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Relative Population of States and Extraction of Emission Temperature in 25 MeV/u ^{40}Ar+^{197}Au

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Two-particle correlations at small relative momenta have been measured for ^{40}Ar induced reactions on ^{197}Au at $E/A = 25$ MeV. The relative populations of states of ^{4}He and ^{8}Be were extracted from p-t and α-α correlation functions, respectively. The temperature of $T = 3.5\pm^{1.3}_{0.8}$ MeV was obtained from relative populations of ^{8}Be states by correcting sequential decay carefully, and the temperature of $T = 3.6 \pm 0.4$ MeV was deduced by modifying the sequential decay yield with 30% on ^{4}He$_{g.s.}$ ground state.

Key words: correlation functions, population of state, emission temperature.

1. INTRODUCTION

In intermediate-energy nucleus-nucleus collisions, a statistical model successfully describes the decay of the compound nucleus. Temperature is a basic quantity in the statistical model. It is important to determine the temperature experimentally. Most attempts to obtain experimental information about the temperature of excited nuclear systems were based on analyses of the kinetic energy spectra of the emitted particles. In the intermediate-energy region the particles are emitted from several sources, and the measurement of their temperature by the usual method could produce large uncertainties; therefore the emitting source must be selected by coincident measurement.

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An alternative determination of the temperature is based on the relative population of states. The complex particles mainly come from the evaporation of a highly excited system [1]. The investigation of such particles may provide detailed information about highly excited nuclear systems. The emission temperature can be determined from the relative population of states if the highly excited system and the emitting subsystem reach nearly to kinetic equilibrium and chemical equilibrium. The emission temperature is the temperature of the equilibrium system when the particles leave it.

2. EXPERIMENTAL DETAILS

The experiment was performed at the Heavy Ion Research Facility of Lanzhou of IMP. A gold target of 1.42 mg/cm^2 was irradiated by ^{40}Ar beam with $E/A = 25$ MeV incident energy. Light particles ($Z \leq 4$) were detected by a close-packed hexagonal array of thirteen ΔE-E telescopes, each of which consisted of a 300-μm-thick silicon detector and a 5-cm-thick BGO scintillator. The detectors were located at a distance of 58 cm from the target; the center of the horoscope was positioned at a laboratory angle of $\theta_{\text{av}} = 20°$. The angular separation between adjacent telescopes was $\Delta\theta = 3.5°$; the maximum relative angle was 13.6°. The energy calibration of the BGO scintillator was deduced by energy loss of the particle passing through the ΔE silicon detectors [3].

Gain shifts of the photomultiplier tubes were corrected by using the high stability of the ΔE silicon detectors. To correct the gain shifts, the raw data were sorted into two-dimensional ΔE-E matrices. Several narrow gates were set on the ΔE axis. Events that fell into these gates were projected onto the E axis. Several peaks, corresponding to different types of particles, were obtained for each gate. Each of these peaks was fitted with a Gaussian function to determine the peak location, P_{i}. The relative gain shift parameter, ξ, was then determined with respect to the calibration run by minimizing the function $f(\xi)$.

$$f(\xi) = \sum_{\text{i}} (\xi P_{\text{i}} - P_{0\text{i}})^2 / P_{0\text{i}}^2, \tag{1}$$

Here, the peak locations determined for the calibration run are denoted by $P_{0\text{i}}$. Coincidence and down-scaled singles events were written on magnetic tape. In the off-line analysis, thresholds of 8, 13, 15, and 24 MeV were used for p, d, t, and ^{4}He, respectively.

3. CORRELATION FUNCTIONS

The two-particle correlation function $R(q)$ is defined as

$$\Sigma Y_{12}(p_1, p_2) = C_{12}[1 + R(q)] \Sigma Y_1(p_1) Y_2(p_2), \tag{2}$$

Here, $Y_{12}(p_1, p_2)$ is the coincidence yield, $Y_1(p_1)$ and $Y_2(p_2)$ are the single-particle yields; p_1 and p_2 are the laboratory momenta of the two particles; $q = |\mu(p_2/m_2 - p_1/m_1)|$ is the momentum of relative motion, μ is the reduced mass; C_{12} is a normalization constant determined by the requirement that $R(q)=0$ for large relative momenta. The sums on both sides of Eq. (2) were extended over all energy and detector combinations corresponding to the given bins of q.

Fig. 1(a) shows the measured α-α correlation function. The correlation function is dominated by the decay of the particle unstable ground state of ^{8}Be($J^\pi = 0^+$, $\Gamma = 6.8$eV, $\Gamma_\alpha/\Gamma = 1.00$). The peak at $q \approx 105$ MeV/c corresponds to the decay of the 3.04 MeV state in ^{8}Be($J^\pi = 2^+$, $\Gamma = 1.5$ MeV, $\Gamma_\alpha/\Gamma = 1.00$). The peak at $q \approx 50$ MeV/c is due to the sequential decay of the 2.43 MeV state in ^{9}Be [2].

The p-t correlation function, shown in Fig. 1(b), exhibits two maxima, corresponding to the decay of the 20.21 MeV state [4] ($J^\pi = 0^+$, $\Gamma = 0.5$ MeV, $\Gamma_\alpha/\Gamma = 1.00$) and the overlapping decay of the $J^\pi = 0^-$ and 2^- states at 20.01 MeV and 21.84 MeV in ^{4}He, respectively.

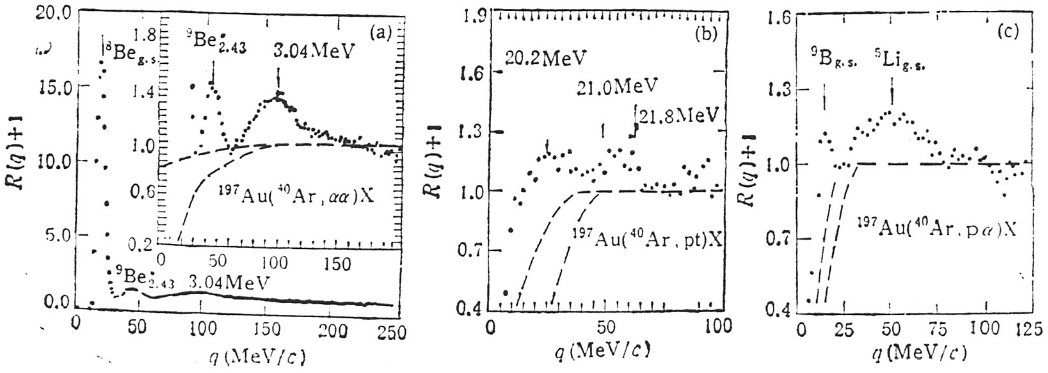

Fig. 1

(a) α-α correlation function. (b) p-t correlation function. (c) p-α correlation function. The dashed lines stand for the background correlation function.

Fig. 1(c) shows the p-α correlation function. The peak at $q \approx 16$ MeV/c is produced by the decay of the particle unstable ground state [5] of ^{9}B($J^\pi=3^-/2$, $\Gamma=0.54$keV, $\Gamma_\alpha/\Gamma=1.00$), $^9\mathrm{B}_{g.s.} \to p + {}^8\mathrm{Be}_{g.s.} \to p + \alpha + \alpha$. The broad peak near $q \approx 50$ MeV/c is related to the unbound ground state of ^{5} Li. The first peak was used to extract the yield of $^9\mathrm{B}_{g.s.}$

4. RELATIVE POPULATIONS OF PARTICLE STATES AND EMISSION TEMPERATURES

The coincidence yield, Y_{12}, is assumed to be given by two terms, $Y_{12} = Y_c + Y_b$. Y_c is the decay yield of particle unstable states. Y_b is the yield of background, which is determined by the background correlation function $R_b(q)$.

$$Y_b(q) = C_{12}\sum Y_1(p_1)Y_2(p_2)[1 + R_b(q)], \tag{3}$$

Since there is no satisfactory method to determine the background correlation function experimentally, the dashed cures in Figs. 1(a–c) indicate the empirical maximum and minimum limits of the background correlation functions.

The yield of particle unstable states is

$$Y_c(q) = Y_{12}(q) - Y_b(q) = C_{12}[R(q) - R_b(q)]\sum Y_1(p_1)Y_2(p_2), \tag{4}$$

The theoretical coincidence decay due to the yield of particle unstable states is

$$Y_c(T) = \int dE[\varepsilon_c(E)\rho_c(E)e^{-E/T}], \tag{5}$$

Here, E is the excitation energy of decay particle; T is the emission temperature; $\varepsilon_c(E)$ is the efficiency function of the horoscope for this decay channel. The expression of $\rho_c(E)$ is

$$\rho_c(E) = \sum_i \frac{(2J_i + 1)\Gamma_i/2}{(E - E_i)^2 + \Gamma_i^2/4} \cdot \frac{\Gamma_{c,i}}{\Gamma_i}, \tag{6}$$

Here, E_i is the resonance energy of the excited state; Γ_i is the width of the level; $\Gamma_{c,i}/\Gamma_i$ is the decay

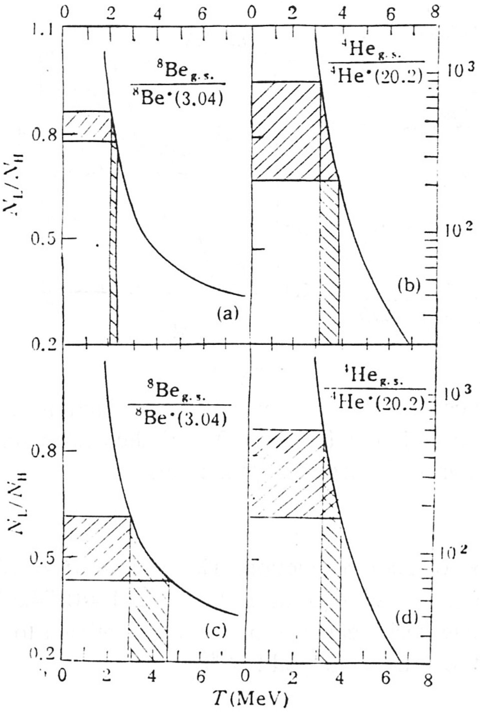

Fig. 2

Yield ratios N_L/N_H as a function of emission temperature. (a) and (b) are not corrected, (c) and (d) are corrected for sequential decay.

branching ratio. All these quantities were assumed to be energy independent. The efficiency function, $\varepsilon_c(E)$, is determined by Monte Carlo calculation. The calculation takes into account the precise geometry of the horoscope, the detector energy resolutions, and the constraints on the particle energies. The decays of the parent nuclei were assumed to be isotropic in their center-of-mass frames. The energy spectrum and angular distribution of the stable isotope of Be were used for the calculation of efficiency functions of ^8Be.

Figs. 2(a, b) show the dependence of the extracted yield ratio from α-α, p-t correlation functions on the emitted temperatures. Here $N_L(T)$ and $N_H(T)$ denote the integrated yields of the states with lower and higher excitation energy, respectively. The dependence of the calculated yield ratio N_L/N_H based on Eq. (5) is shown by the solid line. The hatched area in the figure indicates the range of yield ratios and temperatures that correspond to the region between two extreme background assumptions shown in Figs. 1(a, b). The temperature of 2.2 ± 0.1 MeV is obtained from the relative population of $^{\text{the}}$ ^8Be ground state and 3.04 MeV state; and the temperature obtained from the ^4He ground state and 20.21 MeV state is 3.4 ± 0.4 MeV. Here, only the uncertainty of background correlation functions is taken into account.

5. CORRELATION OF THE SEQUENTIAL DECAY

The measured population of the particle states is not the primary value, because it is distorted by sequential decay of the other unstable particles. The contributions of sequential decay to the lower excited states are greater than those to the higher excited states. The experiment value of N_L/N_H is

Table 1
Parameters for the $^9\beta$e excited state and ^{9}B ground state as well as the decay-branching ratio [6,7].

E_x(MeV)	J^π	Γ(keV)	relative yield	branching ratio	
				to^{8}Be$_{g.s.}$	to^{8}Be(3.04)
1.69	$\frac{1}{2}^+$	217	0.39	1.00	0
2.43	$\frac{5}{2}^-$	0.77	1.00	0.07	0
2.78	$\frac{1}{2}^-$	1080	0.28	1.00	0
3.05	$\frac{5}{2}^+$	282	0.82	0.87	0
4.70	$\frac{3}{2}^+$	743	0.35	0.13	0
6.67	$\frac{7}{2}^-$	1540	0.43	0.02	0.55
11.28	$\frac{3}{2}^-$	575	0.06	0.02	0.14
11.81	$\frac{3}{2}^-$	400	0.05	0.03	0.12
^{9}B$_{g.s.}$	$\frac{3}{2}^-$	0.54		1.00	0

greater than the primary values. For this reason the value obtained from N_L/N_H is the lower limit of the emission temperature. The data of excited states and ground states of two nuclei, which influence the population of the states of ^{8}Be, are listed in Table 1. For ^{9}B, only the ground state was taken into account due to the lack of a decay-branching ratio of the excited states. In the calculation of relative yield of excited states for ^{9}Be the temperature $T = 3.8$ MeV was assumed, and the yield of the ^{9}Be 2.43 MeV state was 1.00. The contributions of sequential decay of ^{9}Be excited states and the ^{9}Be ground state to the ^{8}Be ground state and the 3.04 MeV state may be obtained by summing up every state listed in Table 1 and taking into account their decay-branching ratios.

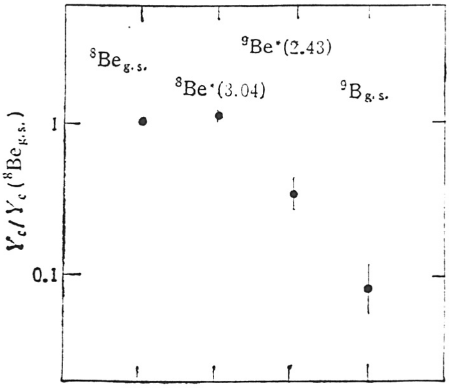

Fig. 3
Relative yields of particle extracted from α-α and p-α correlation functions.

Fig. 3 shows the particle yields obtained from α-α (Fig. 1(a)) and p-α (Fig. 1(c)) correlation functions. In the efficiency calculation, the limits of geometry and energy were taken into account, andthe particle energy spectra and angular distributions of stable isotope of Be were used. By the correction of sequential decay the primary populations of states were obtained. The corrected relative population of the state of ^{8}Be and corresponding emission temperature are shown in Fig. 2(c). The extracted emission temperature is $3.5\pm^{1.3}_{0.8}$MeV. It is difficult to determine experimentally the sequential decay yield for the ^{4}He ground state because there are a large number of sequential decay sources. Fig. 2(d) shows the relative population of states of ^{4}He as a function of the temperature by cutting down the ^{4}He ground state yield by 30%, and the extracted temperate is 3.6 ± 0.4 MeV. The extracted temperature changes by less than 0.2 MeV because the level separation ($\Delta E \approx 20$ MeV) is much larger than the emission temperature.

6. CONCLUSION

The relative populations of states of the ^{8}Be ground state with the 3.04 MeV state and the ^{4}He ground state with the 20.21 MeV state were obtained from the correlation function measurement at small relative momenta for ^{40}Ar induced reaction on ^{197}Au at $E/A = 25$ MeV. Without correction of the sequential decay the extracted emission temperatures were 2.2 ± 0.1 MeV and $3.4 \pm .0.4$ MeV, respectively. After deducting the sequential decays of ^{9}Be and $^9B_{g.s.}$ the emission temperature for ^{8}Be was $3.5\pm^{1.3}_{0.8}$MeV. For ^{4}He the emission temperature was 3.6 ± 0.4 MeV by cutting down the yield of the ^{4}He ground state by 30%.

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