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PROBABILITIES FOR SEQUENTIAL DECAY OF PROJECTILE-LIKE FRAGMENTS IN REACTIONS WITH LIGHT HEAVY IONS

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Probabilities for sequential decay of various projectile-like fragments from ^{14}N induced reactions on ^{159}Tb have been determined via projectile-like fragment-K X-ray coincidence measurements at energies of 115 and 168 MeV. A close correspondence with results from particle-particle correlation studies was obtained.

Particle-particle correlation studies of light heavy ion induced reactions at energies between 10 and 20 MeV/amu have provided ample evidence of the importance of reaction channels in which in addition to a target-like fragment (TLF) and a projectile-like fragment (PLF) (fast) light particles such as protons and α -particles are emitted (refs. [1-3], and references therein). These "non-binary" processes have also recently been observed (as "missing charge") via the K X-ray method, in which characteristic K X-rays from the heavy residual nuclei are measured in coincidence with PLFs [4].

We report in this letter on an investigation of the non-binary processes in the $^{14}\text{N} + ^{159}\text{Tb}$ reactions via the K X-ray method. A close correspondence is found between the probabilities for sequential decay of the PLFs deduced from the present study and those from particle-particle correlation measurements for the same reaction. With these probabilities binary reaction cross sections can be deduced from inclusive particle data.

A metallic ^{159}Tb target of 2.9 mg/cm² thickness was bombarded with ^{14}N beams from the KVI cyclotron at energies of 115 and 168 MeV. The

experimental setup was similar to that described in ref. [4]. It consisted of one or two solid state detector telescopes positioned at forward angles for the detection of heavy ion ejectiles, and of one telescope placed at a backward angle for the detection of evaporation particles. Two Ge X-ray detectors of 10 and 16 mm $\varnothing$ were positioned 6 cm from the target at the flat, thin-windowed side of a "half moon chamber" to detect the K X-rays. The resolution for the K X-rays of interest was ~ 500 eV and the absolute detection efficiency was 0.2% for each of the X-ray detectors. An example of the X-ray spectra obtained is shown in fig. 1. The elemental yields were obtained with a simple fitting procedure taking into account the background due to coincident γ -rays [4].

By detecting the charged fragment e in a heavy-ion telescope and measuring the charge Z_{res} of the residual nucleus via its characteristic K X-rays the K X-ray method permits determination of the charge balance of the reaction channel:

$$Z_p + Z_t = Z_{\text{res}} + Z_e + \Delta Z, \quad (1)$$

where p , t and e label the atomic numbers Z of the projectile, the target, and the fragment e . ΔZ is the unobserved or missing charge associated with the emission of an additional charged particle. The cross section for this channel, denoted by (Z_{res}, e) ,

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Fig. 1. K X-ray spectra measured in coincidence with the detected fragment ^{12}C for $^{14}\text{N} + ^{159}\text{Tb}$ at 115 and 168 MeV. The positions of the various K X-ray peaks belonging to the residual nuclei Dy ($\Delta Z=0$) and Tb ($\Delta Z=1$) are indicated. The increase in the relative K X-ray yield of Tb at 168 MeV should be noted.

where e is detected at an angle θ , is given by

$$d\sigma(Z_{\text{res}}, e)/d\Omega = C \langle M(Z_{\text{res}}, e) \rangle^{-1} Y(Z_{\text{res}}, e), \quad (2)$$

where C determines the overall normalisation, $Y(Z_{\text{res}}, e)$ is the number of coincident events and $\langle M(Z_{\text{res}}, e) \rangle$ is the average K X-ray multiplicity of the residual nuclei with atomic number Z_{res} produced in reactions in which the fragment e is observed. The multiplicities M in general depend on the nuclear structure of the residual nucleus and on the angular momentum transfer [5,6]. This dependence, however, is greatly reduced if the M values are averaged over the several final isotopes contributing to the same channel, as in the present case. This is especially true for deformed residual nuclei, for which $\langle M \rangle$ is rather independent of the angular momentum transfer [6,7]. We therefore assume that $\langle M \rangle$ only depends on Z_{res} , an as-

sumption which is consistent with the values for $\langle M(Z_{\text{res}}, e) \rangle$ presented in ref. [4].

Decay probabilities of PLFs can now be obtained if the additional assumption is made that reactions with $\Delta Z \neq 0$ are binary reactions resulting in the formation of an excited PLF E^* which sequentially decays by emitting one or more light particle(s). This assumption is based on the observation that the contribution of particle evaporation from the TLF to the missing charge cross sections, deduced from the yields of fragments e in coincidence with backward emitted (evaporation) particles, is negligible ($\leq 10\%$) for fragments e with $Z_e \geq 2$. Note, however, that preequilibrium emission of light particles cannot be distinguished from sequential decay with the present method. For $\Delta Z = 1$ we assume emission of a proton from the PLF, for $\Delta Z = 2$ an α -particle, for $\Delta Z = 3$ a proton and an α -particle and for $\Delta Z = 4$ two α -particles. All channels involving the formation of the PLF E in a binary process must have $Z_{\text{res}} = Z_p + Z_t - Z_E$, where Z_E is the charge of E . The probability for the decay of E into e by light particle emission can therefore be obtained from

$$P(E \rightarrow e + x) = \frac{d\sigma(Z_{\text{res}}, e)/d\Omega}{d\sigma(Z_{\text{res}}, e)/d\Omega + \sum_{e'} d\sigma(Z_{\text{res}}, e')/d\Omega} \times \frac{Y(Z_{\text{res}}, e)}{Y(Z_{\text{res}}, e) + \sum_{e'} Y(Z_{\text{res}}, e')}. \quad (3)$$

The summation includes the fragments e' originating from the decay modes of E^* that are taken into account.

The approximations made in eq. (3) in equating the observed yield ratios to those of the cross sections include (i) taking $\langle M \rangle$ to be only dependent on Z_{res} as discussed above, (ii) neglecting PLF decay modes involving deuteron, triton and, most importantly, neutron emission, and (iii) neglecting uncertainties in the emission angle of the excited PLF E^* .

The decay probabilities of various PLFs for the system $^{14}\text{N} + ^{159}\text{Tb}$ at 115 and 168 MeV, obtained with the use of eq. (3), are given in table 1. The 115 MeV data were obtained at 30° , the 168 MeV

Table 1

Probabilities for sequential decay obtained via the K X-ray method and particle-particle correlation studies.

Parent ejectile	Decay mode	115 MeV K X	168 MeV		
			K X	(HI - α) ^{a)}	(HI - α) ^{b)}
¹⁶ O	α	0.41 (19)	0.37 (30)	0.55	0.35
¹⁵ N	p	0.02 (1)	0.03 (1)		
	α	0.08 (1)	0.10 (2)	0.13	0.11
	p + α		0.02 (1)		
	2 α		0.03 (1)		
¹⁴ N	p	0.04 (1)	0.10 (1)		
	α		0.02 (1)	0.05	0.04
	p + α		0.01 (1)		
	2 α		0.01 (1)		
¹³ N	p	0.31 (4)	0.48 (5)		
¹³ C	α	0.02 (1)	0.05 (1)	0.05	0.07
¹² C	p		0.03 (1)		
	3 α	0.13 (1)	0.20 (1)		
	p + α		0.01 (1)		
¹² B	α		0.13 (5)		
¹¹ B	α		0.26 (2)	0.17	0.22
¹⁰ B	p	0.05 (3)	0.16 (3)		
	α	0.10 (3)	0.19 (3)	0.34	0.28

a) Particle-particle correlation data [1].

b) Corrected particle-particle data as discussed in the text.

168 MeV data at 20°. The errors indicated are purely statistical. They do not include errors due to γ -ray "contaminants" in the X-ray spectra, or systematic effects, resulting e.g. from incomplete mass separation. The combined systematic errors including the uncertainties in the derivation of eq. (3) as discussed in the previous paragraph are estimated to be less than 30%. In obtaining this estimate it has been assumed that the decay of the PLF by neutron emission behaves in the same way as the decay by proton emission. Decay channels with insufficient statistics have been omitted.

Table 1 also contains values from particle-particle correlation studies by Bhowmik et al. [1] for the ¹⁴N + ¹⁵⁹Tb system at 168 MeV. It is seen that the decay probabilities obtained via the K X-ray method agree well with those from the particle-particle correlation studies. The restriction of the K X-ray method to channels in which the residual nucleus is sufficiently excited to produce K X-rays therefore does not appear to affect the values of the decay probabilities strongly for the systems studied. The close correspondence between the decay probabilities obtained with two

very different methods is very gratifying. It gives confidence in deducing binary cross sections from inclusive heavy-ion data with the help of the almost complete set of decay probabilities that can be obtained with the K X-ray method without an explicit knowledge of the K X-ray multiplicities, provided that these multiplicities are only dependent on Z_{res} .

It should be noted that the values from the particle-particle correlation studies were obtained [1] by dividing the cross section deduced from detecting α -particles in coincidence with the heavy ion (integrated over all α -particle emission angles) by the inclusive cross section for detecting the "parent ejectile" in a particle stable state, while in eq. (3) the exclusive yields for the production of the parent ejectile enter into the denominator. The particle-particle correlation values have therefore been corrected by making use of ratios of the binary to the inclusive cross sections obtained with the K X-ray method (see table 1). This significantly improves the agreement between the values obtained with both methods, thus lending further support to the method employed.

The decay probabilities determined via the K X-ray method for $^{14}\text{N} + ^{159}\text{Tb}$ at 168 MeV are plotted in fig. 2 versus the separation energy for the corresponding decay channel, $-Q_d$, where Q_d is the decay Q -value. From the figure we can infer that the decay probabilities are a slowly decreasing function of the separation energies. This indicates that the excitation energy distributions of the primary ejectiles have a large width (of the order of 10 MeV).

The decay probabilities for $^{14}\text{N} + ^{159}\text{Tb}$ observed at 168 MeV are systematically larger than those observed at 115 MeV. This is also evident from fig. 1 which shows K X-ray spectra measured in coincidence with the detected fragment ^{12}C for $^{14}\text{N} + ^{159}\text{Tb}$ at 115 and 168 MeV. In the spectrum

Fig. 2. Relative probabilities for heavy-ion ejectiles being formed either in a particle-stable (vertical bar at $-Q_d = 0$) or in particle-unstable state decaying via charged particle emission. The vertical thick bars denoting the probabilities for sequential decay are plotted at the thresholds for the decay of the parent by emitting the particle(s) that are indicated. The threshold for the emission of a neutron is also indicated.

for 168 MeV the component with $\Delta Z \neq 0$ shows up much more strongly.

The dependence of the excitation energy distributions in each ejectile on the reaction characteristics in asymmetric nucleus-nucleus collisions is still poorly known. The present results indicate that the average excitation energies of the ejectiles and/or the widths of their distributions increase quite rapidly with the bombarding energy.

We conclude that the K X-ray method is a promising method to deduce decay probabilities. A close correspondence is observed between the values obtained with this method and those from particle-particle correlation studies, but the K X-ray method has several advantages. It is based on yield ratios and therefore neither absolute detection efficiencies nor K X-ray multiplicities have to be known, provided that the reaction is such that the multiplicity values depend only on the charge of the TLF. There is also the possibility of obtaining data for large range of PLFs and decay modes in one measurement. We particularly stress the possibility to deduce binary reaction cross sections from inclusive ejectile data with the help of decay probabilities obtained via the K X-ray method.

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