Alpha-particle emission from the fusion of ^{32}S with ^{27}Al

G. M. Berkowitz, P. Braun-Munzinger, J. W. Harris,* and C. M. Jachcinski†
Department of Physics, State University of New York, Stony Brook, New York 11794

J. Barrette
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
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Alpha particles produced in the fusion of ^{32}S with ^{27}Al at $E_{lab}=160$ MeV were observed at $\theta_{lab}=15°$, 40°, 45°, 75°, 130°, and 160° in coincidence with evaporation residues detected at $\theta_{lab}=-5.8°$ using a time-of-flight spectrometer. The data were compared to a simple Monte Carlo calculation based on the statistical evaporation of light particles from an equilibrated compound nucleus. The total coincidence energy spectra show no evidence of preequilibrium emission of alpha particles.

[NUCLEAR REACTIONS $^{27}Al(^{32}S, x)$, x = evaporation residues, $E=160$ MeV, measured coincidences with evaporated α particles, deduced limit on pre-equilibrium α emission.]

I. INTRODUCTION

In the analysis of evaporation residue cross sections from heavy ion induced fusion reactions[1–5] it has always been assumed that such reactions proceed via an equilibrated compound nucleus. Using this assumption, a quantitative analysis of the measured mass and charge distributions can be performed in the framework of the statistical model in order to study nuclear shapes and yrast lines. A significant pre-equilibrium component would seriously affect the results of such investigations.

Recent studies of gamma rays and neutrons[6–9] from several heavy ion induced reactions provide evidence for pre-equilibrium emission as well as statistical emission of light particles. This typically occurs at bombarding energies of 7 – 10 MeV/nucleon. For example, in the case of $^{12}C+^{158}Gd$ (Refs. 8, 9) the onset of pre-equilibrium neutron emission occurs at ~ 10 MeV/nucleon, while for $^{14}N+^{159}Tb$ (Refs. 6, 7) pre-equilibrium alpha particle emission is observed at 6.8 MeV/nucleon. The precompound component shows up as a high energy tail in the light particle energy spectra emitted from the composite system after a complete momentum transfer but prior to the system reaching thermal equilibrium. Furthermore, the light particle center of mass angular distributions are peaked about the beam direction and exhibit fore-aft asymmetry.

If such a pre-equilibrium emission also exists for lighter systems and slightly lower energies, analysis of residual mass distributions based on the statistical model assuming a complete fusion process would have to be reconsidered. This paper investigates the possibility of precompound emission for the system $^{32}S+^{27}Al$ at a bombarding energy of $E_{^{32}S}=160$ MeV, i.e., 5 MeV/u. This system was previously studied at the same bombarding energy and the evaporation residue nuclide distribution was successfully reproduced assuming complete fusion followed by statistical evaporation of light particles.[5] This result however, does not preclude a fraction of the measured nuclide distribution originating from an incomplete fusion process. To distinguish better a possible precompound component leading to incomplete fusion of the system $^{32}S+^{27}Al$ the alpha particles emitted in the range $\theta_{lab}=15°-160°$ were measured in coincidence with the evaporation residues detected at forward angles.

II. EXPERIMENTAL METHOD

This experiment was carried out at the Brookhaven National Laboratory Van de Graaff acceleratory by bombarding a 400 $\mu g/cm^2$ Al target with 160 MeV ^{32}S ions. Light particles emitted from the composite system were measured in a ΔE-E solid state telescope with a ΔE thickness of 263 μm and a 2016 μm thick E detector positioned at $\theta_{lab}=15°$ and in five 1000 μm thick solid state detectors at angles between 40° and 160° in coincidence with the evaporation residues in order to eliminate events corresponding to deep inelastic or direct reactions.

Nickel foils of the proper thickness in front of each of the six light particle detectors were used to stop all particles heavier than Li. Protons and alpha particles could be separated kinematically in the five 1000 μm detectors.

A time-of-flight (TOF) spectrometer positioned at an angle of $\theta_{TOF}=5.8°$ on the side of the beam axis opposite the light particle detectors was used to identify the evaporation residues by mass and energy.[10] A solid state detector at the end of the time-of-flight system provided the energy and start signals and a thin film scintillator with a photomultiplier sitting upstream in the entrance to the spectrometer furnished the stop signal. As seen in Fig. 1, the mass resolution of the spectrometer was good enough to allow individual mass identification.

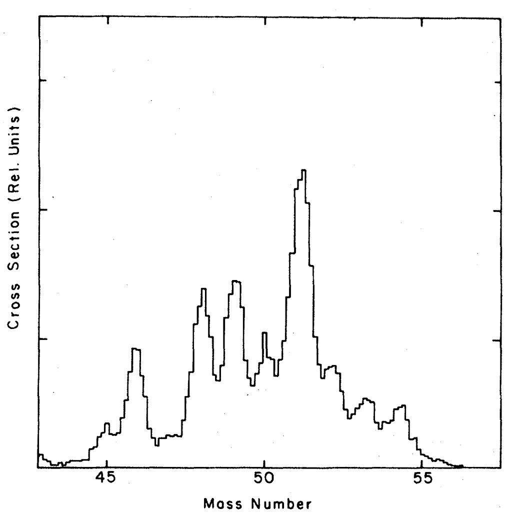

FIG. 1. Mass spectrum of evaporation residues from the reaction $^{32}S+^{27}Al$ obtained with the time-of-flight spectrometer at $\theta_{TOF}=5.8°$.

III. RESULTS AND ANALYSIS

In the section below we will concentrate on the spectra of alpha particles in coincidence with evaporation residues. The data are shown in Figs. 2 and 3 as solid lines for $\theta_{lab}=15°$, 40°, 45°, 75°, 130°, and 160°. In Fig. 2 the laboratory alpha particle energy spectra are plotted in coincidence with evaporation residue (ER) mass numbers $45 \le M_{ER} \le 55$. As demonstrated in Ref. 5, the dominant decay chains leading to those masses contain from 0 to 4 alpha particles. Qualitatively, the spectra already show that there is no strong pre-equilibrium component in the present data. The low energy cutoffs in the alpha particle spectra are due to the cuts necessary to remove the protons from the light particle energy spectra.

A more sensitive test for pre-equilibrium emission is a plot of the alpha particle energy spectra in

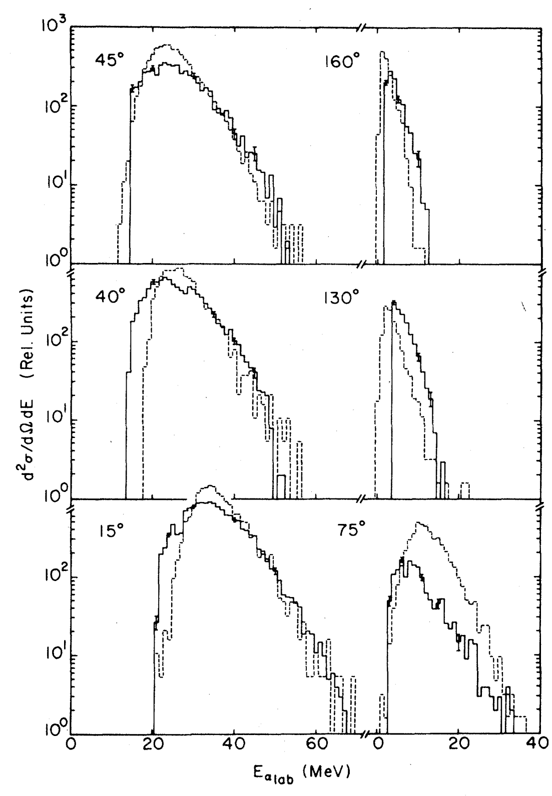

FIG. 2. Alpha particle energy spectra obtained at $\theta_{lab}=15°$, 40°, 45°, 75°, 130°, and 160° in coincidence with evaporation residues of mass numbers $45 \le M_{ER} \le 55$. The solid histograms represent data and the dashed histograms are the results of the Monte Carlo calculation assuming isotropic particle evaporation. Typical error bars are given with data.

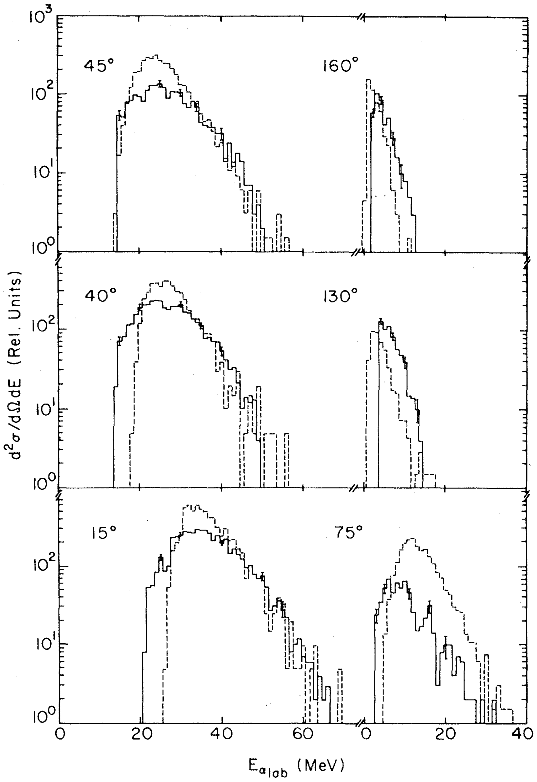

FIG. 3. Alpha particle energy spectra measured at $\theta_{lab}=15°$, 40°, 45°, 75°, 130, and 160° in coincidence with evaporation residues of mass numbers $51 \le M_{ER} \le 53$. The solid histograms represent data and the dashed histograms are the results of the Monte Carlo calculation assuming isotropic particle evaporation. Typical error bars are given with the data.

coincidence with evaporation residue masses $51 \le M_{ER} \le 53$, as shown in Fig. 3. In the statistical model the dominant decay chain leading to these evaporation residues contains only one alpha particle. If the first alpha particle is emitted prior to equilibration, then because of the high energy, multiple alpha particle evaporation is improbable and the residues are likely to be in the mass range $M_{ER} > 51$. Even under these conditions, however, no distinct high energy tail or break in the slope of the tail can be seen in the experimental spectra even for the forward angles.

To analyze the measured spectra more quantitatively, a program was written to simulate the statistical evaporation of light particles from an equilibrated compound nucleus. The program used Monte Carlo techniques to follow decay chains of evaporated particles in order to generate laboratory energy spectra at given angles in coincidence with residual masses at the appropriate laboratory angle. By comparing the data to the results of the Monte Carlo calculations, possible nonstatistical components of the energy spectra can be identified.

A true statistical decay program would have to perform a complete Hauser-Feshbach calculation at each step of the decay chain with Monte Carlo techniques but, due to the necessary concidence condition between the alpha particles and the evaporation residues, such a calculation is very time consuming. To simplify the program, the simple model of Ref. 5 for the same reaction was adopted. There, a combinatorial approach to light particle evaporation assuming equal decay probabilities for neutrons, protons, and alpha particles was shown to yield a reasonable description of the evaporation residue mass spectrum for the present reaction.

For the light particles, an energy distribution in the center of mass of the form $(E-V_{\mathrm{Coul}})\exp[2\sqrt{a(E_{\max}-E)}]$ (Ref. 11) was used, where $E_{\max}$ is the maximum energy with which the light particles may be emitted and the level density parameter $a=A/8$, where A is the mass number of the compound nucleus. Since the code does not treat angular momentum coupling properly, it was assumed that the light particles remove angular momentum from the compound system at a rate of $1\hbar$ for nucleon emission and $4\hbar$ per α-particle emission. This is similar to the method used in the code ALICE.[12] The alpha particle energy spectra were computed assuming that the light particle angular distributions were given by the semiclassical expression of Ericson and Strutinski.[13] Additional calculations were done using both an isotropic and a $1/\sin\theta$ angular distribution for the light particles. These angular distributions are expected from the decay of a compound nucleus with zero spin and very high spin, respectively. The assumed center of mass angular distributions have no appreciable effect on the shape of the calculated energy spectra and the laboratory angular distribution calculated using the isotropic angular distribution is in very good agreement with that employing the Ericson and Strutinski expression. Therefore, to save computer time, isotropic emission was assumed for most calculations.

The evaporated particles were in all cases assumed to have no intrinsic spin. The initial spin of the compound system was derived from a spin distribution of the form $\sigma_l \propto 2l+1$ with a sharp cutoff approximation at l_{crit}, where l is the orbital angular momentum in the entrance channel. A value of $l_{\mathrm{crit}}=37\hbar$ was obtained from the measured fusion cross section of $\sigma_{fus}=870$mb.[5]

A nuclear radius parameter of $r_0=1.3$ fm was used in the Coulomb interaction between the compound system and the evaporated particles. The value of r_0 was chosen in order for the Monte Carlo generated spectra to give reasonable agreement with the observed peak of the energy distribution.

As a first check of the Monte Carlo program the residual mass distribution predicted by the program at $\theta_{TOF}=5.8°$ was compared with data in Fig. 4. The solid bars represent the results of the Monte Carlo calculations. The distribution was normalized to the integral of evaporation residue mass numbers $45 \leq M_{ER} \leq 55$. Consistent with the result of Ref. 5, the Monte Carlo generated mass distribution using the constant branching ratios as described above and justified in more detail in Ref. 5 gives reasonable agreement with the data, particularly in that the features corresponding to peaks

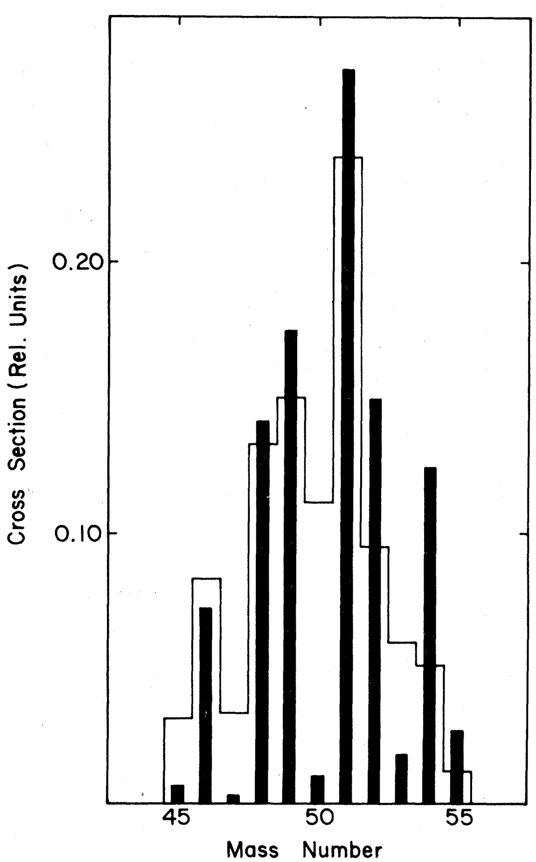

FIG. 4. Experimental mass distribution compared to the results of the Monte Carlo calculation. The distributions were normalized to the integral of evaporation residue mass numbers $45 \leq M_{ER} \leq 55$. The solid bars represent the results of the Monte Carlo calculation.

associated with multiple alpha particle evaporation are correctly reproduced.

In Fig. 2 the Monte Carlo generated alpha particle spectra (dashed lines) in coincidence with evaporation residue mass numbers $45 \leq M_{ER} \leq 55$, are compared to the data. The Monte Carlo spectra were normalized to the data by fitting the high energy tails at $\theta_{lab}=40°$ and 45°. The shapes of the calculated spectra are in good agreement with the data at most angles. The only discrepancy between the data and the Monte Carlo spectrum, at 75°, is probably due to a partial shading of the detector by the target frame. All spectra are consistent with a unique temperature in the compound nucleus. In particular, the positions of the peaks and the high energy tails of the energy spectra are well reproduced. The cutoff in the data at low energies, especially visible at $\theta_{lab}=130°$, indicates the energy below which protons and alpha particles can no longer be separated kinematically. When a $1/\sin\theta$ angular distribution for the emission of light particles was used to generate the Monte Carlo spectra, a somewhat poorer agreement between data and calculations was observed, especially at intermediate angles.

In Fig. 3, the Monte Carlo generated alpha particle spectra (dashed lines) in coincidence with residue mass numbers $51 \leq M_{ER} \leq 53$ are compared to the data. As explained above, these coincidence spectra should be more sensitive to possible pre-equilibrium components in this reaction. The Monte Carlo spectra were again normalized to the data at 40° and 45°. Even in this case, the statistical calculations are consistent with the data with no evidence of a pre-equilibrium component.

Since the Monte Carlo program assuming only statistical decay does not give an upper limit to the fraction of precompound alpha particle emission in the data, the program was modified to simulate such a process. The first alpha particle to be emitted from the composite system was assumed to have an energy distribution corresponding to a temperature three times that of the normal temperature at statistical equilibrium. By varying the probability of pre-equilibrium alpha particles it could be determined that less than 10% of the emitted alpha particles were nonstatistical in the above sense, i.e., corresponding to an effective temperature of $T_{eff} \geq 3 \times T_{eq}$. This is demonstrated in Fig. 5, where α-particle spectra in coincidence with evaporation residues of masses $51 \leq M_{ER} \leq 53$ are compared to a Monte Carlo calculation using the two temperatures as described above. From this

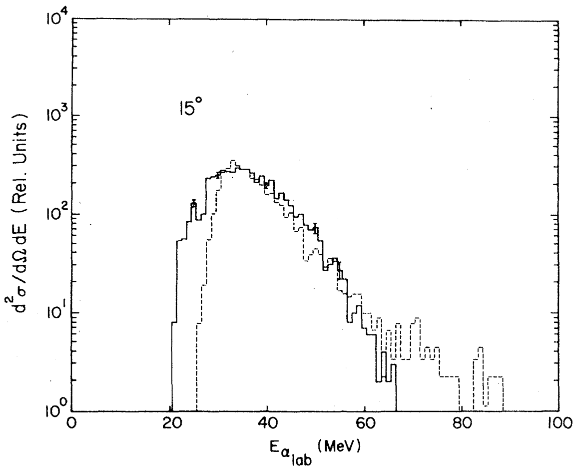

FIG. 5. Alpha particle energy spectrum at $\theta_{lab}=15°$ in coincidence with residue masses $51 \leq M_{ER} \leq 53$. The solid histogram with error bars represents data and the dashed histogram is the prediction of a Monte Carlo calculation assuming isotropic evaporation and three times the statistical temperature for 10% of the first alpha particles emitted within each decay chain.

figure it can be seen that the high energy tail in the energy spectrum predicted by assuming a 10% preequilibrium component in the data is not observed in the measured spectrum. It should be noted that the present measurement would be less sensitive to a pre-equilibrium component having a lower effective temperature or an angular distribution strongly forward peaked at angles much smaller than $\theta_{lab}=15°$.

IV. CONCLUSION

Alpha particles emitted from the composite system of $^{32}S+^{27}Al$ in coincidence with the evaporation residues were measured to determine if any precompound emission existed at a bombarding energy of 5 MeV/nucleon. Monte Carlo methods were employed to generate alpha particle spectra from a statistical evaporation model. They were compared to the measured alpha particle spectra.

The net results of this work indicate that at this energy pre-equilibrium alpha particle emission is not a significant factor in the decay of the present composite system. At most, 10% of all emitted alpha particles could originate from pre-equilibrium emission. It would be interesting to pursue the present technique up to higher energies $E/A \gtrsim 10$ MeV/u, where pre-equilibrium components have been identified for other systems.

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*Now at Lawrence Berkeley Laboratory, Berkeley, California.

†Now at Bell Laboratories, Naperville, Illinois.

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