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THE IMPORTANCE OF SEQUENTIAL EJECTILE DECAY IN THE $^{14}\text{N} + ^{58}\text{Ni}$ REACTION AT 148 MeV

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The previously suggested factorisation of double-differential heavy-ion alpha coincidence cross sections into a product of inclusive cross sections for heavy-ion and alpha detection has been reexamined for the $^{14}\text{N} + ^{58}\text{Ni}$ reaction at 148 MeV. Contrary to the conclusions of previous work the present experiment indicates that these so called "uncorrelated" events are predominantly due to sequential decay of the primary fragments and hence are correlated.

During the last few years particle-particle correlation studies have been the subject of intensive investigations to explore the character of light heavy-ion reactions with more than two particles in the final state. Whereas the presence of sequential decay of the primary fragment in these reactions has been clearly established, the presence or absence of a non-sequential process has been a topic of much interest and of some controversy during recent years. (See ref. [1] and references therein). Conclusive evidence for sequential ejectile decay was obtained from the observation of sharp peaks in the relative energy spectra in the CM system of α -particle and light ejectile, that could be associated with discrete and known states in the α -decaying (parent) fragment [2-7]. In contrast Bhowmik et al. [8] at Birmingham in an investigation of the $^{14}\text{N} + ^{58}\text{Ni}$ system at 148 MeV essentially ascribed the total heavy-ion alpha double-differential cross section to a non-sequential ("uncorrelated") component. The characteristic features of this non-sequential component were found [8] to be a symmetry about the beam direction and the fact that the cross section can be factorised into a product of the inclusive cross section of the detected heavy ion and the α -particle.

In a subsequent study at Groningen of the $^{14}\text{N} + ^{159}\text{Tb}$ system at 140 MeV van Driel et al. [2] and

Bhowmik et al. [1] on the other hand observed in addition to a non-sequential component, similar to that found in the $^{14}\text{N} + ^{58}\text{Ni}$ investigation, a strong sequential component. The same conclusions were reached for the $^{14}\text{N} + ^{93}\text{Nb}$ reaction at 208 MeV by Fukuda et al. [3]. The clear presence of a sequential component in the $^{14}\text{N} + ^{93}\text{Nb}$ and $^{14}\text{N} + ^{159}\text{Tb}$ reactions on one hand, and its apparent absence in the $^{14}\text{N} + ^{58}\text{Ni}$ reaction on the other hand at a very similar beam energy presents an obvious puzzle. To resolve this question we have reinvestigated the $^{14}\text{N} + ^{58}\text{Ni}$ reaction. In contrast to the measurement of Bhowmik et al. [8] we used position sensitive detectors, a technique [2] that revealed the sequential component in the $^{14}\text{N} + ^{159}\text{Tb}$ reaction.

A ^{14}N beam with an energy of 148 MeV from the KVI-cyclotron was used to bombard a 2.5 mg/cm^2 thick ^{58}Ni target. Four Si-detector telescopes were used to detect the heavy ejectiles; three of them consisted of a $50 \mu\text{m}$ ΔE , a position sensitive $500 \mu\text{m}$ E and a 5 mm E detector. These were used to detect and identify all ejectiles from α -particles up to oxygen. The horizontally position sensitive detectors had an active surface of $4 \times 8 \text{ mm}^2$. The total opening angle was about 4° and the angle resolution better than 0.1° . The fourth telescope consisted of a $50 \mu\text{m}$ ΔE and a 5 mm E detector. This detector was used to detect p, d, t and α -particles. The opening angle for this detector

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was about 1° . To allow for a comparison with the earlier experiment of Bhowmik et al. [8] the centers of the telescopes were placed at angles of 26° , 13° , -13° and -39° , with solid angles of respectively 3.4, 2.0, 2.6 and 0.8 msr. A short measurement was carried out on a ^{12}C target in order to determine possible contributions from light-ion contaminants. These were found

to be less than 5% and thus no corrections were made. All possible coincidences between the four telescopes were recorded event by event and written on magnetic tape.

For sequential decay of the primary fragment into a heavy ejectile and an α -particle the excitation energy of the primary fragment is given by the decay thresh-

Fig. 1. The relative energy spectra are shown for the combinations $^7\text{Be} + \alpha$, $^{10}\text{B} + \alpha$, $^{11}\text{B} + \alpha$ and $^{14}\text{N} + \alpha$ for $\beta = 13^\circ$ (a) and $\beta = 26^\circ$ (b).

old plus the relative energy ϵ of the heavy ejectile and the α -particle. The ϵ -spectra were constructed off-line using the following transformation [9] for each event:

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

where β is the relative angle between the two detected fragments, calculated from the position information. The ϵ -spectra for several HI- α combinations are shown in fig. 1 for $\beta = 13^\circ$ (fig. 1a) and $\beta = 26^\circ$ (fig. 1b). The states which correspond to the strong peaks in the ϵ -spectra are the same as those which dominated the $^{14}\text{N} + ^{159}\text{Tb}$ reaction as observed by van Driel et al. [2] and which were also found in other projectile target combinations at various energies [4–6]. It is thus clear from fig. 1a that if β is small the data can be explained completely by the sequential decay process and that other processes, if present, are at least an order of magnitude smaller.

For a larger β , however, the situation is more complicated. The window in excitation energy, resulting from kinematical limitations, shifts to higher energies at which the level density in the primary fragment is larger. Nevertheless, there are discrete states still visible for $\beta = 26^\circ$ as is shown in fig. 1b, especially for those channels for which the Q -value for breakup is small, as is the case for $^{16}\text{O}^* \rightarrow ^{12}\text{C} + \alpha$ and $^{18}\text{F}^* \rightarrow ^{14}\text{N} + \alpha$, for which $Q = -7.16$ and -4.41 MeV, respectively.

In order to find an upper limit for the contribution from non-sequential processes we have estimated a "background" in the ϵ -spectra and attributed all cross section that does not reside in discrete peaks to the non-sequential process. This upper limit has been determined for all HI- α combinations with the heavy ejectile detected at -13° and the α -particle at -26° and 13° . The results have been listed in table 1. From this table we see that for $\beta = 13^\circ$ only a minor fraction of the double-differential cross section can originate from a non-sequential process. But also in the case where $\beta = 26^\circ$ the major part of the cross section for most channels can be ascribed to the sequential decay process. For $\beta = 39^\circ$ it is not possible anymore to see discrete peaks and therefore it is not meaningful to try to separate the two processes for this angle combination. An estimate also has been made of the upper limit of the contribution from the evaporation of α -par-

Table 1

Contributions of the sequential and non-sequential processes (lower and upper limits, respectively) to the double-differential cross section for several detected heavy ejectiles in coincidence with α -particles. The double differential cross section is given in mb/sr² for $\beta = 13^\circ$ ($\theta_{\text{HI}} = -13^\circ$, $\theta_{\alpha} = -26^\circ$) and $\beta = 26^\circ$ ($\theta_{\text{HI}} = -13^\circ$, $\theta_{\alpha} = 13^\circ$).

Ejectile	Sequential		Non-sequential	
	$\beta = 13^\circ$	26°	13°	26°
^6Li	22	14	7	16
^7Li	7	19	4	19
^7Be	9	21	1.4	7
^9Be	3.5	15	0.6	9
^{10}B	15	17	2	14
^{11}B	8	29	1.4	14
^{11}C	4	15	—	7
^{12}C	13	50	1.5	32
^{13}C	3.5	20	—	6
^{13}N	0.8	3.5	—	0.8
^{14}N	3	10	—	5
^{15}N	0.8	7	—	2.3

ticles from the target-like fragment on the basis of the large angle data from ref. [8]. Since this contribution is found to be less than 3%, it has been neglected.

To judge whether the background is due to sequential decay from unresolved states in the excited fragment or if there is indeed a contribution from a non-sequential process, the particle-particle correlation data must be examined in more detail. In fig. 2a the Q -value spectrum is shown for the ^{12}C - α correlation. This Q -value spectrum is divided into four energy bins and the relative energy spectra associated with each bin were projected out and are presented in figs. 2b–2e. The relative energy spectrum integrated over all Q -values is displayed in fig. 2f. For $-3.7 \geq Q > -11.0$ MeV the spectrum exhibits discrete peaks with almost no background, indicating almost exclusively sequential decay, whereas for more negative Q -values there is no clear signature of sequential decay. This leads to the conclusion that if a non-sequential component is present it becomes more important with increasing inelasticity of the reaction. A similar observation was made by Rae et al. [5] for the $^{16}\text{O} + ^{28}\text{Si}$ system at an energy of 140 MeV.

Contrary to the conclusions of Bhowmik et al. [8] that except for the $^6\text{Li} + \alpha$ channel, no evidence for sequential decay was found in the $^{14}\text{N} + ^{58}\text{Ni}$ reaction

Fig. 2. For the $^{12}\text{C}-\alpha$ coincidences with $\beta = 26^\circ$ the Q -value spectrum (a) is divided into 4 bins. The projected e -spectra (b)–(e) corresponding to these bins show different states, depending on the Q -value. The total e -spectrum integrated over all Q -values is displayed in (f).

at 148 MeV, the present investigation indicates that sequential decay is the dominant breakup mode. This apparent contradiction can be explained by the fact that the angular resolution in the setup of Bhowmik et al. was insufficient to observe the excitation of individual states in the primary fragment as discrete peaks in the relative energy spectra.

In the investigation of the $^{14}\text{N} + ^{159}\text{Tb}$ reaction by some of the present authors [1,2] a non-sequential component was found in addition to the sequential component. An *upper limit* for the non-sequential component was deduced by assuming it to be “uncorrelated” following the prescription of the Birmingham group [8] based on their $^{14}\text{N} + ^{58}\text{Ni}$ data. In view of the present investigation doubt is cast on this factorization prescription at least for the quasi-elastic component and it thus seems likely that the upper limit quoted in ref. [1] for the non-sequential component is too large.

In conclusion we can state that the present study of the $^{14}\text{N} + ^{58}\text{Ni}$ system shows that the particle–particle correlation data are dominated by sequential decay. An analysis of such data in terms of the factorization prescription is therefore not very meaningful. A small part of the coincidence cross section, however, does not unambiguously have the signature of sequential decay. This possible non-sequential component occurs for rather inelastic events and is strongest when the HI and α -particle are detected on opposite sides of the beam.

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