NUCLEAR TEMPERATURE MEASUREMENTS AND FEEDING FROM PARTICLE UNBOUND STATES

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Inclusive fragment cross sections and cross sections of coincident γ-ray transitions from the decay of ^{8}Li, ^{7}Be, ^{10}B, ^{12}B and ^{13}C fragments were measured for ^{32}S induced reactions on Ag at 715 MeV. These measurements are compared to quantum statistical model calculations which include sequential feeding from particle unbounds states of heavier fragments. When the uncertainties in the sequential feeding calculations are taken into account, although the measured γ-ray fractions are consistent with temperature, $T \geqslant 4$ MeV; the calculations demonstrate that the investigated γ-ray transitions cannot be used to determine the temperature of highly excited systems.

During the non-equilibrium initial stage of a nuclear reaction, the individual degrees of freedom of the combined system become excited at different rates. Within the simplifying assumption of local thermal equilibrium, the relative populations of different phase-space configurations may be described by a temperature; the extent of thermalization can then be assessed by measurements of this temperature. Temperatures derived from the slopes of energy spectra may be affected by sensitivities of the spectra to collective motion [1] and to the temporal evolution of the emitting system [2–4]. To a certain extent, these problems may be avoided by extracting "emission temperatures" from the relative populations of ground and excited states of emitted fragments [5–9].

Recent measurements [5–9] of emission temperatures have provided contradictory results. The relative populations of particle unstable states of ^{6}Li, ^{5}Li, and ^{8}Be nuclei produced in ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV [6,8] and in ^{14}N induced reactions on ^{197}Au at $E/A = 35$ MeV [9] are consistent with average emission temperatures of about 4–5 MeV. In contrast, measurements of low energy γ-ray transitions from ^{7}Li, ^{8}Li, and ^{7}Be fragments produced in ^{14}N induced reactions on Ag at $E/A = 35$ MeV yielded emission temperatures of less than 1 MeV [5,7]. These low temperatures were attributed to the breakdown of the approximation of local thermal equilibrium [5,7]. We have measured low energy γ-ray transitions in ^{8}Li, ^{7}Be, ^{10}B, ^{12}B, and ^{13}C nuclei emitted in ^{32}S induced reactions on Ag at 715 MeV and have applied the quantum statistical model [10,11] to estimate the effects of sequential decay. We demonstrate that such low emission temperatures are a consequence of sequential feeding from particle unbound states which renders these low energy γ-ray transitions unsuitable for the determination of temperatures greater than 2 MeV.

The experiment was performed at the Holifield Heavy Ion Research Facility of Oak Ridge National Laboratory. Complex fragments with $3 \leqslant Z \leqslant 8$ were detected in five ΔE–ΔE–E surface barrier detector telescopes, positioned at the laboratory angles of $\theta_{\text{lab}} = 20°, 25°, 30°, 45°$, and $50°$, with solid angles of $\Delta\Omega_{\text{lab}} = 9.8$, 10.1, 15.4, 36.3 and 28.6 msr, respectively. Each telescope consisted of two planar ΔE-detectors with thicknesses between 50 and 100 μm and an E-detector with a thickness of 1.5 mm. Coincident γ-rays were detected with six Compton shielded germanium detector modules of the Spin Spectrometer [12].

Clean isotopic resolution in the detector telescopes is essential for these measurements. Cross contaminations between adjacent isotopes were reduced to less than 4% by restricting the analysis to fragments that stopped in the third element of the telescope and which simultaneously satisfied two independent particle identification gates [13]. (This double identification requirement introduced energy thresholds at about $E/A = 8$ MeV for $\theta = 20°, 25°, 30°$ and at about $E/A = 7$ MeV for $\theta = 45°$ and $50°$.) As an example, fig. 1 shows the measured energy spectra of ^{10}B isotopes. As in previous observations [4], the fragment energy spectra have maxima near the exit channel Coulomb barrier and decrease exponentially with increasing fragment energy; the cross sections are strongly enhanced at forward angles. Moving source analyses of the kinetic energy spectra suggest that at least half of the fragments are emitted prior to complete equilibration of the composite system [14].

The energy spectra of coincident γ-rays were transformed into the rest frames of the coincident particles using relativistic jacobians and Doppler shift corrections. Since these transformations shift and broaden γ-ray transitions of the target residues, particular attention was paid to identifying and correcting for spurious structures in the γ-ray background. For this purpose, background spectra were generated by performing similar Doppler shift transformations on raw γ-ray spectra measured in coincidence with ^{6}Li, ^{9}Be, and ^{11}B nuclei. These nuclei have no strong γ-ray transitions at the γ-ray energies studied here; however, these background spectra contained discrete transitions from target residues common to all spectra.

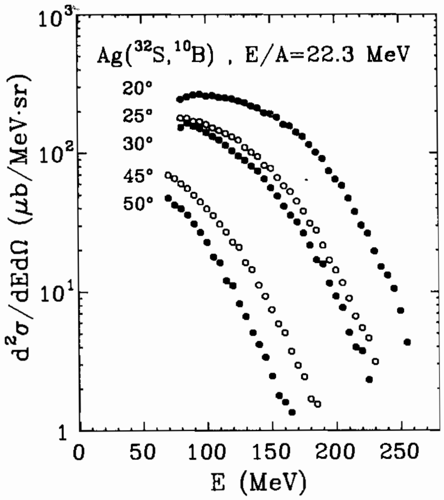

Fig. 1. Single particle inclusive cross sections for ^{10}B nuclei emitted in ^{32}S induced reactions on Ag at $E/A = 22.3$ MeV.

Spectra of γ-rays detected in coincidence with isotopes of ^{8}Li, ^{7}Be, ^{10}B, ^{12}B, and ^{13}C are shown by the histograms in fig. 2. The Doppler shifted background spectra are indicated by the solid dots in the figure. The following transitions were analyzed: ^{8}Li($J^\pi = 1^+$, $E^* = 0.981$ MeV$\rightarrow J^\pi = 2^+$, $E^* = 0.0$ MeV), ^{7}Be($\frac{1}{2}^-$, 0.429 $\rightarrow \frac{3}{2}^-$, 0.0), ^{10}B($1^+$, 2.154 $\rightarrow 0^+$, 1.740), ^{13}C($\frac{5}{2}^+$, 3.854$\rightarrow\frac{3}{2}^-$, 3.684), and overlapping transitions: ^{12}B(2^+, 0.953$\rightarrow 1^+$, 0.0), ^{12}B(1^-, 2.621$\rightarrow 2^-$, 1.674). We did not analyze the transition ^{7}Li($\frac{1}{2}^-$, 0.478 $\rightarrow \frac{3}{2}^-$, 0.0), because the pile-up of two coincident α-particles in the telescopes is misidentified as a ^{7}Li [15], nor the long-lived transition ^{10}B(1^+, 0.718$\rightarrow 3^+$, 0.0; $\tau = 1.02$ ns) [16], because this decay occurs at a considerable distance from the target resulting in major uncertainties in the efficiencies of the γ-ray detectors. The data in fig. 2 were summed over all detectors; the individual detectors provide comparable numerical contributions to the sum. The inclusive fragment yields and fragment-γ-ray coin-

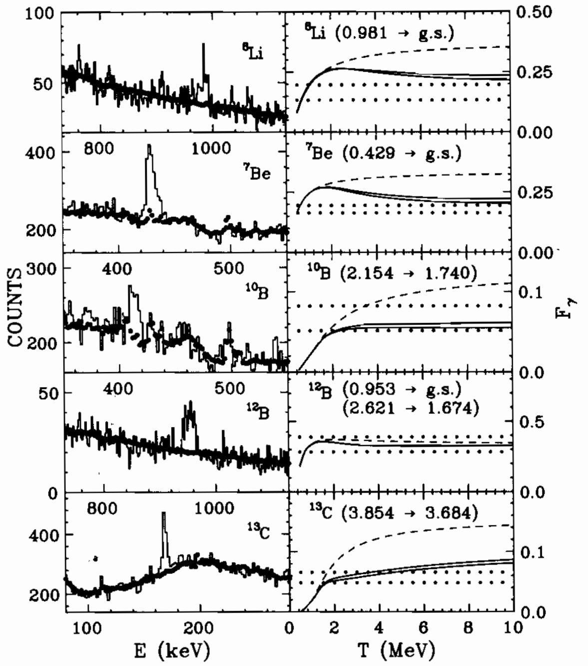

Fig. 2. Left-hand side: γ-ray spectra for ^{8}Li, ^{7}Be, ^{10}B, ^{12}B, and ^{13}C isotopes produced in ^{32}S induced reactions on Ag at $E/A=22.3$ MeV. Right-hand side: fractional probabilities F_γ that an observed fragment is accompanied by the designated γ-ray. Dotted lines denote the range of values for F_γ consistent with the coincidence measurements. Dashed and solid curves are discussed in the text.

cidence yields were summed over angle and combined to extract the fraction [5,7] F_γ of observed fragments which were accompanied by the designated γ-ray. Spin alignments were assumed to be zero. This introduced a spin aligment dependent uncertainty in F_γ of about 3%. Values of F_γ for these transitions are given in table 1.

To assess the magnitude of the sequential decay corrections, we have calculated F_γ with the quantum statistical model [10,11] which has been used to describe fragmentation in energetic nucleus–nucleus collisions [17]. The calculation proceeds in two stages: (i) the initial populations of states of particle stable and unstable fragments are calculated by solving equations of chemical equilibrium for nuclear matter at uniform breakup density [‡1] ρ and temperature T; (ii) the excited states decay [18] sequentially to fragments with larger binding energies according to available information [16] concerning the spins and branching ratios of each excited state.

Table 1
Fractional probabilities F_γ that the observed fragment is accompanied by the designated γ-ray.

Fragment	Transition	F_γ
^{8}Li	$1^+, 0.981 \rightarrow 2^+, 0.0$	0.165 ± 0.032
^{7}Be	$\frac{1}{2}^-, 0.429 \rightarrow \frac{3}{2}^-, 0.0$	0.180 ± 0.016
^{10}B	$1^+, 2.154 \rightarrow 0^+, 1.740$	0.067 ± 0.015
^{12}B	$2^+, 0.953 \rightarrow 1^+, 0.0$ $1^-, 2.621 \rightarrow 2^-, 1.674$	0.336 ± 0.053
^{13}C	$\frac{5}{2}^+, 3.854 \rightarrow \frac{3}{2}^-, 3.684$	0.057 ± 0.009

We first discuss the calculations for F_γ in which sequential feeding from particle unstable states of heavier nuclei is neglected and only the feeding from higher lying γ-unstable excited states of the same nucleus is considered. Values for F_γ consistent with this approximation are shown by the dashed lines in the right-hand side of fig. 2. The dotted lines indicate the upper and lower limits for F_γ consistent with our measurements. If sequential decay were neglected [5,7], temperatures of 0.5 ± 0.1 MeV, 0.9 ± 0.3 MeV, 2.4 ± 0.8 MeV, and 1.6 ± 0.2 MeV would be extracted from the transitions in ^{7}Be, ^{8}Li, ^{10}B, and ^{13}C, respectively. These temperatures are mutually inconsistent. Higher temperatures are extracted for transitions from states with higher excitation energy. This trend can be expected when secondary processes, such as sequential decay, modify the primary populations of ground and excited states [6].

The full calculations, which include sequential feeding from particle unbound states, are shown in the right-hand side of fig. 2 for densities $0.3\rho_0$ (upper solid line) and $0.7\rho_0$ (lower solid line), where ρ_0 denotes normal nuclear matter density. Sequential decay reduces considerably the theoretical values for F_γ bringing them close to the experimental values. For ^{7}Be, ^{8}Li, and ^{12}B nuclei, the dependence of F_γ on temperature is even predicted to be *non-monotonic*. Only at very low temperatures, $T \leqslant 1$–1.3 MeV, can sequential decay be neglected for the calculation of F_γ. At very low bombarding energies where this neglect may be justified, emission temperatures are consistent with the temperature of the equilibrated compound nucleus provided the compound nuclear temperature is less than 1.5 MeV [19]. At higher

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[‡1] The ratio of the proton density to the neutron density was chosen to be 0.82, consistent with the compound nucleus.

bombarding energies corresponding to higher compound nuclear temperatures, however, the experimental F_γ values are smaller than those predicted for negligible feeding; thus, emission temperatures were obtained which were considerably smaller than the temperature of the compound nucleus [19]. Our statistical model calculations show that this trend is mainly due to the increased importance of sequential feeding at the higher bombarding energies.

At temperatures greater than 2 MeV, we estimate an uncertainty of at least 25% in the theoretical values of F_γ arising from our present incomplete understanding of the fragmentation process and due to the lack of information concerning the spins and branching ratios for many of the tabulated [16] particle unstable states. Within this uncertainty, the full calculations, at $T \geqslant 4$ MeV, are consistent with the experimental measurements. Theoretical uncertainties and the insensitivity of the theoretical values of F_γ to temperature prevent the extraction of meaningful emission temperatures, for $T \geqslant 2$ MeV, from these low energy γ-ray transitions. The calculations are nonetheless capable of indicating whether specific transitions are strongly influenced by sequential feeding. In particular, these and other statistical calculations show that the relative populations of particle unstable states presented in refs. [6,8,9] are relatively insensitive to sequential decay at temperatures less than 4 MeV [6,20]. Although sequential decay may strongly influence the relative populations of ^{6}Li and ^{8}Be particle unstable states at higher temperatures, the relative populations of states in ^{5}Li are predicted to be relatively unperturbed by secondary decays for temperatures as large as 10 MeV [6,20].

In summary, we have measured low energy γ-ray transitions in ^{8}Li, ^{7}Be, ^{10}B, ^{12}B and ^{13}C fragments emitted in ^{32}S induced reactions on Ag at $E/A = 22.3$ MeV. When the uncertainties in the calculations are taken into account, the observed γ-ray fractions are consistent with fractions calculated for $T \geqslant 4$ MeV with the quantum statistical model which incorporates sequential feeding from heavier particle unstable fragments. Although the detailed predictions of these calculations have significant uncertainties, they can test the sensitivity of specific transitions to sequential feeding. The calculations demonstrate that, for $T \geqslant 2$ MeV, these low energy γ-ray transitions are more sensitive to the feeding from highly excited primary reaction products than to the temperature of the emitting system; thus these transitions cannot be used to test the assumption of local thermal equilibrium.

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