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We discuss results from a new technique for the determation of the temperature of the source of lithium and beryllium fragments produced in nuclear reactions. The technique relies on the variation of the production of the excited states of the nuclei relative to each ground state as a function of temperature. We show that the population of the ground and excited states of ^{7}Be fragments from the reaction of 8 MeV/A ^{14}N with C are consistent with thermal equilibrium emission from the compound nucleus and thereby verify the plausibility of the technique. The technique was extended to the production of lithium and beryllium fragments from the reaction of 35 MeV/A ^{14}N with Ag. The fraction of nuclei produced in excited states was quite small in this reaction, indicative of a low temperature. The idea that the lithium and beryllium fragments are produced in an equilibrated thermal zone in the 35 MeV/A reaction is thus not supported.

1. INTRODUCTION

Many contributors to this conference have used the phrase "nuclear temperature" at some point in their presentation and in doing so implied the production of nuclear matter with some internal thermal energy which is in a state of equilibrium. The equilibrium should extend over all the degrees of freedom of the nuclear matter, and the observation of a consistent "temperature" among these various degrees of freedom would be a clear signal of the equilibrium. Until recently searches for the production of hot zones of nuclear matter have relied on the temperature as signaled by Maxwell-Boltzmann velocity distributions, i.e., thermalization of kinetic energy degrees of freedom. By extension, we expect that the isotopic distributions of fragments produced by such thermal matter should also be indicative of the temperature through their Q-value dependence, sometimes called chemical equilibrium, and that excited states of any nuclear fragments should also be populated in accordance with the temperature. It is this latter point, thermal production of nuclear excited states,[1,2] that will be the subject of this talk.

The distribution of fragments among their excited states emitted from a system in thermal equilibrium depends on the temperature of the system and the energy level spacing. For a two level system at constant volume the ratio of the populations 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 the statistical weights of the states and by any feeding from higher lying states that γ-ray decay and from more massive nuclei that particle decay. Such decays can have a significant effect on the population distribution and, in general, depend on nonstatistical nuclear structure effects. The A=7 nuclei are particularly good probes of statistical equilibrium because they each have only one excited state which decays by γ-ray emission, the spins of which are $^1/_2$ and therefore emit γ-rays isotropically, and the nuclei have somewhat different feeding from unbound levels in higher mass nuclei.

In the simplest picture of emission of these nuclei in thermal equilibrium with no feeding by particle decay, the ratio, R, of the populations of two states is:

$$R = \frac{(2\, j_{EX} + 1)}{(2\, j_{GS} + 1)}\; e^{-\Delta E/kT} \qquad (1)$$

where j_{GS} and j_{EX} are the spins of the ground and excited states, respectively, ΔE is the energy spacing between the states and kT is the nuclear temperature. This ratio is not directly measurable because the lifetimes of the γ-ray emitting states are short. However, the <u>fraction</u> of the observed nuclei that emit γ-rays, $f=R/(1+R)$, can be obtained from particle-γ-ray coincidence measurements. The variation of this fraction with temperature can be seen, for example, in figure 1 of reference 1.

The production of light nuclei in their ground and excited states was studied in a low energy reaction, ^{14}N + C at 112 MeV, and in an intermediate energy reaction, 490 MeV ^{14}N + Ag. The former case was been well studied and approximately half of the reaction cross section is known to go into the compound nucleus channel, a large fraction of which goes to formation of lithium and beryllium nuclei, as discussed in references 3 and 4. Thus, studying the ^{14}N plus ^{12}C reaction will allow us to check the validity of the technique, and by studying the higher energy reaction we can test for thermal equilibrium in the emitting source.

2. EXPERIMENTAL

Our measurements of the fractions of nuclei in excited states were performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The fractions were determined by a comparison of the γ-ray coincidence counting rate to the inclusive counting rate of each nucleus. The details of the experimental arrangement have been presented in references 1 and 2. Briefly, the light nuclei were completely identified, Z, A and kinetic energy, in one of a set of four Si surface barrier detectors (ΔE 50 or 100μm thick and E 1000μm thick) and the γ-rays were detected in a set of eight 7.6 x 7.6 cm NaI(Tl) detectors. The solid angle of each particle detector was generally 25 msr, and the photopeak efficiency of the γ-ray array was 4.5 percent. As the fraction depends on the ratio of the counting rates, it only depends on the value of the coincidence efficiency of the γ-ray detector array.

3. RESULTS and DISCUSSION

3.1 ^{14}N + ^{12}C Reaction

Lithium, beryllium and boron nuclei were detected at eight angles ranging from 30° to 65° in 5° steps. The inclusive kinetic energy spectra, shown in figure 1, are generally exponential in shape. As a preliminary test for emission from the compound nucleus we fitted the kinetic energy spectra for each isotope to those expected from a single moving source. Such a fit has three independent parameters, the source velocity and temperature and the total cross section. The beta of the source with the lowest chi-squared value (0.071 to 0.075, depending on isotope) agreed very well with that of the compound nucleus (0.0718). The optimum temperature was lower (ranging from 3.1 to 3.4 MeV) than that expected for a degenerate Fermi gas (approximately 4.7 MeV for ^{26}Al). However, the fits to the ^{7}Li kinetic energy spectra were remarkably poorer than those to the other isotopes. For example, the shapes of the spectra at 30° and 35° were much flatter than those predicted by a single source model. This indicates that the ^{7}Li fragments are produced by more than one reaction mechanism and, in addition, the misidentification of the double alpha decay products from ^{8}Be as ^{7}Li fragments.

The fractions of ^{7}Li and ^{7}Be nuclei in their excited states were found to be approximately 0.04±0.01 and 0.28±0.05, respectively, over the angular range of 35° to 60°. The fractions were slightly lower at 30°. This indicates that the

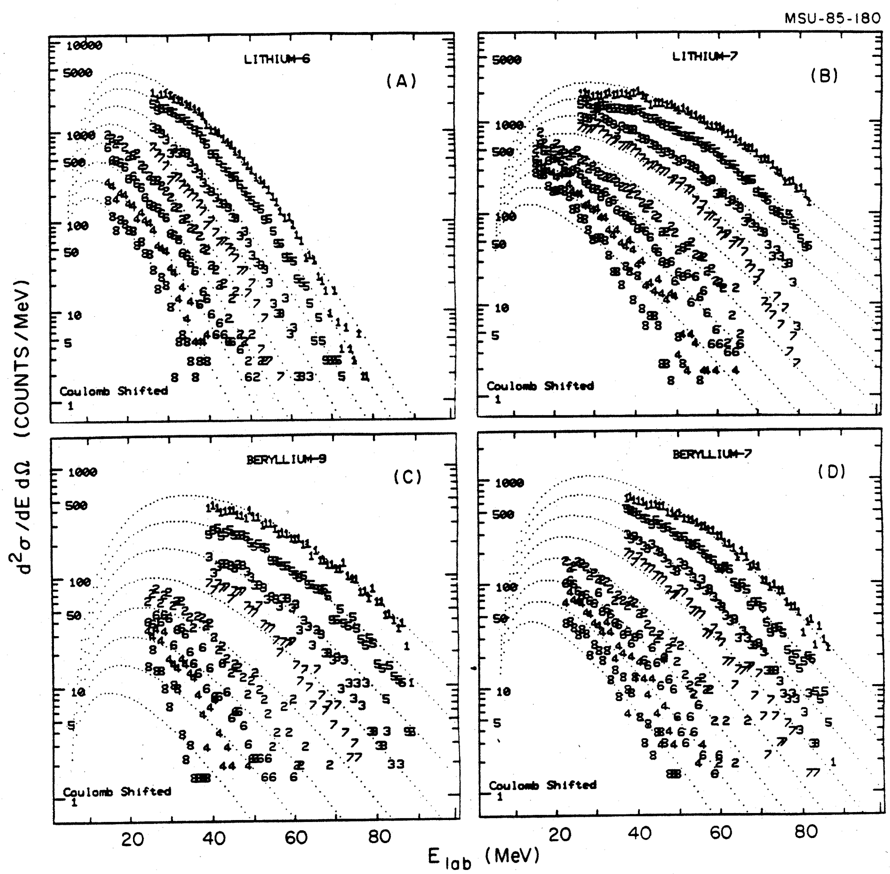

Fig. 1 Inclusive cross sections from the reaction of 112 MeV ^{14}N + C.

population of the excited state of ^{7}Be is approximately saturated as expected for a temperature of 4 MeV (the infinite temperature limit of f is 1/3). However, the population of the ^{7}Li excited state is well below the expected saturated value. This supports the analysis of the inclusive data in which the ^{7}Li data are not consistent with production exclusively by the compound nucleus mechanism.

3.2 ^{14}N + Ag Reaction

The lithium and beryllium fragments for the reaction of 490 MeV ^{14}N (35 MeV/A) with Ag were measured at 50°, 70° and 90°. An analysis of these inclusive kinetic energy spectra in terms of a single moving source of emission indicated a temperature of 12±2 MeV and a source velocity of 2.2±0.3 cm/ns. These values are completely consistent with similar analyses of inclusive data of this type[5].

However, in this reaction the fraction of ^{7}Li and ^{7}Be products in their excited states were approximately 0.11 and 0.20, respectively, again independent of angle. The temperatures that would correspond to these values in the limit of no feeding by particle decay are shown in figure 2. Additional results from measurements of the excited states of ^{6}Li and ^{8}Li are included in the figure. We note the small difference in the results between ^{7}Li and the others which could be due to different particle decay feeding or the miss identification of ^{8}Be.

Models have been proposed to explain these low apparent temperatures based on either thermodynamic equilibrium during the expansion of the zone of emission[6] or by perturbation of the populations by particle decay among the members of the initial thermodynamical equilibrium ensemble[7]. Neither model is able to completely explain our results. Unfortunately, we do not have the space to describe the models in any detail, and we refer the reader to more complete discussions of the comparison of the model results to our data in reference 2.

4. CONCLUSIONS

We have proposed and tested a new technique for measuring the temperature of

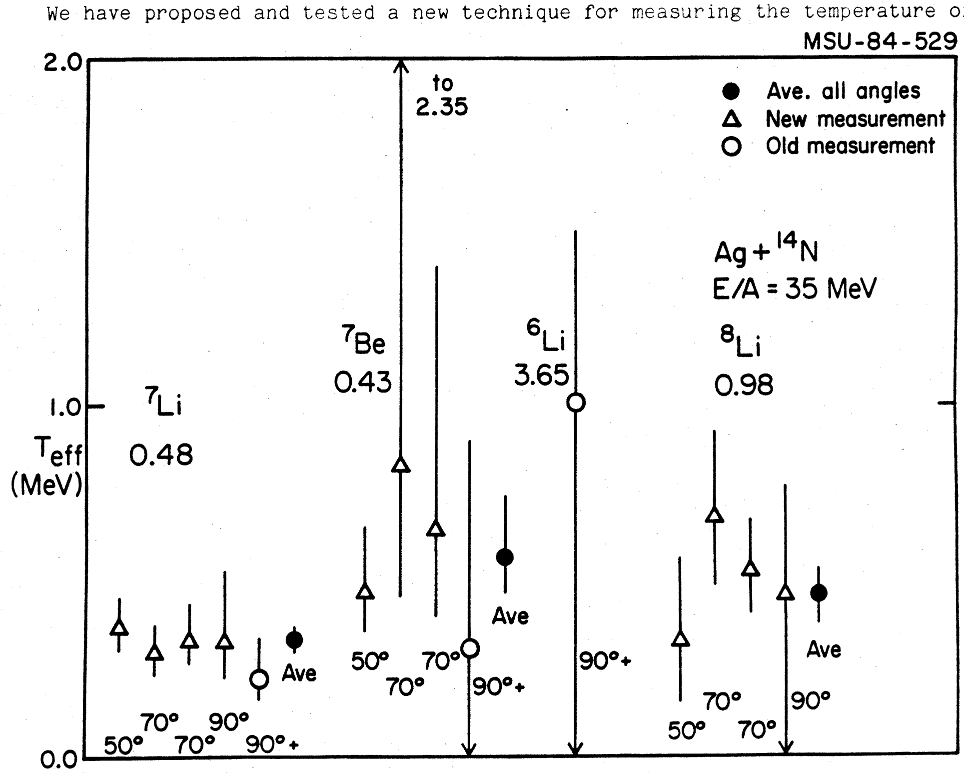

Fig. 2 Calculated temperature of fragments from the reaction of 490 MeV ^{14}N + Ag. The old and new measurements are references 1 and 2.

a nuclear system which relies on the populations of the ground and excited states of emitted nuclei. We have shown that the populations of ^{7}Be nuclei emitted in their ground and excited states from the reaction of 112 MeV ^{14}N + C are consistent with thermal equilibrium. However, neither the kinetic energy spectra nor the populations of ^{7}Li nuclei emitted from the same system were consistent with thermal equilibrium. We also observed the relative populations of thA states of these nuclei emitted from the reaction of 490 MeV ^{14}N + Ag. In this case the production of all the excited states was low in comparison to the "temperature" evidenced in the kinetic energy spectra.

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