EMISSION TEMPERATURES IN INTERMEDIATE ENERGY NUCLEAR COLLISIONS FROM THE RELATIVE POPULATIONS OF WIDELY SEPARATED STATES IN ^{5}Li AND ^{8}Be ☆

J. POCHODZALLA[1,2], W.A. FRIEDMAN[3], C.K. GELBKE, W.G. LYNCH, M. MAIER
National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

D. ARDOUIN, H. DELAGRANGE, H. DOUBRE, C. GRÉGOIRE, A. KYANOWSKI, W. MITTIG, A. PÉGHAIRE, J. PÉTER, F. SAINT-LAURENT, Y.P. VIYOGI[4], B. ZWIEGLINSKI[5]
Laboratoire GANIL, BP 5027, 14021 Caen Cedex, France

G. BIZARD, F. LEFÈBVRES, B. TAMAIN
Laboratoire de Physique Corpusculaire, Université de Caen, 14032 Caen Cedex, France

and

J. QUÉBERT
Centre d'Études Nucléaires de Bordeaux, 33170 Gradignan Cedex, France

Received 26 June 1985

Light particle correlations at small relative momenta were measured for ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV. The relative populations of widely separated states of ^{5}Li and ^{8}Be suggest mean nuclear temperatures at emission of about 5 MeV.

Statistical models have successfully described the emission of complex particles in intermediate and high energy nucleus–nucleus collisions [1–5]. In several of these models, the concept of temperature plays a central role; the experimental determination of this quantity is clearly important.

Most attempts to extract temperatures are based on analyses of the kinetic energy spectra of the emitted particles [6]. The interpretation of such spectra may, however, be complicated by additional sensitivities to the collective motion [7] and the temporal evolution of the emitting system [4,5,8].

An alternative determination of the "emission temperature", i.e. the temperature at the point at which the particles leave the equilibrated subsystem, is based on the relative population of states. First particle–γ-coincidence measurements [9,10] of the population of excited states in Li and Be nuclei were performed for ^{14}N induced reactions on ^{197}Au at $E/A = 35$ MeV. These measurements investigated the population of states at rather low

☆ Experiment performed at Laboratoire National GANIL.
[1] DFG fellow.
[2] On leave from the Max-Planck-Institut für Kernphysik, Heidelberg, West Germany.
[3] Permanent address: Department of Physics, University of Wisconsin, Madison, WI 53706, USA.
[4] Permanent address: Bhabha Atomic Research Center, Calcutta, India.
[5] Permanent address: Institute for Nuclear Science, Warsaw, Poland.

0370-2693/85/$ 03.30

excitation energy; they were interpreted in terms of surprisingly low emission temperatures, $T \leqslant 1$ MeV. However, feeding from higher lying particle unstable states and neutron induced deexcitations may make this temperature determination inaccurate [9–12]. Recently, the relative populations of particle unbound states in ^{6}Li, separated by a few MeV excitation energy, were measured for ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV via particle correlation techniques [12]. These results were consistent with higher emission temperatures, $T \approx 5$ MeV, but could not exclude substantially higher values because of possible interactions after emission [12].

More accurate determinations of the emission temperature can be made by measuring the relative populations of states separated by significantly larger energy intervals. In this letter we present the first quantitative temperature measurement based on the relative populations of states separated by energy intervals of the order of about 15 MeV. Specifically, we have measured the population of states in ^{5}Li and ^{8}Be for ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV. These states are separated by 16.7 and 14.6 MeV, respectively. Although the population of these states is clearly established, the population ratios indicate relatively low temperatures of 4–5 MeV as compared to the value of about 20 MeV characterising the kinetic energy spectra of the emitted particles [13].

The experiment was performed at the Laboratoire GANIL at Caen. A gold target of 10 mg/cm^2 areal density was irradiated by a beam of ^{40}Ar of $E/A = 60$ MeV incident energy. Light particles ($Z \leqslant 3$) were detected by a close packed hexagonal array of 13 $\Delta E - E$ telescopes, each consisting of a 400 μm thick Si detector and a 10 cm thick NaI detector. The center of the hodoscope was positioned at a laboratory angle of 30°. Each telescope subtended a solid angle of 0.46 msr; the angular separation between adjacent telescopes was 4.2°. The energy calibrations of the hodoscope, established for all isotopes with $Z \leqslant 3$, are accurate to within 2%.

We present our data in terms of the correlation function, $R(q)$, which is defined in terms of the singles yields, $Y_1(\boldsymbol{p}_1)$ and $Y_2(\boldsymbol{p}_2)$, and the coincidence yields, $Y_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2)$:

$$Y_{12}(\boldsymbol{p}_1, \boldsymbol{p}_2) = C_{12} Y_1(\boldsymbol{p}_1) Y_2(\boldsymbol{p}_2)[1 + R(q)]. \quad (1)$$

Here, $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ are the laboratory momenta for particles 1 and 2; q is the momentum of relative motion between the two coincident particles; C_{12} is a normalisation constant which was determined by requiring $R(q) = 0$ for large relative momenta. The experimental correlation functions were

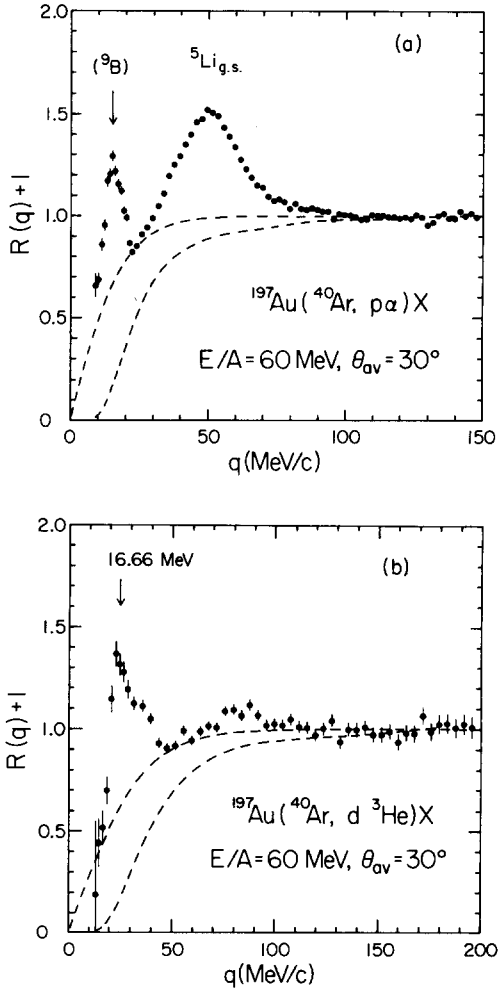

Fig. 1. Correlation functions for coincident protons and alpha particles (a) and coincident deuterons and ^{3}He nuclei (b) measured for ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV. The dashed lines indicate the extremes within which the background correlation functions were assumed to lie.

obtained by inserting the measured cross sections into eq. (1) and summing both sides of the equation over all energies and angles corresponding to a given momentum q.

Figs. 1 and 2 show the measured p–α, d–^{3}He, α–α, and p–^{7}Li correlation functions, respectively. The p–α correlation function, shown in fig. 1a,

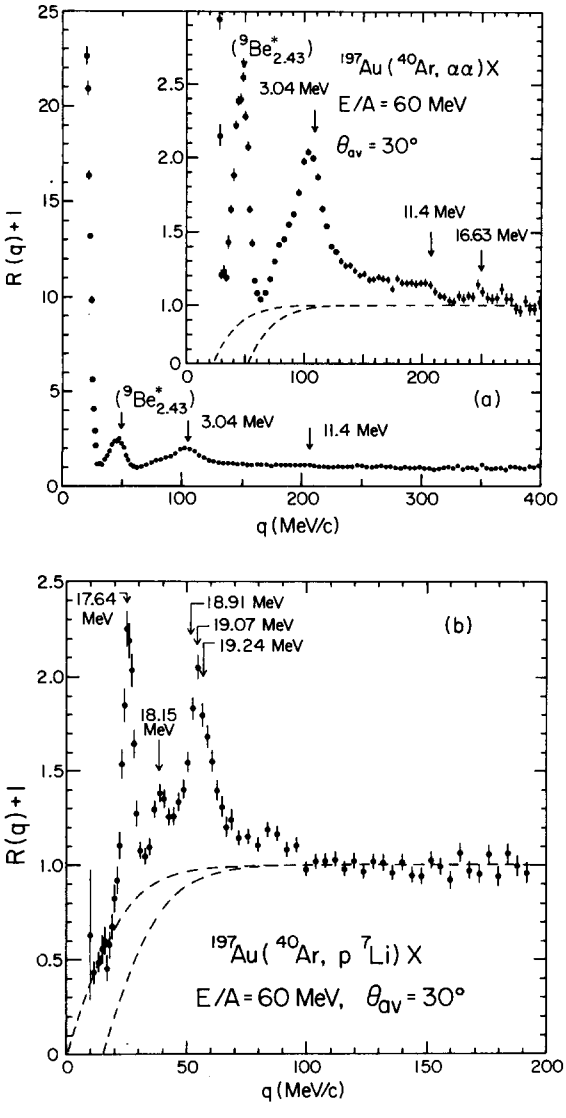

Fig. 2. Correlation functions for coincident alpha particles (a) and coincident protons and ^{7}Li nuclei (b) measured for ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV. The dashed lines indicate the extremes within which the background correlation functions were assumed to lie.

exhibits two peaks which have been identified [14] as due to the decay of the particle unstable ground states of ^{9}B and ^{5}Li. The ground state [15] of ^{5}Li ($J^\pi = \frac{3}{2}^-$, $\Gamma \approx 1.5$ MeV, $\Gamma_p/\Gamma_{tot} = 1.00$) will be used in our analysis. The most pronounced peak in the d–^{3}He correlation function, shown in fig. 1b, corresponds to the decay of the 16.66 MeV state [15] in ^{5}Li ($J^\pi = \frac{3}{2}^+$, $\Gamma \approx 0.3$ MeV, $\Gamma_d/\Gamma_{tot} = 0.86$). The α–α correlation function, shown in fig. 2a, shows the tail of the peak resulting from the decay of the particle unstable ground state of ^{8}Be. The structure at $q \approx 50$ MeV/c is caused by the decay of ^{9}Be$^*_{2.43}$[14], the structure at $q \approx 105$ MeV/c is caused by the decay of the 3.04 MeV state [15] in ^{8}Be ($J^\pi = 2^+$, $\Gamma = 1.5$ MeV, $\Gamma_\alpha/\Gamma_{tot} = 1.00$); this peak will be used in our analysis. The p–^{7}Li correlation function, shown in fig. 2b, exhibits several sharp structures resulting from the decay of high lying states in ^{8}Be. For our analysis we will use the first peak which corresponds to the decay of the 17.64 MeV state [15] in ^{8}Be ($J^\pi = 1^+$, $\Gamma = 0.01$ MeV, $\Gamma_p/\Gamma_{tot} = 1.00$).

The coincidence yield, Y_c, corresponding to the decay of a given particle unstable isotope was extracted by assuming that the total coincidence yield, Y_{12}, is given by: $Y_{12} = Y_c + Y_b$, where Y_b denotes the "background" yield. In our analysis, we have described this background yield in terms of the background correlation function $R_b(q)$:

$$Y_b(q) = C_{12} Y_1(\boldsymbol{p}_1) Y_2(\boldsymbol{p}_2)[1 + R_b(q)].$$

The background correlation functions were assumed to lie within the extremes indicated by the dashed lines in figs. 1 and 2.

The decay coincidence yields Y_c were calculated for each decay channel according to the equation

$$Y_c(E^*, T) = \int \mathrm{d}E \left[\varepsilon_c(E^*, E)\rho_c(E)\mathrm{e}^{-E/T}\right], \quad (2)$$

where E and E^* denote the actual and measured excitation energies of the decaying parent nucleus, respectively; T is the emission temperature, $\varepsilon_c(E^*, E)$ is the efficiency function of the hodoscope for the detection of the specific decay channel, and

$$\rho_c(E) = \sum \frac{(2J_i + 1)\Gamma_i/2\pi}{(E - E_i)^2 + \Gamma_i^2/4} \frac{\Gamma_{c,i}}{\Gamma_i}. \quad (3)$$

The sum in eq. (3) includes the relevant resonances characterised by the excitation energies E_i, the widths Γ_i, and the branching ratios $\Gamma_{c,i}/\Gamma_i$. Penetrability effects were included. The efficiency functions, $\varepsilon_c(E^*, E)$, were calculated for the precise geometry, detection thresholds and energy resolution of the experiment. In these calculations, each resonance was assumed to decay isotropically in its center-of-mass frame. The laboratory energy spectra and angular distributions of the parent states were parameterised with simple analytic functions which had been used previously to describe the measured energy spectra and angular distributions of particle stable ^{6}Li and ^{7}Li nuclei [12]. Calculated yield ratios for two resonances of a given isotope were found to be rather insensitive to the specific choice of parameterisation.

To determine the relative populations of the four particle unstable resonances, $^5\mathrm{Li}_{0.0} \rightarrow \alpha + \mathrm{p}$, $^5\mathrm{Li}_{16.7} \rightarrow \mathrm{d} + {}^3\mathrm{He}$, $^8\mathrm{Be}_{3.04} \rightarrow 2\alpha$, $^8\mathrm{Be}_{17.6} \rightarrow \mathrm{p} + {}^7\mathrm{Li}$, the calculated decay yields were integrated over the range of excitation energy for which the coincidence yields were dominated by these respective decays. The corresponding integrals were performed for the experimental decay yields. The integrals over the two states at low and high excitation energies for a given particle unstable nucleus are denoted by $N_L(T)$ and $N_H(T)$, respectively. The functional dependence of the calculated yield ratios N_L/N_H for particle unstable ^{5}Li and ^{8}Be nuclei is shown by the solid lines in fig. 3. The hatched regions in the figure indicate the range of yield ratios and emission temperatures which are consistent with the extreme background assumptions shown in figs. 1 and 2. The relative populations of states in ^{5}Li and ^{8}Be correspond to emission temperatures of $T = 4.6 \pm 0.7$ MeV and $T = 4.2 \pm 0.5$ MeV, respectively. (It should be stressed that the uncertainties are *not* statistical; they result directly from our rather conservative estimates of the uncertainties of the background.) These temperatures are consistent with the results of our recent analysis of the α–d coincidence spectrum [12]. At the same time, they are considerably lower than the temperature parameters of about 20 MeV which characterise the kinetic energy spectra of the emitted particles. The large energy spacing between the states at low

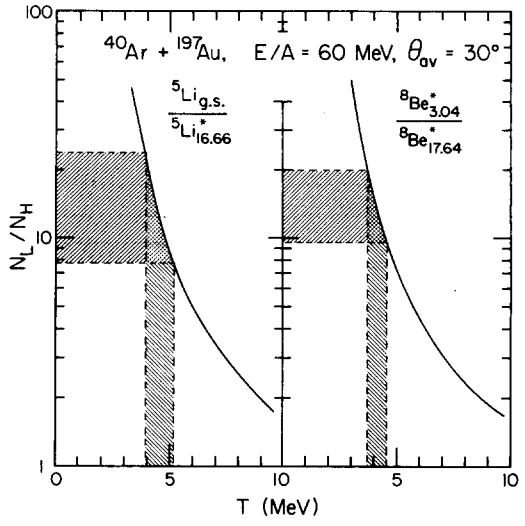

Fig. 3. Yield ratios N_L/N_H corresponding to the decays of ^{5}Li and ^{8}Be nuclei. The solid curves show the calculated ratios as a function of the emission temperature and the hatched regions indicate the range of values consistent with our assumptions for the background coincidence cross sections.

and high excitation energy ensures that the extracted temperatures are relatively insensitive to the effects of sequential decay. Thus both significantly higher and lower emission temperatures are precluded.

Our experiment clearly establishes the emission of complex nuclei in highly excited particle unstable states. For ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV, the populations of high lying states in ^{5}Li and ^{8}Be indicate emission temperatures of about 4–5 MeV. These values are consistent with a recent analysis of the α–d coincidence spectrum, but considerably lower than the temperature parameters which characterise the kinetic energy spectra of particles emitted in ^{40}Ar induced reactions on ^{197}Au at $E/A = 60$ MeV. Future theoretical treatment of the disintegration of highly excited nuclear matter will be required to quantitatively explain this low emission temperature.

This paper is based upon work supported by the National Science Foundation under grants PHY 83-12245 and PHY 84-01845, and by the Centre National de la Recherche Scientifique under contract DRCI-AI No. 49.85.22.

References

[1] G.D. Westfall et al., Phys. Rev. Lett. 37 (1976) 1202.
[2] J. Gosset et al., Phys. Rev. C18 (1978) 844.
[3] J. Knoll, Phys. Rev. C20 (1979) 773.
[4] W.A. Friedman and W.G. Lynch, Phys. Rev. C28 (1983) 16.
[5] D.J. Fields et al., Phys. Rev. C30 (1984) 1912.
[6] G.D. Westfall et al., Phys. Lett. 116B (1982) 118.
[7] P.J. Siemens and J.O. Rasmussen, Phys. Rev. Lett. 42 (1979) 880.
[8] H. Stöcker et al., Z. Phys. A303 (1981) 259.
[9] D.J. Morrissey et al., Phys. Lett. 148B (1984) 423.
[10] D.J. Morrissey et al., Michigan State University preprint MSUCL-517 (1985), and to be published.
[11] D.H. Boal, Phys. Rev. C30 (1984) 749.
[12] J. Pochodzalla et al., Michigan State University preprint MSUCL-518 (1985), and to be published.
[13] B.V. Jacak et al., Phys. Rev. Lett. 54 (1983) 1846.
[14] J. Pochodzalla et al., to be published.
[15] F. Ajzenberg-Selove, Nucl. Phys. A413 (1985) 302.