Nuclear temperatures in the reaction of ^{14}N with Ag at 35 MeV/nucleon

D. J. Morrissey
National Superconducting Cyclotron Laboratory and Department of Chemistry, Michigan State University, East Lansing, Michigan 48824

W. Benenson, E. Kashy, C. Bloch, and M. Lowe
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824

R. A. Blue, R. M. Ronningen, B. Sherrill, and H. Utsunomiya
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

I. Kelson
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
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The population of excited states of Li and Be nuclei emitted in the $^{14}N+Ag$ reaction $E/A=35$ MeV has been measured. The results confirm a recently measured disagreement between the temperature determined from the slopes of the energy distributions and that obtained from the excited state populations. Recent models which were developed to explain the discrepancy are discussed.

I. INTRODUCTION AND BACKGROUND

The existence of an equilibrated hot zone of nuclear matter has become 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 of hydrogen and helium nuclei which were in rough agreement with the experimental data. An independent test of the existence of such a thermalized zone has been made by a recent measurement of the excited state populations of complex fragments.[2] The principle of equal partition of energy among the degrees of freedom of a system dictates that the temperature of that system will be reflected in the excited state populations as well as in kinetic energy of motion. The initial measurements of the population of the excited states of lithium and beryllium nuclei observed near 90° from the reaction of 490 MeV ^{14}N with silver showed much lower populations than that calculated from temperatures determined from their velocity distributions.[2] Estimates of the temperatures using the two methods were different by more than an order of magnitude. Such a discrepancy would have important consequences for thermal models of heavy-ion reactions and therefore needed to be verified. In the present paper, we report a new measurement of the production of excited states of lithium and beryllium nuclei from the reaction of 490 MeV ^{14}N with Ag. The experimental technique used in our previous measurement was improved so that accurate values of the small fractions of nuclei in excited states could be obtained.

The basis of the measurement of temperature by means of nuclear excited state population is briefly described below. 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. The distribution of the populations of observable nuclear systems, such as ^{7}Li, ^{8}Li, and ^{7}Be nuclei, will be modified by statistical factors which reflect the number of magnetic substates and by any feeding from both higher lying states that γ-ray decay and from more massive nuclei that 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}Li just above the neutron separation energy decay by neutron emission almost exclusively to the ground state of ^{7}Li, whereas there is essentially no neutron decay of ^{8}Be to any ^{7}Be states.[3]

The ^{7}Li and ^{7}Be nuclei are particularly good probes of statistical equilibrium for three reasons: (a) they have virtually only one excited state that decays by γ-ray emission,[3] and this state cannot be appreciably fed from above; (b) the gamma emitting states of both $A=7$ nuclei are spin $\frac{1}{2}^-$, and therefore the states decay by isotropic γ-ray emission; and (c) the two nuclei have somewhat different feeding from unbound higher mass nuclei, which provides an internal check on the importance of any feeding. However, the energy level spacings of ^{7}Li and ^{7}Be are only 478 and 429 keV, respectively, and this limits the sensitivity of their population distributions to temperatures of a few MeV or less. Two other lithium nuclei, ^{6}Li and ^{8}Li, are also good probes of temperature over a broader range. The excitation energies of the levels are 981 and 3562 keV with spins of 1^+ and 0^+ for the ^{8}Li and ^{6}Li nuclei, respectively. These latter nuclei also have only one excited state that decays by γ-ray emission,[3] but the ^{6}Li γ ray is diffi-

cult to measure, and the ^{8}Li γ ray is anisotropic.

In the simplest picture of a system in thermal equilibrium with no feeding by particle decay, the ratio R of the populations of two states is

$$R = \frac{(2j_{ex}+1)}{(2j_{g.s.}+1)} e^{-\Delta E/kT}, \quad (1)$$

where $j_{g.s.}$ and j_{ex} are the spins of the ground and excited states, respectively, and ΔE is the energy difference between the states. This ratio is not directly measurable, as the lifetimes of the γ-ray emitting states under consideration are short compared to the flight time of the nuclei from the target to the particle detectors. Thus, γ-ray detectors can measure the excited state populations via their decay, while particle detectors can 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 related to the population ratio by the equation: $f = R/(1+R)$. Under the assumption of thermal equilibrium, the dependence of the fraction f with temperature is the simple expression plotted in Fig. 1 for the lithium and beryllium nuclei suitable for these studies.

Our previous measurement of nuclear reaction temperatures with excited state populations gave a value which was much lower than that obtained from a moving source fit to the velocity distributions.[2] However, the number of γ rays that we observed was small, and consequently, the value of the fraction of nuclei in their excited state was not well determined. We have improved the experimental apparatus by increasing the number and solid angles of the γ-ray detectors and by improving the energy resolution of the γ-ray detectors. Such improvement of the γ-ray energy resolution is important, as the technique relies on an accurate measurement of the number of excited state γ rays (about 0.1 per detected fragment) in the presence of continuum γ rays from the reaction partner (about 10 per detected fragment, as discussed below).

In the present paper we report the results of a measurement of single particle inclusive and γ-ray coincidence spectra for ^{7}Li, ^{8}Li, and ^{7}Be nuclei emitted from the reaction of 490 MeV ^{14}N with silver. The present measurement overlaps part of the previous work,[2] extends the angular range of the detected particles, and includes a new temperature measurement from ^{8}Li fragments. The previous measurements showed that the fraction of ^{6}Li nuclei in excited states was extremely small, but consistent with the $A=7$ results. Thus, the present measurements were extended to include the excited states of ^{8}Li but not that of ^{6}Li. The details of the experimental setup and calibrations are given in Sec. II. The results are presented in Sec. III. The inclusive data are analyzed in terms of a moving source model, and the population distributions were determined from the γ-ray coincidence data. The present study confirms the previously reported discrepancy between the temperatures derived with the two techniques. The predictions of recent models that were developed to explain this difference are also discussed.

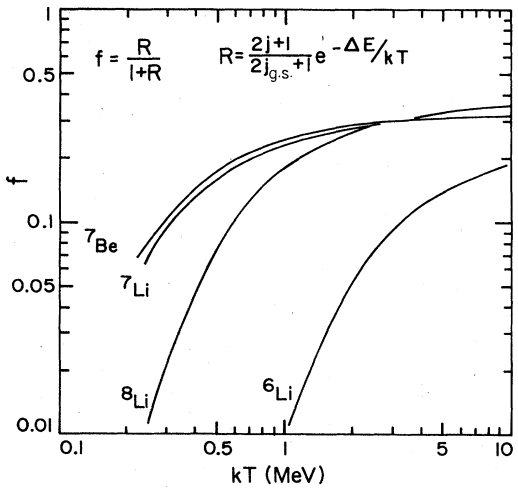

FIG. 1. The fraction of nuclei in their excited states as a function of temperature for a system in thermal equilibrium; see the text.

II. EXPERIMENTAL

Lithium and beryllium nuclei were produced by the interaction of nitrogen ions with a silver target. A beam of 490 MeV $^{14}N^{5+}$ ions was provided by the K500 cyclotron of the National Superconducting Cyclotron Laboratory at Michigan State University. The target was a self-supporting foil of natural silver, 2.0 mg/cm^2 thick, with its plane at 45° 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 0.1 and 0.3 particle nA. Such a low beam intensity was used to maintain the count rates in the γ-ray detectors below 20 000 per second, and thereby avoid gain shifts. A ^{137}Cs γ-ray source was placed in the center of the NaI(Tl) array during the second half of the experiment. This source emits a single γ ray per decay which would be detected in random coincidence with the charged particles. This source provided an in-beam monitoring of the energy resolution.

The light ion products were detected in a set of two-element Si surface barrier telescopes located at $+50°$, $\pm 70°$, and $-90°$ with respect to the beam (positive angles clockwise with respect to the beam). Placing the particle telescopes at these large angles reduces the possibility of detecting projectile fragments or direct reaction products (the classical grazing angle is only 5°). The first element of each particle telescope was either a 100 μm ($+50°, -90°$) or a 50 μm ($\pm 70°$) ΔE detector, and the second element of each particle telescope was a 1000 μm E detector. The planarity of the ΔE detectors provided excellent isotope resolution which was maintained throughout the experiment by cooling the detectors to -30 °C. Gold cover foils, approximately 3 mg/cm^2 thick, were placed on the collimators of the particle telescopes. The effective solid angle of each particle telescope was approximately 24 msr. An energy calibration was obtained for each Si detector with a ^{212}Pb source, and the linearity of the analog electronics was checked with a pulser.

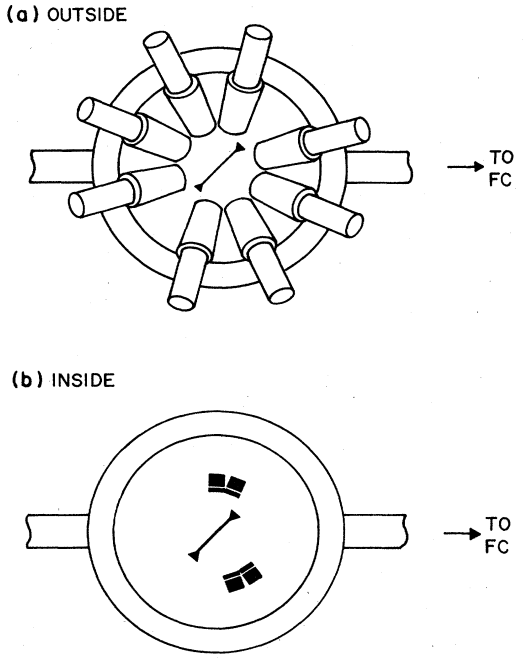

FIG. 2. (a) Schematic diagram of the NaI(Tl) array. The detectors were placed at 25°, 65°, 105°, 165°, 205°, 245°, 285°, and 345° with respect to the beam. (b) Schematic diagram of the particle detectors inside the vacuum chamber.

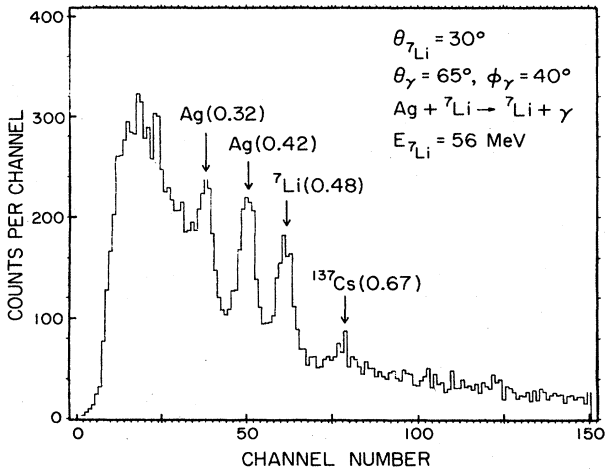

FIG. 3. Laboratory γ-ray spectrum in coincidence with inelastically scattered ^{7}Li nuclei at 50°. Production of the low lying silver states near 0.32 and 0.42 MeV, and the lithium state at 0.48 MeV is clearly shown. The line from the ^{137}Cs random-calibration source is barely visible.

A set of eight NaI(Tl) scintillation detectors, 7.6 cm × 7.6 cm right cylinders, was used to detect γ rays in coincidence with the particles. The center lines of the detectors were placed above the scattering plane on the surface of a right cylindrical cone, centered on the target. A schematic diagram of the experimental setup is shown in Fig. 2. The good resolution ($\leq$6.5% at 662 keV) of the NaI(Tl) scintillators (as compared to 14% for the bismuth germanate detectors used in the previous work) was necessary for the present study to accurately determine the small value of the population of the excited states (approximately 0.1) in the presence of approximately ten continuum γ rays from the target residue. The gains of the γ-ray amplifiers were adjusted to observe a maximum of about 2.5 MeV, and thus the 3.562 MeV γ ray from ^{6}Li was not observed. The detection efficiency for γ rays of this energy was, in any case, too low to permit a meaningful measurement. The energy calibrations of the NaI(Tl) detectors were obtained with γ-ray sources. The overall efficiency of the coincidence electronics was measured with a ^{249}Cf source. This source emits an α particle in coincidence with a 388 keV γ ray which allowed us to measure the coincidence efficiency of the entire setup including the effect of γ-ray absorbers, the electronics, and the data acquisition computer. Most of the beam time was used to record coincidences between particles and γ rays. The noncoincident inclusive particle spectra were measured at intervals during the course of the experiment.

An additional check of the electronics and data acquisition system was made after the ^{14}N run by measuring inelastic scattering of ^{7}Li. A beam of 56 MeV ^{7}Li interacted with the same silver target, and scattered lithium nuclei were detected at $\pm$30°, $\pm$50°. The low lying silver states and the ^{7}Li excited state are clearly seen in the coincident γ-ray spectrum shown in Fig. 3. Even though the data provided a good verification that all parts of the system were working properly, these data could not be used to check the overall efficiency due to the combined effects of the degradation of the energy resolution of the particle detectors during the ^{14}N run and the fact that the excited states of silver intervene between the lithium ground and excited states.

In order to extract the number of γ rays emitted by the excited states, the raw data were converted from channel numbers into energies and then corrected for Doppler shifts on an event-by-event basis as if all the γ rays were emitted from the light products. The average velocities of the particles were low, and thus the average Doppler shifts were small, typically slightly larger than the energy resolution of the γ-ray detectors. A histogram was made of the number of γ rays as a function of their Doppler shifted energy for each isotope in each particle-detector/γ-ray-detector combination. Then a histogram of the γ rays in random coincidence with the same isotope in the same detector combination was subtracted from it. To improve statistics, the eight histograms from the γ-ray detectors were summed together after having been corrected for random coincidences. An inspection of the individual spectra showed that they were essentially identical.

III. RESULTS

A. Inclusive particle data

The inclusive energy and angular distributions of the fragments were obtained for comparison to our previous study and as input for the moving-source model fits. Figure 4 shows a comparison of the energy spectra of ^{7}Li as a

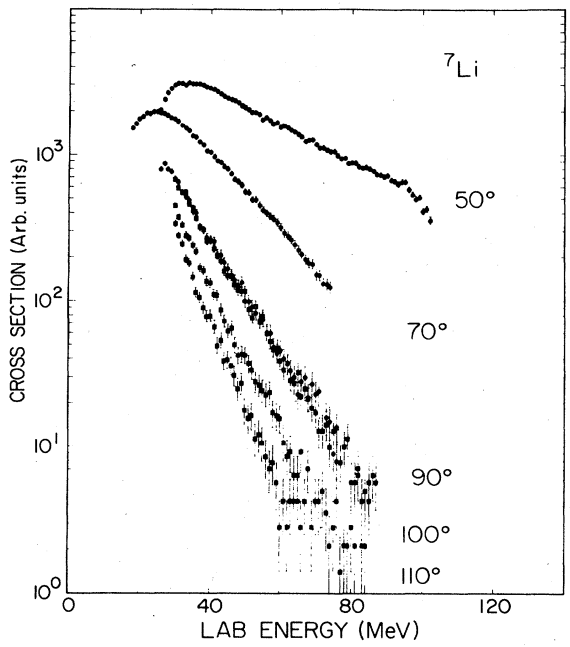

FIG. 4. Comparison of the ^{7}Li kinetic energy spectra as a function of angle from this (50° to 90°) and the previous measurement (90° to 110°) (Ref. 2).

function of angle for the present experiment (50°–90°) with those obtained previously (90°–110°).[2] The present results are in excellent agreement with previous data. The laboratory energy spectra of all the lithium and beryllium isotopes range between 20 and 120 MeV and exhibit an exponential shape, as shown in Fig. 5. The spectra are a strong function of laboratory angle, which suggests that they are emitted from a moving frame.

Inclusive data of this type have been extensively used to characterize a moving source of emission in terms of its size, velocity, and temperature. The curves superimposed on the data in Fig. 5 were obtained with such a moving source fit[4] to the four spectra of each isotope. A chi-squared minimization procedure was used to obtain the best values of the parameters of a Maxwell-Boltzmann function:

$$N(E) \propto E e^{-E/kT}, \tag{2}$$

where E is the kinetic energy corrected for the Coulomb barrier, and T is the temperature. The numerical results of the fitting procedure are shown in Fig. 6 as a function of fragment mass number. The error bars on the data points indicate the variation in the parameters necessary to increase the chi-squared by 1. This method probably underestimates the error because of the small number of angles in the present measurement. A more realistic estimate of the errors should be taken as the width of the distribution about the average, $\langle T \rangle = 12 \pm 2$ MeV and $\langle v \rangle = 2.2 \pm 0.3$ cm/ns.

The fact that the slope parameters and source velocities are larger than those expected for a fully equilibrated compound nucleus (a nucleus with $A \approx 122$ at an excitation energy of ≈ 430 MeV implies $kT \approx 5.3$ MeV) is usually taken to indicate a "localized" and relatively small region of "thermal equilibrium," e.g., a fireball.[1,2,4,5] The good fit to the large angle data is not surprising, since moving sources seem capable of describing spectra of fragments with $A = 1$ to $A = 14$ in very similar systems; for example, see Fig. 2 of Ref. 4. Moreover, the slope parameters or temperatures extracted from this data are very close to those expected from previous systematics.[6] If we use the average temperature of 12 MeV, we would expect from the Boltzmann factor to find $f = 0.32$, 0.35, and 0.33 for ^{7}Li, ^{8}Li, and ^{7}Be, respectively.

The distribution of the inclusive isotopic cross sections, integrated over angle, should also reflect the temperature of a thermal zone of emission in the same sense as the excited state populations. We have used an equation similar to the Saha equation in an attempt to extract what is referred to as the ionization temperature[7] in astrophysics. In such an equation the isotropic production cross section per degree of freedom is proportional to an exponential function of the Q value divided by the temperature. Figure 7 shows the variation of the inclusive fragment production cross section, divided by the statistical factor, for several isotopes as a function of the negative of the Q value. The curve drawn through the data represents the best fit to the data which was obtained with a temperature of 8 ± 1 MeV. In this case the compound system was assumed to have $A = 23$ or 24 (nearly twice the projectile A), and the Q values were calculated under the assumption that two neutrons were emitted simultaneously with the fragments. In an attempt to mitigate sensitivity to odd-even effects, the Q value used in the fitting was averaged over compound nuclei assumed to be either ^{21}F, ^{22}F, ^{21}Ne, or ^{22}Ne. The fit was not very sensitive to the choice of compound nucleus nor to the number of neutrons emitted, provided that they were not too far from the above values. The inclusive cross sections shown in Fig. 7 were taken from the moving-source fits, as neither the complete energy spectrum nor angular distribution of these isotopes was measured. This analysis indicates that analysis of the inclusive cross sections does not agree with the "slope parameters" of the kinetic energy spectra.

B. Coincident gamma radiation

Figure 8 shows the summed γ-ray spectra in the fragment rest frame (fragments emitted at 70° in the laboratory) for the beryllium nucleus and three lithium nuclei. The γ ray corresponding to the decay of the excited state is clearly visible for ^{7}Li, ^{8}Li, and ^{7}Be, as is some hint of the ^{137}Cs peak now broadened by the variation in the various Doppler shifts. Note that the ^{7}Li γ-ray peak is slightly broader than expected (compare with Fig. 3, for example) and that a small "bump" is visible in the ^{6}Li spectrum, Fig. 8(b), near 500 keV, probably due to a target γ ray or annihilation radiation. Only a small fraction of the γ rays expected from a Boltzmann distribution were observed. The number of γ rays emitted by the decay of the excited states of each fragment can be dramatized by tak-

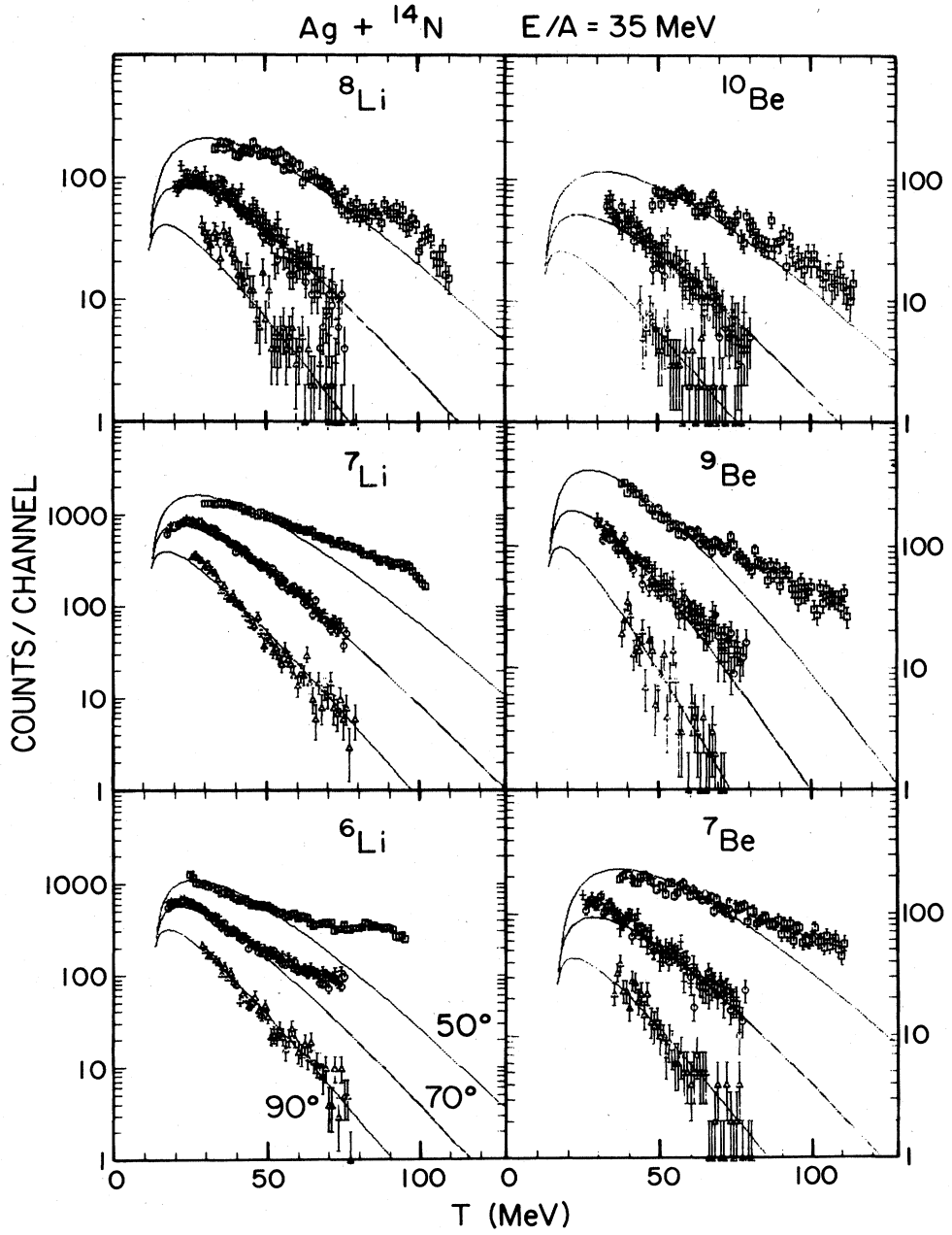

FIG. 5. Laboratory kinetic energy spectra from the present study. The curves drawn through the data represent moving-source fits described in the text. The laboratory angles of the data and calculations are the same for all six nuclei and are indicated in the lower left panel.

ing the ratio of the coincidence spectrum of interest to that in coincidence with ^{6}Li. Recall that the γ ray from the decay of the excited state of ^{6}Li lies off the high end of the scale and can only contribute to the observed spectrum via Compton processes. We expect that the continuum γ rays emitted by the targetlike fragment should be essentially the same for similar light fragments. The channel-by-channel ratio of the ^{7}Li γ-ray spectrum to that of ^{6}Li, normalized by the inclusive ratio of ^{7}Li to ^{6}Li nuclei, is shown in Fig. 9. The ratio clearly indicates the presence of only the 478 keV γ ray in the ^{7}Li spectrum, since the "bump" apparent in the ^{6}Li spectrum near 500 keV is apparently common to both spectra. Note that Fig. 9 does not strictly represent the ratio of Fig. 8(a) to 8(b), as the same Doppler shift (that suitable for an $A=7$ fragment) was applied to both sets of event-by-event data before taking the ratio.

The fraction of nuclei in the excited state was obtained from the number of counts in the full energy γ-ray peak of each isotope at each angle N_γ with the expression

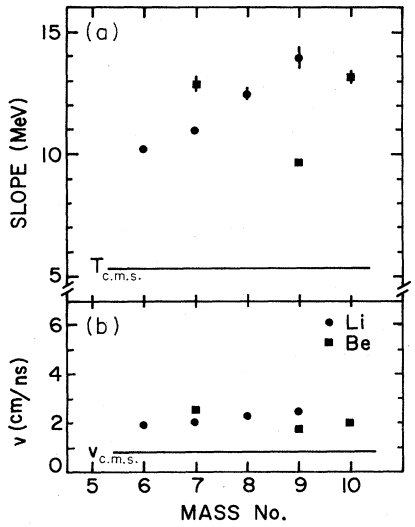

FIG. 6. Values of the slope parameter (a) and velocity (b) for the fitted curves shown in Fig. 5. The temperature of the equilibrated compound system, $T_{c.m.s.}$, and the velocity of the center of mass, $v_{c.m.s.}$, are also indicated.

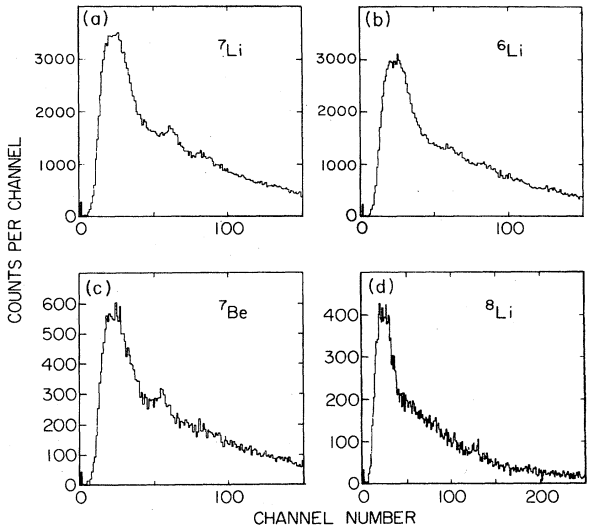

FIG. 8. Random-corrected coincident γ-ray spectra in the rest frame of ^{7}Li, (a); ^{6}Li, (b); ^{7}Be, (c), and ^{8}Li, (d). The energy scale has been compressed for ^{8}Li.

$$f=\frac{N_\gamma}{\epsilon_\gamma}\frac{1}{N_I}\frac{1}{\mu C}\,, \tag{3}$$

where ϵ_γ is the total photopeak efficiency of the eight γ-ray detectors, N_I is the number of inclusive fragments per microCoulomb of beam current, and μC is the number of microCoulombs during the coincidence run. The statistical errors and systematic errors in evaluating N_γ dominated the other sources of error. The number of γ rays and the corresponding fractions are given in Table I and are compared to the previous measurement in Fig. 10. The present results indicate that the fraction does not depend on angle over the 40° angular range studied, and that small differences are observed among the three average values of the fraction. However, all three fractions give a temperature which is more than an order of magnitude lower than those expected from the kinetic energy spectra.

The large majority of the coincident γ rays observed in the present experiment consisted of continuum γ rays emitted by the targetlike fragment. The central moments of the γ-ray multiplicity distribution were obtained from the relative probabilities of observing successively higher or-

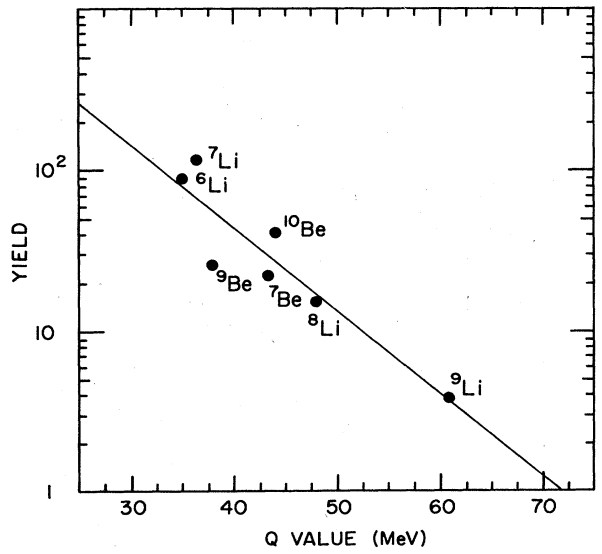

FIG. 7. Comparison of the fitted Saha-type equation to the relative inclusive cross sections per degree of freedom; see the text.

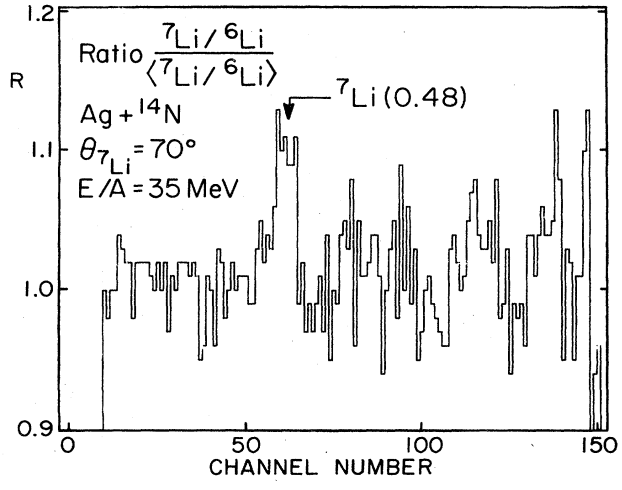

FIG. 9. The channel-by-channel ratio of the γ-ray spectra in coincidence with ^{7}Li and ^{6}Li, normalized by the ratio of their inclusive production cross sections.

TABLE I. Summary of numerical results.

Isotope	E_γ (MeV)	f (ke[a])	Angle	Counts	f (obs)	kT[b] (MeV)
^{7}Li	0.478	0.32	50°	1546±252	0.119±0.025	0.370+0.08/−0.07
			70°	477±152	0.091±0.034	0.295+0.09/−0.07
			−70°	620±164	0.106±0.033	0.330+0.10/−0.07
			−90°	117±68	0.102±0.064	0.325+0.20/−0.10
^{8}Li	0.981	0.35	50°	51±38	0.027±0.022	0.330+0.08/−0.15
			70°	76±29	0.123±0.052	0.680+0.24/−0.20
			−70°	59±24	0.081±0.037	0.520+0.14/−0.13
			−90°	9±12	0.061±0.081	0.455+0.31/−0.46
^{7}Be	0.428	0.33	50°	422±81	0.168±0.040	0.480+0.18/−0.12
			70°	194±47	0.229±0.066	0.830+1.5/−0.37
			−70°	200±49	0.209±0.062	0.650+0.75/−0.25
			−90°	0±15	0.0 ±0.135	0.0 +0.38/−0.0

[a] From fitting kinetic energy spectra; see the text.
[b] Simple result representative of the population distributions. The errors are asymmetric due to the logarithmic function.

der coincidences in the NaI(Tl) array by applying the method of Ockels.[8] The average multiplicity and the width of the γ-ray multiplicity distribution for several isotopes are given in Table II as a function of angle. The γ-ray multiplicity distribution associated with a light fragment has an average value of approximately 12 and a width of 7 to 8 units. Such a value of the multiplicity indicates that spins of approximately $20\hbar$ are present in the unobserved reaction partner (e.g., a targetlike fragment). This can be taken to be rather indirect evidence for the existence of a heavy reaction partner. Previous workers have used the peak of the fragment kinetic energy spectrum to estimate the effective Coulomb barrier and thus estimate the Z of the reaction partner.[9] The ^{7}Li inclusive spectra peak at approximately 20 MeV in the rest frame of the moving source. A simple estimate of the Coulomb barrier, $Z_1Z_2e^2/R_{12}$, where $R_{12}=1.4\ (A_1^{1/3}+A_2^{1/3})$, gives a value of $Z_2\approx 43$ for $Z_1=3$. For the purposes of this estimate, we have assumed that the large fragment has the same neutron to proton ratio as the Ag target, i.e., $Z_2=(47/108)A_2$. This value is consistent, though slightly larger than, that of the fragment remaining after removal of the source assumed to be present in the Saha equation.

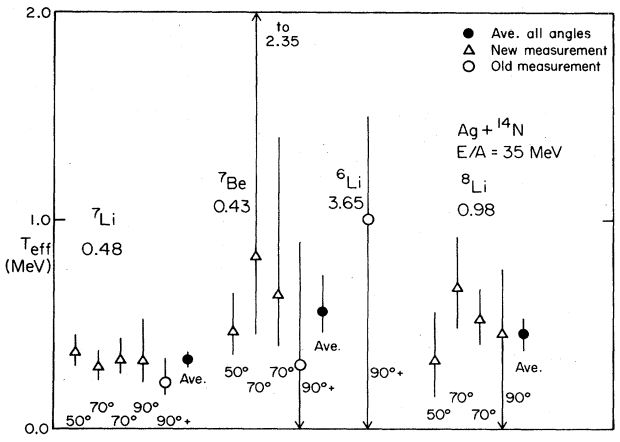

FIG. 10. Effective nuclear temperatures obtained from the excited state population in the present and the previous measurements (Ref. 2).

TABLE II. Gamma ray multiplicity distributions.

Isotope	Angle	$\langle M_\gamma \rangle$	σ
^{6}Li	50°	11.8	7.0
	70°	12.1	7.7
	90°	11.1	7.3
^{7}Li	50°	12.0	7.1
	70°	12.2	7.0
	90°	11.3	6.3
^{8}Li	50°	11.3	6.7
	70°	12.1	8.3
	90°	12.2	6.2
^{9}Li	50°	10.5	5.2
	70°	12.0	7.8
	90°	11	7
^{7}Be	50°	11.9	7.9
	70°	12.6	8.6
	90°	11.8	6.0
^{9}Be	50°	11.4	7.3
	70°	11.8	7.1
	90°	10.5	8.2
^{10}Be	50°	12.2	7.8
	70°	12.6	8.0
	90°	13	4

IV. DISCUSSION

We have observed excited state populations of light nuclei that are not consistent with the effective temperature implied by the analysis of kinetic energy spectra. The effective temperatures or slope parameters are, however, completely consistent with the systematic variation established by other workers. Thus, we must consider reasons why the two temperature determinations might give different results. Several possibilities are immediately apparent: the reaction may be a very complex multistep process in which equilibrium is never established and the concept of temperature is not relevant, final state interactions among the expanding ensemble of nucleons and nuclei may depopulate the excited states, or the lithium nuclei may be produced by the sequential decay of heavier nuclei produced in the primary reaction which would lead to a distribution governed by nuclear structure through sequential decay. Two somewhat different models that each consider one of these two possibilities will now briefly be discussed.

An important assumption of the "region of local equilibrium" is that the nucleons and complex fragments are emitted at the same time. The ensemble expands and at some point goes out of equilibrium. Boal has recognized[10] that the nucleons in the ensemble will interact with the complex fragments at times (or ranges) after the energy density (or alternatively the temperature) has dropped substantially. These final state interactions can have dramatic effects on the population distribution. However, the extent of the final state interactions will be very sensitive to the underlying nuclear structure and the numbers of interacting nucleons that are emitted with a given complex fragment and, of course, the time of emission relative to the fragment emission. Unfortunately, neither the times nor the associated multiplicities of the emitted particles are known. In an initial calculation, Boal used an unrealistically high associated multiplicity of 20 (estimated from unpublished values of the *inclusive* proton and alpha particle multiplicities) in order to predict the temperature at which lithium nuclei go out of equilibrium. The temperature value in this estimate was slightly higher than our results, which indicates the possible importance of final state interactions. The assumed associated multiplicity of 20 neutrons used by Boal seems to be too large, since production of each neutron requires an average energy of approximately $(kT+S_n)$ in the moving frame, where T is the temperature and S_n is the separation energy, thus requiring more energy than is available in the center of mass even before considering the energy of the lithium nucleus. Boal's model also predicts that the depopulation should depend on the kinetic energy of the complex fragments, as the high energy fragments should outrun the average nucleons. As the number of observed deexcitation γ rays was small, and the kinetic energy distributions are peaked at low values, we are only able to say that the present data do not appear to show a population that depends on fragment energy. The depopulation of the excited states by final state interactions must be present, and a more detailed calculation than that by Boal would be useful.

We have attempted to obtain a more quantitative estimate of the effect of the final state interactions which explicitly incorporates some of the general considerations mentioned above. In these estimates we have used a basically classical hydrodynamic description of the system with two fairly different sets of parameter values. Common to both estimates are the following: a nuclear equation of state; specification of the initial conditions—size and shape of the fireball, and its density and temperature profiles; law of heat transfer; formation and transport of composite particles (e.g., ^{7}Li in its ground and excited states); and microscopic cross sections for the interaction of composites with background nucleons (primarily excitation and deexcitation of the relevant state by inelastic scattering). There is obviously a wide variety of possible sets of assumptions, particularly in the absence of independent information about many of the physical parameters involved. We will describe the results obtained in cases which represent extremes as far as estimating the cooling effect of final state interactions.

The first picture, model I, may be referred to as a two-fluid model. The nuclear matter is described as a mixture of a nucleon fluid and a composite particle fluid. The latter is parasitic in the sense that it does not affect the temporal evolution of the density and is simply dragged along by the former. The nucleon matter is described as an ideal, noninteracting gas, and the initial density profile is a Gaussian,

$$\rho(r,t=0) \propto e^{-r^2/2\beta^2} , \tag{4}$$

with a uniform temperature T_0. The temperature $T(t)$ is assumed to be uniform at all times, which corresponds to infinitely fast heat diffusion. The composite particle fluid is completely described by a global temperature $T_c(t)$, which is coupled to $T(t)$ by the equation

$$\frac{d}{dt}(T_c-T)=\frac{1}{\tau}(T_c-T)=\langle n\sigma v\rangle(T_c-T) , \tag{5}$$

where $\langle n\sigma v\rangle$ represents averages of the local nucleon density n, relative thermal velocities v, and microscopic cross sections $\sigma(v)$. Thus this model is similar to that of Boal. It provides a well-defined algorithm for obtaining the asymptotic (observed) temperature of the composite particles. It clearly represents an overestimate of the magnitude of the effect, primarily because of the suppression of any relative motion between the two components and because of the total absence of temperature gradients.

A second picture, model II, may be called a hybrid one-fluid model. A semirealistic equation of state is utilized in which a parabolic zero-temperature isotherm is included in addition to thermal energy. The system is assumed to be initially at a uniform density ρ_0, and at uniform temperature T_0. Heat diffusion is totally neglected, and the composite particles are again present from the outset and play a parasitic role in the hydrodynamic evolution of the system. Typically, at time t, such that $t<R_0/V_S$, where R_0 is the initial radius and V_s the sound velocity, the system will not have completely disintegrated yet. It will be composed of an unperturbed central region of radius $R(t)$, for which

$$\rho(r,t)=\rho_0, \quad T(r,t)=T_0 \ [r<R(t)] \tag{6}$$

along with an expanding, cooling corona, where [for $r>R(t)$] $T(r,t)$ and $\rho(r,t)$ are monotonically decreasing functions of r. We now assume that the composite particles [e.g., ^{7} Li(g.s.) and ^{7}Li*] are emitted from the central region (with the appropriate temperature-dependent ratio). This ratio is modified by interactions in the corona by averaging over the time of emission, and the emission probability per unit time is taken to be proportional to the surface area of the central region at any given time. Model II, by limiting the cooling to the corona region, is less efficient because of the relative translation between the two interacting hot components.

Figure 11 shows the calculated observable temperature T_{obs} as a function of the initial temperature T_0 for both models using the same microscopic input as Boal[10] ($\sigma=500$ mb for inelastic scattering on the ^{7}Li excited state), and taking the initial fireball to be $A=30$. The straight line where $T_{obs}=T_0$ is included in this figure for reference. Thus, we would predict that the initial lithium population distribution for 12 MeV would be modified (cooled) to the extent that it would appear to have been produced at temperatures between 1.2 and 4.5 MeV. The experimental results are, of course, still much lower than this, e.g., approximately 0.3 MeV.

From a very different starting point, Stöcker has developed a quantum-statistical model[11] of the decay of a hot zone of nuclear matter which partitions the thermal energy among those nuclear ground and excited states with mass numbers between 1 and 40. The thermal zone is characterized by a temperature (or equivalently an entropy) and a size. The quantum statistical model also includes production of the final nuclei by the decay of unbound levels after the partition. The calculated fraction of the ^{7}Li nuclei in their excited state is shown as a function of temperature in Fig. 12. This calculation is identical to Ref. 11 except that the details of the decay properties of the unbound ^{8}Li states were taken into account. The function for the primary distribution looks very similar to that in Fig. 1, since the underlying physics is the same. However, when the decay of ^{8}Li excited states via neutron emission is taken into account, the secondary function can be significantly different from the primary function (e.g., temperatures above 1.5 MeV). The prediction of this model for a temperature of 12 MeV, $f=0.2$ for ^{7}Li, is quite a bit larger than the results of the present experiment. It would be very interesting to extend these calculations to include the decay of unbound levels in nuclei other than ^{8}Li. The differences in the temperatures obtained from the various Li and Be isotopes might be related to this sequential feeding mechanism.

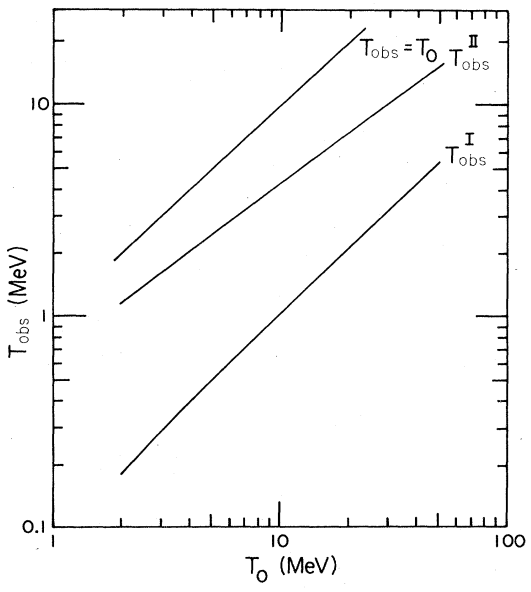

FIG. 11. The calculated observable temperature for the excited state of the ^{7}Li after final state interactions as a function of initial temperature, T_0. The two model curves correspond to extreme pictures of the cooling process and may be regarded as upper and lower limit estimates; see the text.

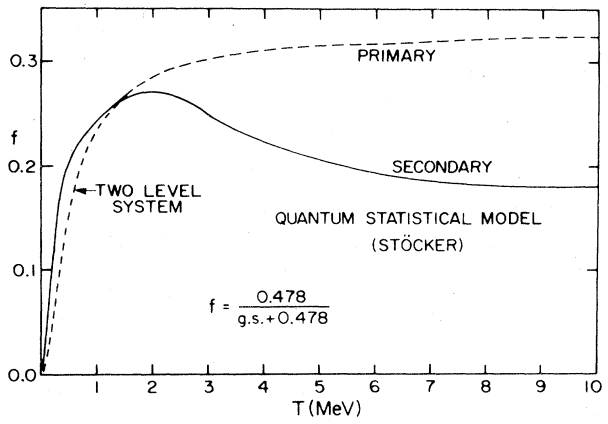

FIG. 12. The fraction of ^{7}Li nuclei in the excited state as a function of temperature in the quantum statistical model (Ref. 7), see the text.

An important feature of this latter model of the complex fragment production is that a sizable fraction of the free nucleons is emitted by the sequential decay of the particle-unstable states and therefore could not take part in the final state interactions suggested by Boal. The process described in Stöker's model must contribute to the yield of fragments and nucleons in these reactions, but calculations which take into account the specific nuclear structure of each decaying level may not be feasible.

V. CONCLUSION

The main purpose of the present experiment was to verify the very low excited state production observed in a previous experiment.[2] The present results have much better precision, and an additional nucleus was studied. The conclusion is the same, namely that the fraction of nuclei in excited states is substantially smaller than expected from models of the reaction which assume equilibrium. Two proposed models which would help to explain the effect and still maintain equilibrium are dis-

cussed and are shown to be inadequate. Therefore, at present the most likely explanation for the low excited state production seems to be a failure of the assumption of thermal equilibrium, at least for this specific reaction. In the future more redefined models of the reaction mechanism will need to predict this new measurable quantity, the excited state production, as well as the energy spectra and angular distributions of fragments produced in the reaction.

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