

## EXCITED STATE PRODUCTION AND TEMPERATURE MEASUREMENT IN A HEAVY ION REACTION

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An effective temperature inferred from the slope of kinetic energy spectra of the emitted fragments is not reflected in the relative populations of excited states of the emitted nuclei. We found that the excited state populations of  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and  ${}^7\text{Be}$  emitted near  $90^\circ$  in the lab from the reaction of  $490\text{ MeV } {}^{14}\text{N}$  with Ag are significantly lower than those expected on the basis of their effective temperature.

The formation of an equilibrated hot zone of nuclear matter has been a tenet of relativistic heavy-ion reaction models since the introduction of the fireball model some years ago [1]. This model used the properties of an expanding nucleon gas to predict kinetic energy spectra for hydrogen and helium nuclei which were in rough agreement with the experimental data. The success of the early model can be attributed to a large extent to the thermal appearance of the experimental data. Recent measurements at 42–137 MeV/nucleon have shown that intermediate-rapidity complex fragments (masses in the range of  $A = 1\text{--}14$ ) can also be described in the framework of emission from a single source with a temperature that depends on the beam energy but not the fragment mass [2]. At slightly lower bombarding energies such intermediate mass fragments have also been used as evidence for a

thermal zone of emission [3]. The kinetic energy spectra and mass distributions of these intermediate mass fragments suggest that they are emitted from compound nuclei [4,5]. Acceptance of the formation of such a thermalized zone is so widespread that new models of such collisions completely rely on its existence [6].

An independent test of the existence of such a thermalized zone can be made by comparing the temperatures obtained from fitting energy spectra to temperatures obtained by observing the relative populations of excited states. The population distribution among the excited states of a system in statistical equilibrium depends on the temperature of the system and the energy level spacing. For a two-level system at constant volume the dependence is given simply by the Boltzmann factor. For nuclear systems, such as  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and  ${}^7\text{Be}$  nuclei, the populations will be modified by

statistical factors which represent the number of magnetic substates and by any feeding from both higher lying states and more massive nuclei which undergo particle decay. Such decays could have a significant effect on the population distribution depending, of course, on the nuclear structure of the states. For example, the excited states of  $^8\text{Li}$  decay by neutron emission to both states of  $^7\text{Li}$ .

The nuclei  $^6\text{Li}$ ,  $^7\text{Li}$ , and  $^7\text{Be}$  are particularly good probes for this test of statistical equilibrium for three reasons: (a) they have effectively only one excited state that decays by  $\gamma$ -ray emission [7]<sup>†</sup> and this state can not be fed from above, (b) the upper state of both  $A = 7$  nuclei is spin  $\frac{1}{2}^-$  and that of  $^6\text{Li}$  is  $0^+$ , and therefore all three states decay by isotropic  $\gamma$ -ray emission, and (c) the three nuclei have different level spacings which provides an internal consistency check. However, the energy level spacings of  $^7\text{Li}$  and  $^7\text{Be}$  are only 478 and 429 keV, respectively, thus limiting the sensitivity of their population distributions to temperatures on the order of a few MeV. The excitation energy of the  $^6\text{Li}$  level is 3562 keV which provides sensitivity over a broader temperature range.

In the simplest picture with no particle decay, the ratio,  $R$ , of the populations of two states is:

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

where  $j_l$  and  $j_u$  are the spins of the lower and upper states, respectively, and  $\Delta E$  is the energy difference between the states. The lifetimes of the three  $\gamma$ -ray emitting states that we are considering are short compared to the flight time of the nuclei from the target to the detectors. Thus, the  $\gamma$ -ray detectors measure the excited state populations while the particle detectors measure the production of both the excited and ground states. The ratio of the two measurements is the fraction,  $f$ , in the excited state and is a simple function of the temperature which is related to the population ratio by the equation  $f = R/(1 + R)$ .

In the present experiment lithium and beryllium nuclei were produced by the interaction of

nitrogen ions with a silver target. A beam of 490 MeV  $^{14}\text{N}^{5+}$  ions was provided by the K500 cyclotron of the National Superconducting Laboratory at Michigan State University. The target was a self supporting foil of natural silver,  $0.3 \text{ mg/cm}^2$  thick with its plane at  $50^\circ$  with respect to the beam. No beam collimators were used in the vicinity of the scattering chamber. The beam was stopped in a Faraday cup approximately 3.2 m downstream, which was surrounded by water and lead shielding. The beam intensity was generally between 1 and 3 particle nA. This modest intensity kept the count rates in all the detectors low and gave a real-to-random coincidence ratio of 17:1.

The light ion products were detected in a set of three-element Si surface barrier telescopes located at  $90^\circ$ ,  $100^\circ$ , and  $110^\circ$  with respect to the beam. Placing the particle telescopes at these large angles reduces the possibility of detecting projectile fragments for which the temperature is expected to be low. The three elements of the particle telescopes were a  $\Delta E$  ( $100 \mu\text{m}$ ), an  $E$  ( $1000 \mu\text{m}$ ), and a reject counter ( $100 \mu\text{m}$ ). The effective solid angles of the particle telescopes were determined to be approximately 24 msr each. An energy calibration was obtained for each Si detector with a  $^{212}\text{Pb}$  source and the system linearity was checked with a pulser. A large majority of the beam time was used to record coincidences between particles and  $\gamma$ -rays. Particle singles were measured at intervals during the remaining beam time.

A set of four bismuth germanate (BGO) scintillation counters,  $7.6 \text{ cm} \times 7.6 \text{ cm}$  right cylinders, were used to detect  $\gamma$ -rays in coincidence with the particles. Two detectors were placed on each side of the beam at  $60^\circ$  and  $120^\circ$  in the reaction plane. BGO scintillators were used in the present study because they have a high photopeak efficiency for the 3.562 MeV  $\gamma$ -ray expected from the decay of  $^6\text{Li}$  nuclei. The energy and time resolution as well as the photopeak efficiency of these detectors have been previously measured [8]. The coincidence electronics were set up with a  $^{249}\text{Cf}$  source. This source emits an  $\alpha$ -particle in coincidence with a 388 keV  $\gamma$ -ray. The coincidence efficiency of the BGO detectors

<sup>†</sup> Only one state has been observed to  $\gamma$ -decay for both  $^7\text{Li}$  and  $^7\text{Be}$ ,  $^6\text{Li}$  has only one state with a significant  $\gamma$ -ray branch.

was measured after the run with three  $\gamma$ -ray cascade sources,  $^{60}\text{Co}$ ,  $^{134}\text{Cs}$ , and  $^{207}\text{Bi}$ . The substitution of a NaI(Tl) detector for the  $\Delta E(\text{Si}-1)$  allowed us to measure the coincidence efficiency of the entire setup including the effect of the absorbers, the electronics, and data acquisition computer. The photopeak efficiency of the entire set of BGO detectors was found to be  $0.013 \pm 0.001$  at 450 keV and  $0.0067 \pm 0.001$  at 3500 keV by extrapolation of the known response function [8].

After the run the data analysis followed a simple path. Histograms of the single particle inclusive energy spectra were obtained for each isotope. The coincident  $\gamma$ -ray energy signals were converted from channel numbers into energies and then corrected for Doppler shifts on an event-by-event basis as if all the  $\gamma$ -rays were emitted from the light products. The average velocities of the particles were low and thus the average Doppler shifts were small, typically less than or comparable to the energy resolution of the  $\gamma$ -ray detectors. A histogram of the calculated energy for each detector combination and for each isotope was made. Then a randomly gated histogram of the same detector combination and isotope was subtracted from it. To improve statistics all the resulting histograms for the individual telescopes and  $\gamma$ -ray detectors were summed together.

The particle singles data collected in this experiment are consistent with previously reported data for similar reaction systems [2,3] both in cross section and in spectral shape. The laboratory energy spectra of the  $^6\text{Li}$ ,  $^7\text{Li}$  and  $^7\text{Be}$  ranged between 30 and 90 MeV and show an exponential shape with a slope parameter or effective temperature of 8.6 MeV as shown in fig. 1. This temperature was obtained with a moving source fit [2] which used a Maxwell-Boltzmann function

$$N(E) \propto E^N \exp(-E/kT) \quad (2)$$

with  $N = 1$  and where  $E$  is the kinetic energy and  $kT$  is the temperature (the source velocity was found to be 0.13 that of the projectile). If we accept this temperature at face value, we would expect that  $f = 0.180$ , 0.321 and 0.322 for  $^6\text{Li}$ ,  $^7\text{Li}$  and  $^7\text{Be}$ , respectively. The moving source fit is also shown in fig. 1. The  $^6\text{Li}$  and  $^7\text{Be}$  spectra and the

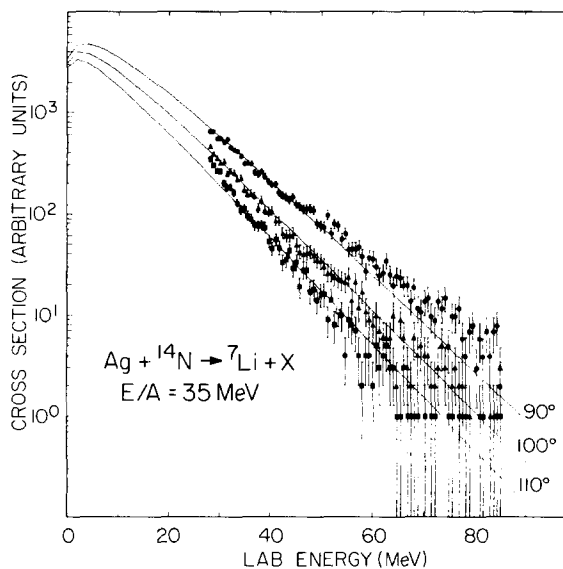


Fig. 1. Laboratory energy spectra of  $^7\text{Li}$  nuclei emitted at  $90^\circ$ ,  $100^\circ$ , and  $110^\circ$ . The solid lines are a moving source fit as described in the text.

fits to them are very similar. This is not surprising since moving source fits seem capable of fitting spectra of fragments with  $A = 1$  to  $A = 14$  in very similar systems, see fig. 2 of ref. [2].

Only a small fraction of the expected deexcitation  $\gamma$ -rays were observed. The part of the  $\gamma$ -ray spectrum where the full energy peak should lie for each of the three reaction products is shown in fig. 2. Also shown in fig. 2 is a peak with the height and area expected for a temperature of 8.6 MeV. In an attempt to quantify the discrepancy values of the fraction,  $f$ , and temperature were calculated from statistical fits of a gaussian peak plus a smooth background to the data which are presented in table 1; two of the temperatures are

Table 1  
Summary of numerical results.

Isotope	$E_\gamma$ (MeV)	$f$ (expected <sup>a)</sup> )	Counts	$f$ (obs)	$kT$ <sup>b)</sup> (MeV)
$^6\text{Li}$	3.562	0.180	$5^{+3}_{-5}$	$0.01^{+0.02}_{-0.01}$	$1.0^{+0.5}_{-1.0}$
$^7\text{Li}$	0.478	0.321	$80^{+110}_{-40}$	$0.05^{+0.06}_{-0.02}$	$0.21^{+0.13}_{-0.04}$
$^7\text{Be}$	0.429	0.322	$15^{+22}_{-15}$	$0.09^{+0.14}_{-0.09}$	$0.3^{+0.6}_{-0.3}$

<sup>a)</sup> From fitting kinetic energy spectra, see text.

<sup>b)</sup> Simple result representative of the population distributions.

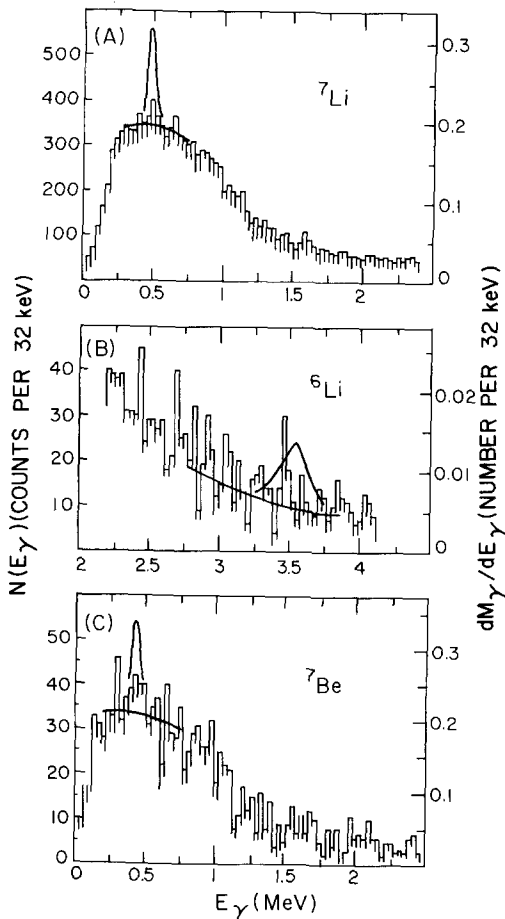


Fig. 2. Random-corrected  $\gamma$ -ray spectra obtained in coincidence with  ${}^7\text{Li}$  nuclei, (A), with  ${}^6\text{Li}$  nuclei, (B), and with  ${}^7\text{Be}$  nuclei, (C). Curves representative of the expected  $\gamma$ -ray peaks on the fitted background are shown.

consistent with zero, and all three are an order of magnitude smaller than the temperature derived from the energy spectra.

Most of the coincident  $\gamma$ -rays observed in the present experiment were continuum  $\gamma$ -rays. Briefly, the spectra showed the presence of two components. Rotational  $\gamma$ -rays were observed in the region of 0–1 MeV, and the underlying statistical transitions extended over the entire range of the data. A fit of the expected shape [9], eq. (2) with  $N = 2$ , to the high energy region of the  ${}^7\text{Li}$   $\gamma$ -ray spectrum where the statistical  $\gamma$ -rays stand out gave a temperature of 0.6 MeV. This value is consistent with other measurements [9] and the

expectation that nuclei cool by particle emission prior to  $\gamma$ -ray emission. An estimate of the average  $\gamma$ -ray multiplicity can be obtained from the ratio of the number of particle- $\gamma$ -ray coincidences to the number of particle singles times the coincidence efficiency for each of the lithium and beryllium products. These average multiplicities were found to be 7, 8, and 9 for  ${}^6\text{Li}$ ,  ${}^7\text{Li}$  and  ${}^7\text{Be}$ , respectively, which indicates a relatively low spin for the otherwise uncharacterized emitting nucleus.

In conclusion, we have not observed the population of the excited states of light nuclei that would be consistent with the effective temperature implied by their kinetic energy spectra. One can question whether true statistical equilibrium, or even something close to it, can be established for an object which contains such a small number of particles and which lives for such a brief time. The reaction may be a very complex multistep process in which equilibrium is never established. An example of such a process would be that in which lithium nuclei are produced by the sequential decay of heavier nuclei. The quantum statistical model of Stöcker [10] includes production by the decay of unbound levels but does not predict a ratio different from the statistical factors. This calculation did not include specific nuclear structure information on the decay of these states but used some average value. Even if these states are assumed to decay entirely to the ground states, which is not the case, the population ratio will not change enough to explain the present data. It has also been suggested [11] that Li nuclei can interact with simultaneously emitted nucleons and be deexcited (without  $\gamma$ -ray emission) even when the system has expanded substantially and has cooled accordingly. In any case the present experiment presents a new observable for models of the reaction mechanism.

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