Final-State Interactions in the Production of Hydrogen and Helium Isotopes by Relativistic Heavy Ions on Uranium*

H. H. Gutbrod
Gesellschaft für Schwerionenforschung, Darmstadt, Germany, and Lawrence Berkeley Laboratory, Berkeley, California 94720

and

A. Sandoval
Fachbereich Physik, Universität Marburg, Marburg, Germany, and Lawrence Berkeley Laboratory, Berkeley, California 94720

and

P. J. Johansen,† A. M. Poskanzer, J. Gosset,‡ W. G. Meyer, and G. D. Westfall
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

R. Stock
Fachbereich Physik, Universität Marburg, Marburg, Germany

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Double-differential cross sections have been measured for high-energy p, d, t, ^{3}He, and ^{4}He particles emitted from uranium targets irradiated with ^{20}Ne ions at energies of 250, 400, and 2100 MeV/nucleon and ^{4}He ions at 400 MeV/nucleon. By using the shape and yield of the proton energy spectra, the shape and yield of the d, t, ^{3}He, and ^{4}He energy spectra can be deduced at all measured angles for all incident projectile energies by assuming that they are formed by a coalescence of cascade nucleons, using a model analogous to that of Butler and Pearson, and Schwarzschild and Zupančič.

Recently, we presented the energy spectra and the angular distributions for ^{3}He and ^{4}He fragments from uranium and silver targets bombarded with relativistic heavy ions.[1] The cross section for these high-energy products were two and three orders of magnitude higher than those found for proton-induced reactions at comparable incident velocities. The larger yield of high-energy ^{3}He, as compared to that of ^{4}He, raised doubts whether there was a common reaction mechanism which could explain both production processes. In high-energy proton-induced reactions, the observation of deuterons was explained by Butler and Pearson[2] as the coalescence of cascade nucleons. This model, which was modified by Schwarzschild and Zupančič,[3] assumes that among the many knock-on cascade nucleons there will be pairs that have small relative momenta. These nucleons can form a deuteron by interacting with each other and with the nuclear field to which the excess momentum and energy are transferred. The model thus relates the energy spectra of the emitted complex particles to the proton and neutron spectra. We propose a slightly modified version of this model to explain our data on the high-energy light fragments emitted in relativistic heavy-ion reactions. Since the energy spectra and angular distributions of the emitted composite particles fall off more steeply than those of the nucleons in a manner consistent with this model, it is important that calculations of nuclear matter ejected in relativistic heavy-ion collisions only be compared directly to data for the emission of nucleons, but not of the composite fragments.

Experimentally, we have measured the energy spectra from 30 to 120 MeV/nucleon at several laboratory angles for protons, deuterons, tritons, ^{3}He, and ^{4}He emitted from uranium bombarded with 250-, 400-, and 2100-MeV/nucleon ^{20}Ne beams and a 400-MeV/nucleon ^{4}He beam from the Bevalac. The charge and mass of the hydrogen and helium isotopes were identified in a ΔE-E telescope, consisting of a 2-mm-thick silicon ΔE counter (300 mm^2) and a 10-cm-long plastic scintillator (Pilot B, coupled to a 2.5-cm-diam phototube) as an E detector. The natural uranium target had a thickness of 240 mg/cm^2 and its normal was 55° to the beam. The energy of each particle was determined from its energy loss in the silicon ΔE counter after the particle charge and mass were determined using a two-dimensional contour display of the analog particle identification function verus the energy loss in the plastic scintillator. The relative cross sections, which are accurate to within 20%, were obtained by normalizing to a monitor telescope fixed at 90° with respect to the beam. The absolute cross sections were obtained by normalizing to previously measured data.[4]

Double-differential cross sections for the various emitted particles are presented in Figs. 1 and 2. Although many more angles have been measured, only some of the spectra are shown. Similar to the ^{4}He- and ^{16}O-induced reactions,[1] the energy spectra of all products are smooth and show no peaks. The slopes of the energy spectra become steeper with increasing angle and also with increasing mass of the emitted particle.

Schwarzschild and Zupančič[3] predict that the deuteron density in momentum space is proportional to the proton density times the probability of finding a neutron within a small sphere of radius p_0 around the proton momentum. A straightforward generalization to more complex particles in the limit of low density in momentum space and and high multiplicity leads to

$$\frac{d^2n(N)}{p^2dp\,d\Omega}=\frac{1}{N!}\,\frac{d^2n}{p^2dp\,d\Omega}\left(\frac{d^2n}{p^2dp\,d\Omega}\,\frac{4\pi}{3}\,\gamma p_0^{\,3}\right)^{N-1}. \quad (1)$$

N is the mass number of the emitted fragments, p is the momentum per nucleon, $d^2n/p^2dp\,d\Omega$ is the number of nucleons per event per unit element of momentum space, $d^2n(N)/p^2dp\,d\Omega$ is the number of coalesced clusters with N nucleons per event per unit element of momentum space, and $\gamma=[1+(p^2/m^2)]^{1/2}$ where m is the nucleon mass.

We apply this formalism to heavy-ion-induced reactions assuming that the protons and neutrons have the same momentum distribution and that their relative yield is equal to the neutron-to-proton ratio in the projectile plus target. We get

$$\frac{d^2\sigma(x,y)}{dE\,d\Omega}=\left(\frac{d^2\sigma(\text{prot})}{dE\,d\Omega}\right)^{x+y}\frac{K(x,y}{\{m[E(E+2m)]^{1/2}\}^{x+y-1}}, \quad (2)$$

$$K(x,y)=\left(\frac{4\pi p_0^{\,3}}{3\sigma_0}\right)^{x+y-1}\frac{1}{x!\,y!}\left(\frac{N_p+N_t}{Z_p+Z_t}\right)^{y}, \quad (3)$$

where E is the laboratory kinetic energy per nucleon, x is the number of protons and y is the number of neutrons in the cluster, N_p and Z_p are, respectively, the neutron and proton number of the projectile, and N_t and Z_t are, respectively, the neutron and proton number of the target. The quantity σ_0, the nucleus-nucleus total reaction cross section calculated by Karol,[5] is 4.1 b for ^{20}Ne + U and 2.6 b for ^{4}He + U.

In Fig. 3 we show the measured double-differential cross sections for d, t, ^{3}He, and ^{4}He as compared to the calculations based on Eq. (2) and the measured proton spectra shown in Fig. 2. For each projectile, incident energy, and fragment we extract one value for p_0, the radius of the momentum sphere for coalescence. These values are listed in Table I. The values are much smaller than those found in Ref. 3 and are of reasonable magnitude since they are a fraction of the Fermi momenta of the clusters. This simple phase-space calculation of coalescence involves only one adjustable parameter for each

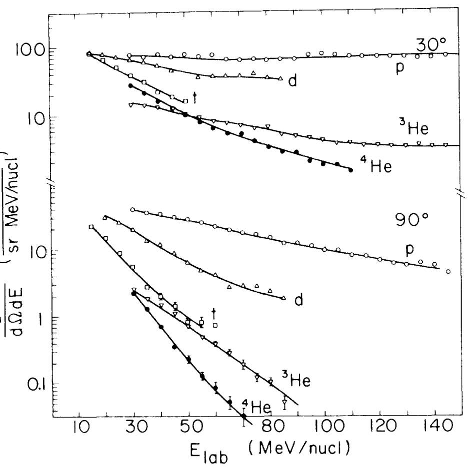

FIG. 1. Double-differential cross sections for fragments from the irradiation of uranium by 400-MeV/nucleon ^{20}Ne ions.

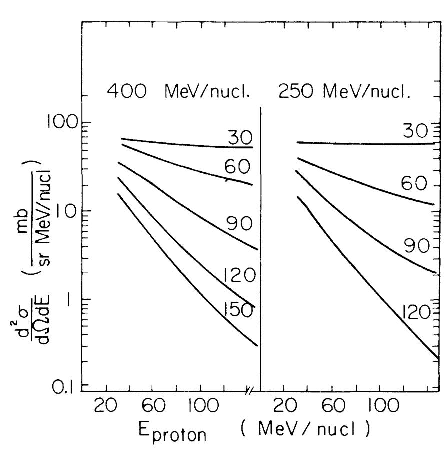

FIG. 2. Double-differential cross sections for protons emitted from the irradiation of uranium by ^{20}Ne ions at 250 and 400 MeV/nucleon.

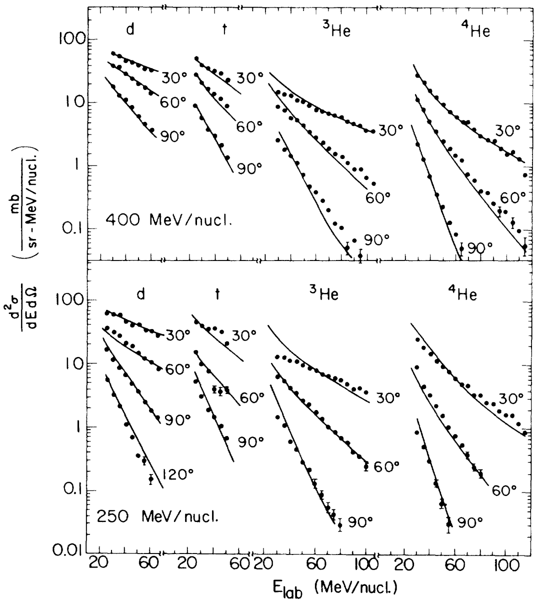

FIG. 3. Experimental points and calculated lines for the double-differential cross sections of fragments from the irradiation of uranium by ^{20}Ne ions at 250 and 400 MeV/nucleon.

fragment, the value of p_0, for calculating the absolute cross sections, energy spectra, and angular distributions. The p_0 values are remarkably uniform, even though absorbed into this parameter are the many factors, including correlations, not explicitly accounted for in this very simple model.

In conclusion, we have found strong evidence for final-state interactions in the production of high-energy fragments (30 to 120 MeV/nucleon) in relativistic heavy-ion-induced reactions. This result could suggest that future work concerning the possible detection of density effects in these collisions should concentrate on the nucleon and meson spectra since the energy spectra of the composite particles can be obtained from Eq. (2) and are shifted in energy and angle relative to those of the nucleons. On the other hand, we have data showing that the particle multiplicity increases with the size of the fragment. Thus the observation of the larger composite particles might be a way of selecting central collisions and may be a sensitive probe of density effects. We do not, however, have an understanding of the detailed mechanism leading to coalescence. Equation (2) leads to a different fragment energy dependence from that found in the original work of Butler and Pearson.[2] Further theoretical work is needed to understand the difference between the two models. Earlier experimental results of Crawford *et al.*[6] on high-energy boron to oxygen fragments are also consistent with this model. The high-energy tails in the energy spectra of helium to beryllium fragments from uranium irradiated by 5-GeV protons[7] can now be understood by this mechanism with a reasonable value of p_0 of about 140 MeV/c. This eliminates the previously postulated apparent temperatures of 20 MeV needed to explain these tails. This model could also aid in the understanding of the scaling effect seen in the production of d, t, ^{3}He, and ^{4}He by high-energy pions and protons.[8]

TABLE I. Radius p_0 (MeV/c) of the momentum sphere for coalescence.

	d	t	^{3}He	^{4}He
^{20}Ne + U				
250 MeV/nucleon	126	140	135	147
400 MeV/nucleon	129	129	129	142
2.1 GeV/nucleon	106	116	106	118
^{4}He + U				
400 MeV/nucleon	126	127	127	132

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[†] Permanent address: Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark.

[‡] Permanent address: Centre d'Etudes Nucléaires de Saclay, 91190 Gif-sur-Yvette, France.

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New Resonances in the Low-Energy ^{12}C-^{12}C Spectrum*

K. A. Erb, R. R. Betts, D. L. Hanson, M. W. Sachs, R. L. White, P. P. Tung, and D. A. Bromley
Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06520

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Angular distributions of transitions to low-lying states in ^{20}Ne have been measured for the reaction $^{12}C(^{12}C, \alpha)$ in 62.5-keV steps for $6.5 \leq E_{c.m.} < 11$ MeV. Two new nonstatistical structures are identified at $E_{c.m.} = 7.71$ and 9.84 MeV, with $J^\pi = 4^+$ and 8^+, respectively. These observations support the quasimolecular interpretations of the low-energy structure in the ^{12}C-^{12}C interaction.

The resonances in the low-energy ^{12}C-^{12}C interaction, first observed some fifteen years ago and postulated to result from the formation of nuclear molecules,[1] have been a subject of continuing interest and speculation. The sustained interest results from the general agreement that the sub-Coulomb structures reflect a new type of nuclear interaction; this interest has been heightened recently through the discovery of additional possible quasimolecular structures at much higher excitation in the nuclear continuum[2] and by a growing realization that this type of interaction may be a more general feature of heavy-ion interactions than had earlier been suspected. The importance of the $^{12}C + ^{12}C$ system in nuclear astrophysics and the crucial role of the possible resonant structures in determining the extrapolation of the interaction from the measured energies to thermonuclear ones provide additional motivation for study of this particular system.

Theoretical efforts to reproduce the sub-Coulomb structure in the $^{12}C + ^{12}C$ system have proceeded along several distinct lines. The earliest works[1,3,4] discussed the sub-Coulomb structures in terms of single-particle resonances in an effective $^{12}C + ^{12}C$ potential. Imanishi[5] found that the energies and widths of the then known resonances could also be reproduced by a model in which carbon-carbon quasimolecules were formed as a result of the coupling between the elastic channel and inelastic excitations. The failure of these early models to account for the subsequent observation[6-8] of additional lower energy structures implied that a mechanism with additional degrees of freedom was required. A suggestion by Michaud and Vogt[9] that the resonances resulted from the formation of intermediate α clusters satisfied this requirement; and it also offered an appealing explanation of some observed exit-channel branching ratios. Besides encompassing *qualitatively* the presence of additional resonances, the α clustering in the Michaud-Vogt model leads to an optical potential which supports "absorption under the barrier," thus profoundly affecting the estimates of stellar carbon burning rates.

Several recent calculations[10-12] have revived interest in the nuclear molecule models by showing that they *can* indeed accommodate a large number of resonances. A noteworthy aspect of these new calculations with Imanishi-type models is that the increase in barrier penetrability at energies of astrophysical significance results from the presence of isolated resonances, rather than from absorption under the barrier. Furthermore, at higher energies, new resonances are predicted, the presence or absence of which would test the validity of the model calculations.

The purpose of the present work is to determine, in particular, whether there exists a group of resonances with $J^\pi = 4^+, 6^+$, and 8^+, as predicted by Kondo, Matsuse, and Abe[11] between $E_{c.m.} = 7$ and 8 MeV. Previous measurements in this energy region include elastic scattering[13-15] and also a study[16] of α particle and proton yields at two angles. The latter work reported a resonance of unknown spin at $E_{c.m.} = 7.55$ MeV.

We have measured angular distributions as a function of beam energy for the reaction $^{12}C(^{12}C, \alpha)$ populating the low-lying levels of ^{20}Ne. Data were obtained at 5° intervals in 125-keV steps over the range $10° \leq \theta_{lab} \leq 80°$ and $13 \leq E_{lab} \leq 22$ MeV (above 18 MeV, measurements were also made at $\theta_{lab} = 5°$). The targets were 30 $\mu g/cm^2$