Light particle spectra from 35 MeV/nucleon ^{12}C-induced reactions on ^{197}Au

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Energy spectra for p, d, t, ^{3}He, ^{4}He, and ^{6}He from the reaction ^{12}C+^{197}Au at 35 MeV/nucleon are presented. A common intermediate rapidity source is identified using a moving source fit to the spectra that yields cross sections which are compared to analogous data at other bombarding energies and to several different models. The excitation function of the composite to proton ratios is compared with quantum statistical, hydrodynamic, and thermal models.

A recent systematic study[1] of inclusive data on light particle emission from asymmetric nucleus-nucleus collisions at various bombarding energies[1-4] has revealed that light fragments emitted at angles $\geq 50°$ can be attributed to a common, intermediate rapidity source. Data are scarce, however, in the intermediate energy region of $20 < E_{\rm lab} < 100$ MeV/nucleon. This first set of measurements using beams from the K500 Superconducting Cyclotron at MSU was designed to supplement our previous systematics and to fill the gap existing at intermediate beam energies. We measured angular distributions and energy spectra for light fragments produced in the reaction of 35 MeV/nucleon ^{12}C + ^{197}Au. We extracted cross sections, temperatures, and velocities for p, d, t, ^{3}He, ^{4}He, and ^{6}He fragments using single moving source fits as described in Ref. 1. The present data combined with the previously observed excitation function for composite to proton ratios are compared to quantum statistical,[5] hydrodynamical,[6] and thermal models.[1,7]

The 35 MeV/nucleon ^{12}C^{4+} beam from the K500 Superconducting Cyclotron averaged about 3 particle nA. The target was a 9.6 mg/cm^2 self-supporting natural gold foil. Particles were detected with two telescopes each consisting of a 0.4 mm thick Si ΔE counter and a 10 cm thick NaI E counter. Each telescope had a solid angle of 3.0 msr. The energy spectra were corrected for reaction losses. The overall normalization was done using a shielded Faraday cup coupled to a charge integrator and was reproducible to within 5%.

The double differential cross sections of p, d, t, ^{3}He, ^{4}He, and ^{6}He fragments are shown in Fig. 1 for the laboratory angles 40°, 60°, 75°, 90°, 105°, 120°, and 140°. The depicted errors are statistical. A shoulder is visible in the p, d, and t spectra at 40° near the beam energy per nucleon. A nearly isotropic distribution is observed for these three fragments below 20 MeV.

The large angle and high energy parts of the fragment spectra have been attributed to a hot, intermediate rapidity source.[1] We extract information concerning fragments from this source in the same way as was done in Ref. 1. The solid lines in Fig. 1 correspond to single moving source fits in which a relativistic Boltzmann distribution in the rest frame of the moving source was assumed. This distribution is characterized by a temperature, T, and a normalization factor, σ_0, identified with the production cross section. A 10 MeV Coulomb shift was applied for $Z=1$ fragments and 18 MeV was used for $Z=2$ frag-

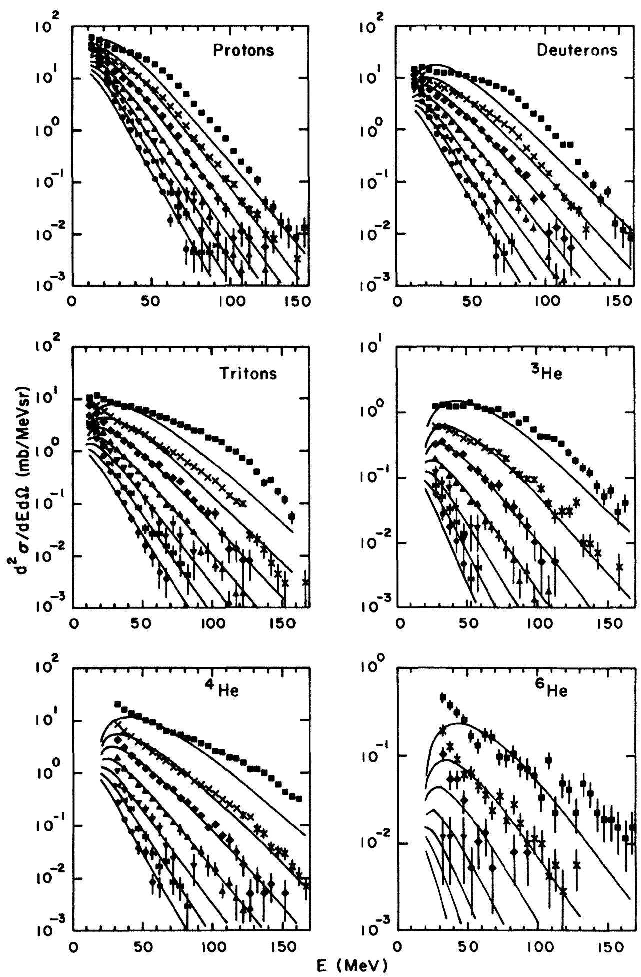

FIG. 1. Energy spectra of p, d, t, ^{3}He, ^{4}He, and ^{6}He from the reaction of 35 MeV/nucleon ^{12}C + Au. The angles measured are 40° (squares), 60° (crosses), 75° (diamonds), 90° (triangles), 105° (inverted triangles), 120° (double triangles), and 140° (circles) in the laboratory. The errors depicted are statistical. The solid lines correspond to moving source fits as described in the text.

TABLE I. Extracted moving source parameters for 35 MeV/nucleon ^{12}C + Au.

Particle	Temperature T (MeV)	Cross section σ_0 (mb)	Velocity β (c)
p	9.2±0.5	8500±850	0.093±0.01
d	11.0±0.6	3430±340	0.099±0.01
t	12.9±0.6	1760±180	0.094±0.01
^{3}He	12.7±0.6	365±44	0.125±0.01
^{4}He	12.5±0.6	2660±266	0.097±0.01
^{6}He	12.3±0.6	57±6	0.093±0.01

ments.[1,4] The laboratory spectra were calculated assuming the source is moving with a velocity, β, in the laboratory. The three parameters T, σ_0, and β were determined using a least squares fit.[8] The extracted temperature, cross sections, and velocities are shown in Table I. The velocities and temperatures smoothly follow the previously obtained systematics. It has been shown in Ref. 2 that the large angle spectra of light fragments are associated with high multiplicity. Thus inclusive data can be biased toward near central collisions by studying the large angle spectra.

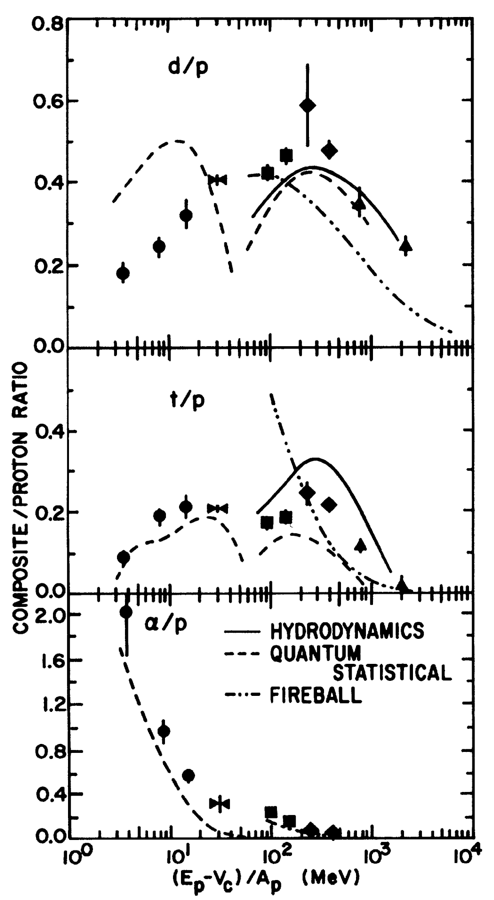

FIG. 2. Extracted composite/p cross section ratios using a moving source parametrization as in the text compared with the cross sections from the reactions O + Au (Ref. 4) (circles), Ne + Au (Ref. 1) (squares), Ne + U (Ref. 2) (diamonds), and Ne + Pb (Ref. 3) (triangles) plotted versus laboratory energy per nucleon above the Coulomb barrier. The current data are shown as double triangles. The theoretical curves are described in the text.

The cross section ratios d/p, t/p, and ^{4}He/p are compared in Fig. 2 with the corresponding quantities obtained from ^{16}O- and ^{20}Ne-induced reactions on heavy targets.[1–4] The extracted d/p ratio increases with increasing beam energy up to about 200 MeV/nucleon, where it decreases again. This effect was predicted earlier[7] using a model incorporating chemical equilibrium where the d/p ratio is strongly affected by the decay of particle unstable, excited nuclei. On the other hand, the t/p ratio seems to be almost constant (t/p$\approx$0.2) between 8 and 400 MeV/nucleon, with some indication of structure between 30 and 200 MeV/nucleon, and decreases at lower and higher energies. The ^{4}He/p ratio decreases monotonically with increasing beam energy, becoming very small above 100 MeV/nucleon. The solid lines in Fig. 2 correspond to hydrodynamic (HD) calculations including a quantum statistical treatment of the breakup[6] performed at a density of 0.7 of normal nuclear density, $\rho_0=0.15$ fm^{-3}. The dashed lines represent a quantum statistical (QS) model calculation incorporating in-medium corrections and critical phenomena[5] performed at a density of $\rho_0/3$. The dash—double-dot line represents a fireball (FB) calculation[7] at a freezeout density of $0.8\rho_0$. The QS model is related to the bombarding energy through the observed temperature, while the HD and FB calculations are carried out at the impact parameter with the maximum weight, b_{mw}. The QS and HD calculations are for symmetric systems, while the FB model takes the number of protons and neutrons from the fireball geometry at b_{mw}. All three models are shown only for the beam energies (temperatures) where the underlying assumptions of each model are reasonable.

At energies above 100 MeV/nucleon the HD, QS, and FB calculations[1,5–7] agree qualitatively with the observed composite/p ratios. The maxima near 200 MeV/nucleon for both d/p and t/p ratios are predicted by the HD and QS models, while for the FB model the d/p ratio peaks at too low an energy and the t/p ratio predictions are too high at the lower beam energies. All three models predict the strong decrease in the d/p, t/p, and ^{4}He/p ratios at high incident energies which is due to the fact that at high temperatures the emitted particles are predominantly nucleons. The results for the HD model are not shown for the ^{4}He/p ratio because they are very similar to the FB predictions.

At energies below 50 MeV/nucleon, the QS model predicts a second maximum in the d/p and t/p ratios near $E_{lab}=30$ MeV/nucleon. The resulting minima are predicted to occur at an incident energy corresponding to a temperature of about 20 MeV which is the critical temperature of a liquid-vapor phase transition. The large qualitative disagreement of the theoretical and observed d/p ratio is attributed[5] to inadequacies in the deuteron wave function used in the calculation. On the other hand, the observed excitation function for the t/p ratio exhibits some structure between 30 and 200 MeV/nucleon, in qualitative agreement with the predictions of the QS model. However, the departure from completely smooth behavior could be due to the fact that several different systems are being considered here, O + Au (Ref. 4), Ne + Au (Ref. 1), Ne + U (Ref. 2), and Ne + Pb (Ref. 3).

In summary, we have measured light particle spectra from the reaction of 35 MeV/nucleon $^{12}C + ^{197}Au$ and have fit them with a moving source model to extract source velocities, temperatures, and production cross sections. These parameters extend previous systematics of ^{16}O- and ^{20}Ne-induced reactions on heavy targets.[1-4] From a theoretical point of view there are two clearly distinct regions of the composite to proton cross section ratios. The region above $E_{lab} = 100$ MeV/nucleon can be understood in terms of HD and QS models incorporating thermal and chemical equilibrium. Below 100 MeV/nucleon the ratios can be understood in terms of the QS model except for the d/p ratios. On the other hand, the available data seem to change smoothly between the two energy regimes, which may be indicative of a common mechanism at the high and low energies. Structure in the t/p ratio for incident energies between 8 and 400 MeV/nucleon resembles the QS calculation that incorporates the effects of a liquid-vapor phase transition. Because the present results incorporate data from several different systems, the measurement of additional light particle spectra for intermediate energies, $35 \le E_{lab} \le 100$ MeV/nucleon, is necessary in order to allow the conclusive confirmation or rejection of the existence of this structure.

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[8]The contributions from evaporation from target and projectile residual nuclei were a concern and we therefore included only a subset of the data in the fits. The applied cuts suppressed the 40° spectra and the low energy, isotropic components. For example, the proton spectra exhibit a nearly isotropic component between 10 and 20 MeV and show a bump in the 40° spectrum near the beam energy per nucleon. We attribute these features to target and projectile evaporation, respectively.