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ABSTRACT

From the observation of excited ^{7}Li and ^{7}Be fragments at backward angles (120° and 150°) in the reaction $^{20}Ne + ^{60}Ni$ at 742 MeV, an emission temperature compatible with that inferred from the slope of the particle energy spectra has been obtained. The use of a high resolution Compton suppressed gamma-ray detector has played a crucial role.

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In the last few years the availability of heavy-ion beams in the 20-100 MeV/nucleon energy range has allowed the observation of complex fragments ($Z \geq 3$) emitted by highly excited composite systems. In fact the large angular momentum and/or temperature of such systems make the cross section of these deexcitation channels sizable [1,2]. Their observation has been considered [3-6] as manifestation of the early stages of the deexcitation of a fully equilibrated system. This feature should be reflected in the relative yield of excited to ground state emissions of such fragments [7]. Recently Morrissey et al. [7,8] have deduced population ratios for Li and Be isotopes in strong disagreement with the above hypothesis, from the measurement of coincidences between the complex fragments and their deexcitation gamma-rays in the reaction ^{14}N + Ag at 35 MeV/nucleon.

In the present work, in order to accurately study the population of excited complex fragments in the reaction $^{20}Ne + ^{60}Ni$ at 742 MeV, a high resolution gamma-ray detection system has been employed. The experiment was performed at the SARA facility in Grenoble. The complex fragments were detected at 14°, 120° and 150° to the beam axis both in singles and in coincidence with the gamma-rays emitted at 90° with respect to the reaction plane. Two solid state telescopes consisting of three silicon detectors with thicknesses of 23 μ, 75μ and 5mm and 13μ, 53μ and 5mm were positioned at 120° and 150°, respectively. A third telescope consisting of two silicon detectors (48μ and 1000 μ) followed by a 10cm thick NaI crystal was placed at 14°. A gamma-X Ge detector with an energy resolution of 1.9 keV at 1.33 MeV and 21% efficiency surrounded by an asymmetrical NaI antiCompton shield was used for the gamma-ray detection. The angular range covered by the gamma-ray detector was $90° \pm 6°$. An isotopically enriched selfsupporting ^{60}Ni target of a thickness of $1 mg/cm^2$ was bombarded with a ^{20}Ne (9^+) beam whose average intensity was 30 enA. The collected charge was measured in a Faraday cup located 6m downstream from the target and shielded with paraffine and lead. Data were stored event by event on magnetic tape. From the raw data particle energy spectra were obtained setting appropriate contours on two dimensional E-ΔE histograms. Concerning the forward angle measurements the resolution of the ΔE detectors allowed the separation of the Li and Be isotopes. After subtraction of random coincidences the gamma-ray spectra gated by each particle were obtained.

Fig. 1 shows part of the spectra in coincidence with Li and Be ions detected at $\theta = 14°$ with velocities $v/c > 18.5\%$. It can be seen that the gamma-ray lines spanning over the energy ranges 460-480 keV and 410-430 keV are cleary standing out of the underlying background in the spectra in coincidence with ^7Li and ^7Be ions, respectively. On the contrary, no lines are present in these energy ranges in the spectra in coincidence with ^6Li and ^9Be ions. The observed gamma-rays originate by the deexcitation of the only bound

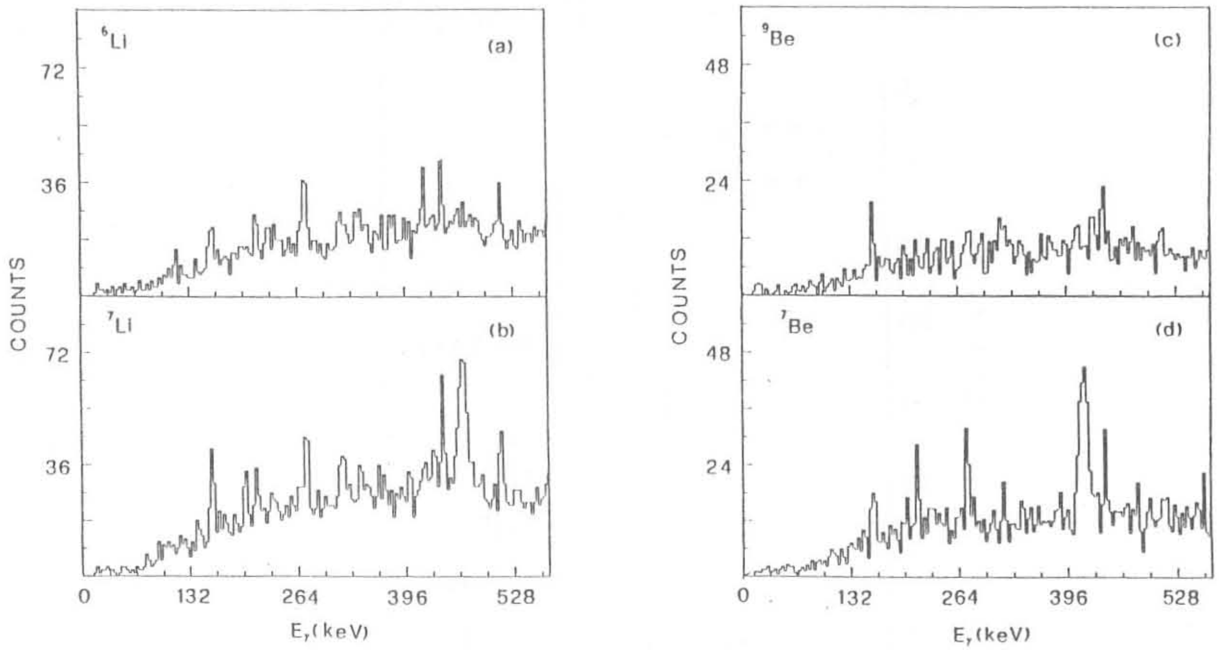

Fig.1 - Gamma-ray spectra in coincidence with complex fragments with velocities $v/c \geq 18.5\%$ detected at $\Theta=14°$: (a) ^{6}Li (b) ^{7}Li (c) ^{9}Be (d) ^{7}Be.

levels of ^{7}Li and ^{7}Be lying at energies of 477.6 keV and 429.2 keV, respectively and both being spin $1/2^{-}$.

In Fig. 2 the dependence of the gamma-ray Doppler shift on the coincident ^{7}Li ion velocity is visualized. In particular, the background subtracted gamma-ray lineshapes gated by ^{7}Li ions detected at 14° with velocities v/c>9.5% (full line) and in the velocity range of 9.5 - 18.5% (dashed line) are shown as a function of energy displacement. In the upper side of Fig. 2 an ion velocity scale corresponding to the energy shift scale, calculated by means of the relativistic Doppler formula at 90°, is also reported.

In Fig. 3 we present part of the gamma-ray spectrum in coincidence with Li ions detected at 120° and 150° summed over the two angles. It can be clearly seen the gamma-ray at 477.6 keV superimposed to a low background. The energy spectrum of Li ions detected at 150° (full line) is presented in Fig. 4. Due to the relatively low velocities of ^{7}Li ions at backward angles the Doppler effect on the gamma-ray lineshape of Fig. 3 appears as a small centroid displacement with respect to the 477.6 keV energy, toward lower energies.

From the area of gamma-ray peaks in the coincidence run, integrated charge, target thickness, absolute efficiency of Ge detector (measured with calibrated sources) and solid angles of particle detectors, the population cross sections of the excited states have been deduced. An isotropic angular distribution for these gamma transitions results from

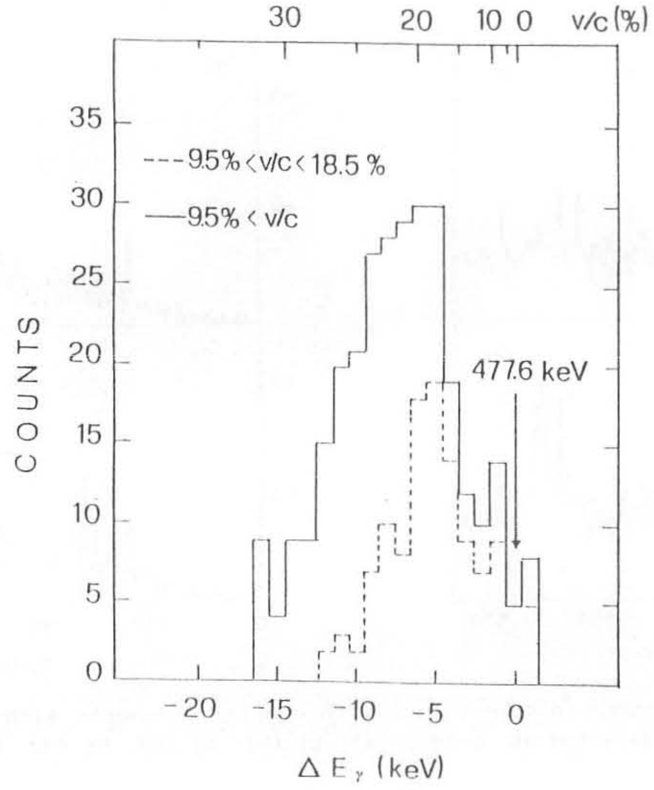

Fig.2 - Background subtracted gamma-ray spectrum in coincidence with ^{7}Li ions at $\theta = 14°$ as a function of energy Doppler shift. See text for more details.

the 1/2 spin of the emitting levels. From the singles particle spectra the total production cross sections for ^{7}Li and for ^{7}Be were determined. As far as the backward angles are concerned, the total production cross sections were extracted using the $^{7}Li/^{6}Li$ and $^{7}Be/^{9}Be$ ratios measured at 14°. In table 1 the resulting differential cross sections for total and excited states production of ^{7}Li and ^{7}Be are given. The values for backward angles have not been corrected for the number of undetected particles having energy below the experimental threshold.

In table 1 the ratio f of the excited state cross section to the total cross section is also given. This f value is a measure of the fraction of the nuclei emitted in the excited state if one neglects the feeding from particle decay [(6-8)]. In this simplified picture the f can be related to the temperature T of the equilibrated system assumed to be responsible for the emission of the complex fragment through the formulas

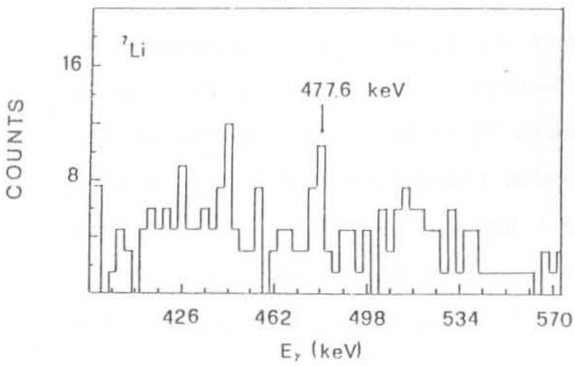

Fig.3 - Gamma-ray spectrum in coincidence with lithium ions detected at 120° and 150°, summed over the two angles.

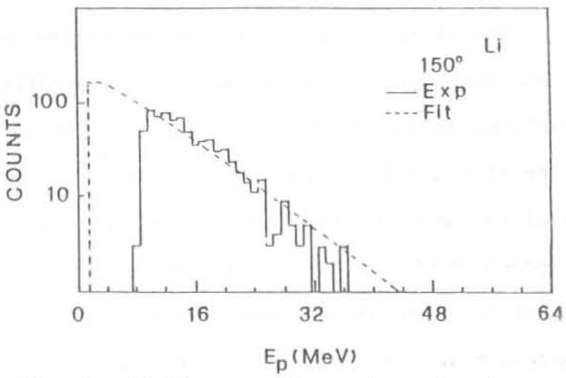

Fig.4 - Lithium spectrum in coincidence with gammas (detected at 90°) measured at 150°. The dashed curve represents the results of a best fit to the experimental data obtained using a Maxwell-Boltzmann function coupled to a 1/sin θ angular distribution in the source reference frame.

$$f = R/(R+1)$$

$$R = [(2j_u+1)/(2j_l+1)]\ \exp(-\Delta E/T)$$

where j_u and j_l are the spins of the upper and lower levels, respectively and ΔE the

<u>Table 1 - Total and excited state cross sections for ^{7}Li an ^{7}Be ions</u>

Fragment	θ	$(d\sigma/d\Omega)_{tot}$ (a) (mb/sr)	$(d\sigma/d\Omega)_{ex}$ (b) (mb/sr)	f (c)
^{7}Li	120°+150°	0.41±0.01	0.12±0.03	0.29±0.07
	14°	285±50	49±3	0.17±0.03
^{7}Be	120°+150°	0.75±0.015	0.038±0.015	0.51±0.22
	14°	127±24	37±2.5	0.29±0.06

a) Total cross section.

b) Excited state cross section.

c) f is defined as the fraction of excited state cross section to the total cross section.

energy level spacing.

The observation of complex particles at backward angles is generally considered as an evidence of the emission from an equilibrated system. As a matter of fact the f fractions measured at 120° + 150° (Table 1) correspond to emission temperatures of the order of few MeV. In particular, for ^{7}Li ions an emission temperature of $2.4^{+\infty}_{-1.6}$ MeV is obtained, whereas for ^{7}Be ions a lower limit of 2.1 MeV can be deduced from the one standard deviation interval for f. As far as the forward angles are concerned no temperature has been deduced since the f values may be affected by the contribution of a quasi-projectile component in the particle spectra.

In conclusion, in the present investigation, with the use of a very high resolution gamma-ray detection system we have been able to measure complex fragment population ratios. The extracted emission temperatures are not incompatible with the value of about 7 MeV deduced from the slope of the laboratory energy spectrum of lithium ions (Fig. 4). With the aim of estimating the particle-decay feeding of final states and simultaneously predicting the relative yield of different complex fragments, a more realistic description, based on Hauser-Feshbach calculations, is in progress.

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