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SELECTION OF HEAVY ION REACTION CHANNELS VIA PARTICLE K X-RAY COINCIDENCES

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To identify the residual nuclei in very asymmetric heavy-ion reactions heavy-ion K X-ray coincidences have been measured. The usefulness and limitations of this method are discussed, and its feasibility is demonstrated in a study of the $^{14}N + ^{197}Au$ reaction at 140 MeV.

Incomplete fusion reactions over the last few years have been the subject of extensive studies. They are fast binary processes in asymmetric nucleus–nucleus collisions in which a part of the projectile fuses with the target, while the remnant continues its flight with approximately beam velocity. Selection and identification of the residual nuclei has usually been accomplished [1–4] by detecting characteristic γ-rays in coincidence with projectile-like fragments (PLF). This technique, however, is limited to cases in which there are not too many exit channels (i.e. to relatively low bombarding energies) and in which the γ-ray spectra of all the residual nuclei are known. We present in this letter an alternative method which does not have these restrictions.

From the particle-γ-ray coincidence studies it was conjectured that the target-like reaction products formed in the incomplete fusion process of very asymmetric systems predominantly deexcite via statistical particle evaporation (mainly neutrons for heavy nuclei), followed by a γ-ray cascade. The cross sections of interest thus are those summed over all the evaporation residues with the same Z from a given reaction channel. A measurement of the characteristic K X-rays in coincidence with the PLF therefore can serve as an alternative means to identify the reaction channel The K X-rays result from inner shell ionization of the evaporation residues caused by internal conversion of γ-rays deexciting these residues. To obtain cross sections, the K X-ray multiplicities, M, have to be known The values of M depend strongly on the nuclear structure and entry state population [5]. For heavy elements studied in this work values of $M \simeq 2$ and 3 have been reported [6,7] for even and odd Z, respectively

We have measured particle-X-ray coincidences to study the $^{14}N + ^{197}Au$ reaction A 2.1 mg/cm^2 gold target was bombarded with a 140 MeV ^{14}N beam from the Groningen AVF cyclotron. Light ejectiles ranging from α-particles to oxygen ions were detected at 35° with a solid state $\Delta E - E$ detector telescope (50 μm and 2100 μm) subtending a solid angle of 9 msr. Two γ X-detectors of 45 mm ϕ and one X-ray detector of 16 mm ϕ were used. The resolutions for the X-rays of interest were ~1.2 keV for the γ X-detectors and ~500 eV for the X-ray detector, the solid angles 1%, 1% and 0.3% respectively. Count rates were smaller than 5 kHz in the X-ray detector, and smaller than 20 kHz in the γ X-detectors. The three detectors were positioned close to each other at the flat side of the "half-moon" scattering chamber. Because of the isotropy of the K X-ray emission the angular position of the detectors could be chosen arbitrarily Parcle–X and particle–X–X coincidences as well as pre-

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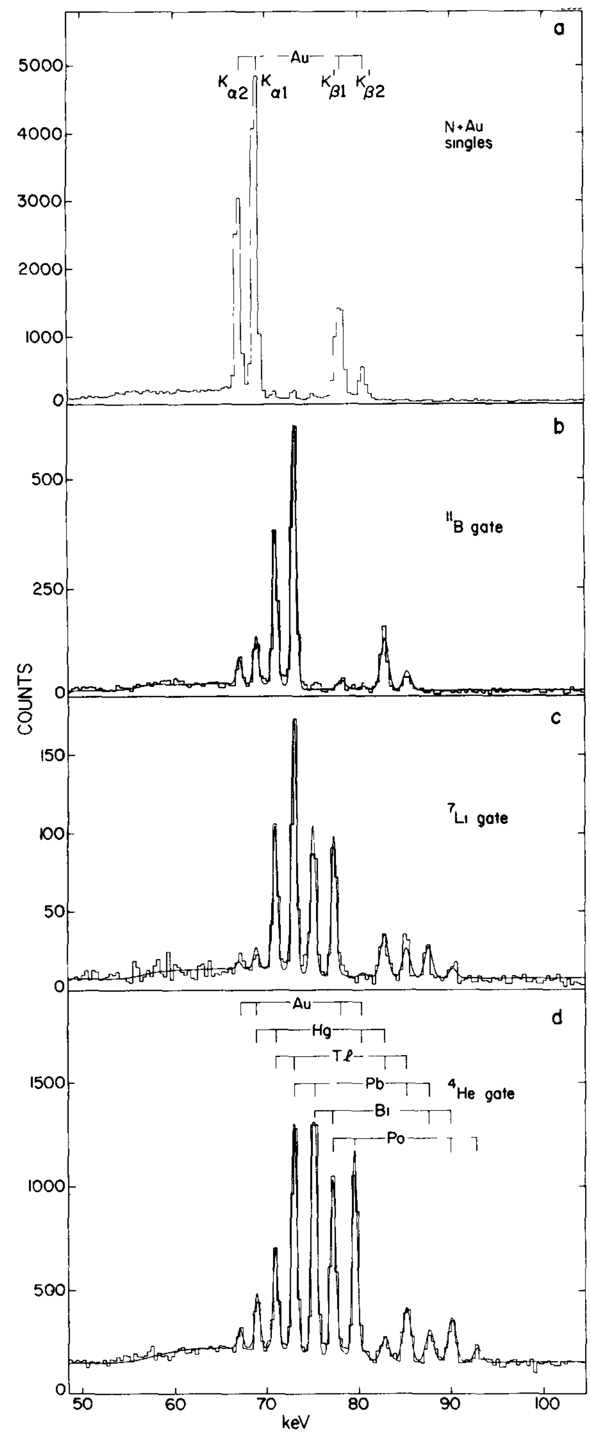

Fig. 1. Some examples of X-ray spectra. (a) Singles X-ray spectrum. The characteristic K X-rays are mainly due to target ionization. (b, c and d) Coincident X-ray spectra showing the contributions of various reaction channels (see text). The lines through the data points are obtained from the fitting procedure that was used to determine the elemental yields.

scaled singles data were written event by event on tape for later analysis.

Examples of the K X-ray spectra measured in coincidence with various ejectiles are shown in fig. 1. The spectra are seen to be rather complex, especially for the lighter ejectiles. A simple fitting procedure was applied to obtain the elemental yields by making use of the known energies and relative intensities of the four components $K_{\alpha1}$, $K_{\alpha2}$, $K'_{\beta1}$ and $K'_{\beta2}$ for the different Z's. As discussed in ref. [5] effects due to multiple ionization [8] for vacancies produced by internal conversion are negligible due to the much longer lifetimes of the decaying nuclear states as compared with those of the electron vacancies.

The K X-ray multiplicities for various Z_{res} have been obtained from the ratios, R, of the particle–X–X to particle–X coincidence counting rates

$$R = \langle M(M-1)\rangle \epsilon / \langle M \rangle = \sigma_{PXX}/\sigma_{PX}, \quad (1)$$

where ϵ is the efficiency of the γ X-detector. A similar technique recently has been applied [6,7] to studies of ^{6}Li induced complete fusion reactions, in which coincidence (X–X) to singles X-ray yield ratios were determined. If a Poisson distribution for M is assumed [7], then

$$\langle M(M-1)\rangle / \langle M \rangle = \langle M \rangle . \quad (2)$$

Average multiplicities $\langle M \rangle$ deduced with this assumption are listed together with the cross sections for the corresponding reaction channels in table 1. The statistical uncertainties associated with the multiplicities are rather large because of the low triple-coincidence yield.

The most striking feature of the particle-gated X-ray spectra is the observation of *all* atomic numbers Z in the range $Z_t \leqslant Z_{res} \leqslant Z_p + Z_t - Z_e$, where p, t, e label the projectile, the target and the ejectile, respectively. Hitherto, from particle–γ studies of incomplete fusion reactions, only the binary channels with $Z_{res} = Z_p + Z_t - Z_e$ could be identified.

From the figure and the table it is seen that for ejectiles with $Z \geqslant 4$ the binary (incomplete fusion) reaction channel with $Z_{res} = Z_p + Z_t - Z_e$ gives the largest contribution (fig. 1b). For the lighter ejectiles, in contrast, the largest K X-ray yields are found for $Z_{res} = Z_p + Z_t - Z_e - 2$ (fig. 1c) indicating the emission of most likely an α-particle in addition to the PLF. The α-particle might originate from sequential decays from excited projectile- or target-like fragments following incomplete fusion as well as from a fast process in which a non-equilibrium α-particle is emitted from the combined system target plus projectile. All three processes have been observed in recent particle–particle correlation studies [9] of the $^{14}N + ^{159}Tb$ reaction at 140 MeV. For the Be and B isotopes the binary reaction with $Z_{res} = Z_p + Z_t - Z_e$ contributes (40–60)% of the inclusive cross sections. For the C isotopes this fraction probably is even larger; the multiplicities for these channels, however, are too small to be determined reliably. For ^7Li ejectiles the reaction $^{197}Au(^{14}N, {}^7Li)Bi$ accounts for only 10% of the inclusive cross section.

The inclusive spectra of light particles from HI induced reactions are usually dominated by alpha particles. It is therefore of particular interest to notice, that in the present case less than 10% of the inclusive

Table 1
Partial results of inclusive and exclusive measurements for the ^{197}Au + 140 MeV ^{14}N reaction at $\theta = 35°$.

Ejectile	$(d\sigma/d\Omega)_{incl}$ a) (mb)	Z_{res}	$\langle M\rangle(d\sigma/d\Omega)_{Z_{res}}$ (mb)	$\langle M\rangle$	$(d\sigma/d\Omega)_{Z_{res}}$ (mb)
α	128	79	3.9 ± 0.5	<2.6	
		80	4.5 ± 0.6	<3.6	
		81	12.7 ± 0.6	2.3 ± 0.6	5.5 ± 1.5
		82	28.4 ± 0.6	2.4 ± 0.2	11.8 ± 1.0
		83	9.2 ± 0.6	1.8 ± 0.7	5.1 ± 2.0
		84	24.2 ± 0.5	2.5 ± 0.3	9.7 ± 1.2
^7Li	5.9	79	0.2 ± 0.1		
		80	0.3 ± 0.1		
		81	3.4 ± 0.1	2.7 ± 0.6	1.3 ± 0 3
		82	1.2 ± 0.1	1.6 ± 1.0	0.75 ± 0.5
		83	2.1 ± 0.1	3.2 ± 0.9	0 7 ± 0.2
^9Be	3.9	79	0.4 ± 0.1		
		80	<0.15		
		81	0.8 ± 0.1	2.3 ± 1.6	0.3 ± 0.2
		82	2.3 ± 0.1	1.2 ± 0.6	1.9 ± 1.0
^{10}Be	2.7	79	<0.05		
		80	0.1 ± 0.1		
		81	0.3 ± 0.1		
		82	1.7 ± 0.1	1 6 ± 0.6	1.1 ± 0.4
^{10}B	5.6	79	0.6 ± 0.1		
		80	<0.1		
		81	6.7 ± 0.1	1.8 ± 0.3	3.7 ± 0.6
^{11}B	15.9	79	2.7 ± 0.2		
		80	<0.2		
		81	15.2 ± 0.2	2.1 ± 0.3	7.2 ± 1.0
^{12}B	3.2	79	<0.05		
		80	<0.05		
		81	3.1 ± 0.05	2.1 ± 0.6	1.5 ± 0.4
^{13}C	30	79	1.2 ± 0.1		
		80	5.9 ± 0.1	<0.3	>20
^{15}N	70	79	34.6 ± 0.4	0.3 ± 0.1	1153 ± 40

a) Uncertainty of the absolute normalization is less than 25%.

α-particle cross section can be attributed to the ^{197}Au(^{14}N, α) Po incomplete fusion reaction. A fraction of these 10% might moreover be due to evaporation following complete fusion.

We also note the observation of odd-Z "missing charges". They originate most likely from proton emission. As was found in a parallel and as yet unpublished investigation of the ^{14}N + ^{159}Tb reaction via K X-rays, particle–γ and particle–particle correlations, these protons most likely result both from the particle decays of excited ejectiles as well as from the evaporation from target-like fragments. The K X-rays from the target $Z = 79$ point towards inelastic projectile breakup, as well as to reactions of the type (^{14}N, ^{15}N*).

The inclusive cross-sections of table 1 for lighter ejectiles (large mass transfers) often exceed the summed values of the corresponding exclusive ones. This excess can be at least partly attributed to incomplete fusion followed by fission and to elastic breakup.

The present method is most powerful to obtain a global overview of the different reaction channels that are involved, and to study the evolution of the reaction mechanism as a function of energy. The method is also especially suited to select specific reaction channels for the determination of e.g. exclusive particle spectra or of γ-ray multiplicities in particle–X respectively particle–X γ measurements. In these latter applications the determination of the X-ray multiplicities is not necessary. The great sensitivity of the K X-ray method, as compared to particle–γ measurements should be noted. Cross sections as low as ~1 mb can be determined.

A limitation of the present method is that to obtain cross sections the X-ray multiplicities have to be known. In the present investigation the X-ray multiplicities were determined from particle–X–X coincides, a method that suffers from low counting statistics. The assumption of a Poisson distribution in eq. (2) also may not be valid if more than one reaction path will contribute to the same residue-ejectile combination. Investigations of X-ray multiplicities for strongly deformed rare earth nuclei [5], while exhibiting strong odd–even-A staggerings, have demonstrated practically an independence of M on entry state population. This is in contrast to the transitional region, where a strong variation of M with the input angular momentum is found [5]. Thus for the deformed rare earth mass region it might suffice to determine M independently from the complete fusion evaporation reactions with different projectiles and targets.

In summary, we conclude that the measurement of particle–K X-ray coincidences constitutes a useful tool for the investigation of asymmetric heavy-ion reactions. It offers the possibility to readily identify the atomic number of the heavy residual nuclei and to determine the cross sections for a large fraction of the exit channels. In contrast to the measurement of particle-γ coincidences in which identification of numerous discrete γ-transitions is a very difficult task, especially at higher bombarding energies, the particle-K X-ray method yields at "one glance" an overview of all the important reaction channels in a simple and easy to unfold form.

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