent the uncorrelated component with its angular dependence taken to be that of the singles α -particles.

coincidence with alpha particles. With the detectors on opposite sides of the beam the double differential cross section is seen to fall off exponentially, whereas on the same side of the beam the cross section is enhanced.

In a similar study of the ${}^{14}\text{N} + {}^{58}\text{Ni}$ reaction at $E_{14\text{N}} = 148$ MeV it was observed by Bhowmik et al. [4] (who did not find the enhanced cross sections for close geometries) that the double-differential and energy-integrated cross section for heavy-ion alpha coincidences could be written as a product of the inclusive singles cross sections:

$$d^2\sigma/d\Omega_\alpha d\Omega_{\text{HI}} = k(d\sigma/d\Omega)_\alpha(d\sigma/d\Omega)_{\text{HI}}, \quad (1)$$

where k is a constant that was found to have the same value ($k = 0.5 \text{ b}^{-1}$) for all ejectiles. Events satisfying (1) are spatially uncorrelated. The curves in fig. 1 have been obtained using relation (1) with k -values of $(0.26 \pm 0.08) \text{ b}^{-1}$, $(0.35 \pm 0.04) \text{ b}^{-1}$ and $(0.26 \pm 0.05) \text{ b}^{-1}$ at $E_{14\text{N}} = 112$ MeV, 140 MeV and 168 MeV, respec-

tively. These k -values are rather close to that of Bhowmik et al. [4] ($k = 0.5 \text{ b}^{-1}$) for ${}^{58}\text{Ni} + {}^{14}\text{N}$, indicating that k does not depend much on target mass. The k -values obtained for the Li, Be and B coincidence data separately are the same within their errors.

From the good description with relation (1) of the coincidence data with the α -particle and heavy-ion detectors on opposite sides of the beam we conclude that these events are due to uncorrelated breakup processes similar to those reported in ref. [4]. As we will show in the following the enhanced cross sections, obtained with the heavy-ion and the alpha detector placed close to each other, are due to sequential ejectile decay.

To study the sequential ejectile decay in more detail and to obtain conclusive evidence for its presence, we measured the alpha-particle heavy-ion coincidences at $E_{14\text{N}} = 140$ MeV with two position-sensitive detector telescopes, as discussed above. Total energy spectra ($E_{\text{tot}} = E_{\text{HI}} + E_\alpha$) as well as the relative energy spectra in the c.m. system of heavy-ion and alpha particle are shown in fig. 2. The relative energy ϵ in the c.m. system that corresponds to the excitation energy of the ejectile before breakup, minus the separation energy, is given by the relation:

$$\epsilon = (M_\alpha + M_{\text{HI}})^{-1} \times [M_\alpha E_{\text{HI}} + M_{\text{HI}} E_\alpha - 2(M_\alpha M_{\text{HI}} E_\alpha E_{\text{HI}})^{1/2} \cos \beta], \quad (2)$$

where β is the angle between the two fragments. A precise knowledge of β is crucial to obtain a good energy resolution in ϵ , as is demonstrated in fig. 3 for the ${}^{15}\text{N}^* \rightarrow {}^{11}\text{B} + \alpha$ system.

Sharp peaks ($\Delta E < 150$ keV) that can be related to known, α -decaying states in ${}^{10}\text{B}$, ${}^{14}\text{N}$ and ${}^{15}\text{N}$ are seen in the relative energy spectra of the ${}^6\text{Li} + \alpha$, ${}^{10}\text{B} + \alpha$ and ${}^{11}\text{B} + \alpha$ systems (fig. 2, top). There is a close correspondence between resonances in the ${}^{14}\text{N}(n, \alpha){}^{11}\text{B}$ reaction [8] and the peaks seen in the ${}^{11}\text{B} + \alpha$ system. In the ${}^{10}\text{B} + \alpha$ system we observe a strong peak at $E_x = 12.72 \pm 0.05$ MeV and a weaker one at $E_x = 13.1 \pm 0.10$ MeV. These appear to be the same states that are strongly excited in inelastic scattering [9] on ${}^{14}\text{N}$. For both systems ($\text{B} + \alpha$) most of the strength in the total energy spectrum is concentrated in one peak, corresponding to no or low excitation of the target-like residual nucleus. All these observations point towards a quasielastic (direct) reaction in which the ex-

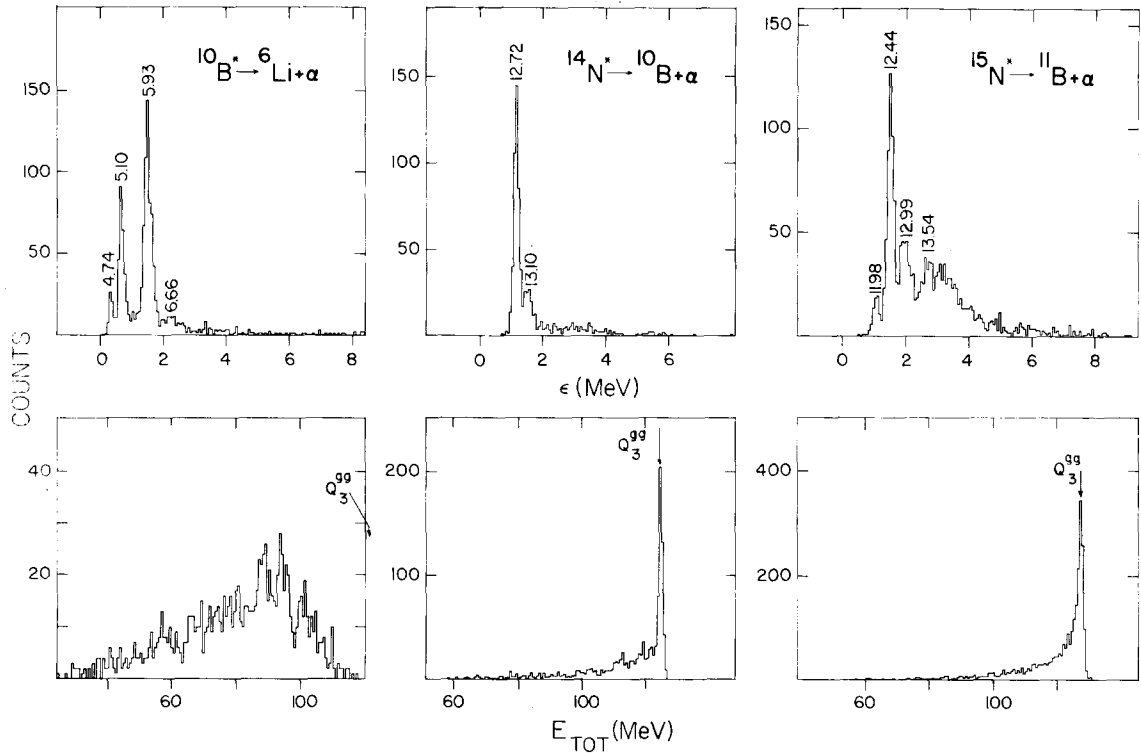
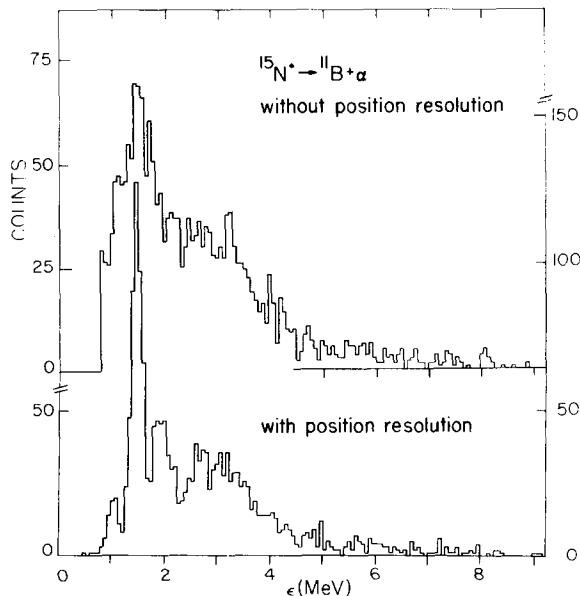


Fig. 2. Relative energy spectra (top) in the c.m. system of the two fragments, and total energy spectra (bottom) for the $^6\text{Li} + \alpha$, $^{10}\text{B} + \alpha$ and $^{11}\text{B} + \alpha$ systems, respectively. For distinct peaks in the relative energy spectra the excitation energies (determined with an accuracy of about 100 keV) are indicated.



cited ejectile is formed, that subsequently then decays. The differences in the total energy spectra between the $^6\text{Li} + \alpha$ and the $\text{B} + \alpha$ spectra can be accounted for by different optimum Q -values, or alternatively, a four particle final state (three fragments plus the target) can explain the $^6\text{Li} + \alpha$ total energy spectrum.

Having demonstrated the presence of two distinct components in the heavy-ion-alpha coincidence data we propose to use relation (1) to divide the double-differential cross sections into these two parts and thus to obtain an estimate of their relative contribution to the inclusive heavy-ion cross sections. To obtain the uncorrelated part we assume rotational symmetry

Fig. 3. Relative energy spectrum in the c.m. system of $^{11}\text{B} + \alpha$ measured without position resolution (top), and with optimum angular resolution $\Delta\beta = 0.4^\circ$ (bottom), respectively. The range of the relative angles covered by the telescopes was $6.8^\circ < \beta < 14.2^\circ$.

Table 1

Differential cross sections, $d\sigma/d\Omega$ ($\theta_{\text{HI}} = 20^\circ$), in mb/sr for various reactions at $E_{^{14}\text{N}} = 140$ MeV. The uncertainties in the cross sections do not include a possible error ($\approx 15\%$) in the absolute normalization.

Reaction mode	Reaction product		
	$6\text{--}8\text{Li}$	$7,9,10\text{Be}$	$10\text{--}12\text{B}$
uncorrelated breakup	8.7 ± 2.1	8.5 ± 2.0	27 ± 6
sequential breakup	6.5 ± 1.6	3.6 ± 0.9	11 ± 3
incomplete fusion	<9	11.0 ± 2.0	23 ± 5
inclusive cross section	28.3 ± 1.5	27.4 ± 1.3	87 ± 3

around the beam axis and use relation (1). The assumption of rotational symmetry around the beam axis was checked by an out-of-plane correlation measurement with both detectors at $\theta = 20^\circ$ and $\phi_2 = 120^\circ$ and 180° , respectively. Both measurements agreed within their errors. To compute the cross section due to sequential decay we integrate around the direction of the excited ejectile, again assuming rotational symmetry in the absence of a more complete knowledge of the detailed angular distributions. Since most of the cross section originates from events within a narrow cone, deviations from rotational symmetry should have a small effect on the angle-integrated cross section. All results for $E_{^{14}\text{N}} = 140$ MeV, are listed in table 1, in which we have also included the cross sections for incomplete fusion, as obtained from a particle- γ coincidence measurement [10], and the inclusive heavy-ion cross sections for the $^{14}\text{N} + ^{159}\text{Tb}$ reaction. Sequential decay, the uncorrelated event, and incomplete fusion are seen to account for most of the inclusive beryllium and boron cross section at 20° (about 80% and 70%, respectively).

Although the exact origin of the uncorrelated events that follow relation (1) is presently not known, it is tempting to relate these to the inelastic breakup seen in reactions with light projectiles [7], in which one of the two fragments undergoes an inelastic collision with the target. The interaction of the fragments

with the target is much stronger than between the fragments, and therefore no correlation between the fragments remains. Whereas the sequential ejectile decays as discussed above seem to originate from quasi-elastic and thus surface reactions, with a clear time-ordering between the formation of the excited ejectile and its decay, we suspect the inelastic breakup to originate from more violent collisions in competition with incomplete fusion.

In conclusion we have shown the presence of uncorrelated events due most likely to inelastic breakup, and of sequential ejectile decay in the $^{14}\text{N} + ^{159}\text{Tb}$ reaction at $E/A = 10$ MeV. The factorization procedure of Bhowmik et al. [4] derived for $^{14}\text{N} + ^{58}\text{Ni}$ was found to be equally applicable to the present data. Conclusive evidence for sequential ejectile decay was deduced from the observation of sharp peaks in the relative energy spectrum of the two fragments. The relative importance of inelastic breakup and of sequential ejectile decay was determined. In combination with incomplete fusion data it was possible to account for most of the inclusive differential heavy-ion cross section.

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