For Symposium on Macroscopic Features of Heavy-Ion Collisions, Argonne, Illinois, April 1-3, 1976

CONF-760424--3

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FUSION OF $^{14}N + ^{12}C$ AT HIGH ENERGIES†

R. G. Stokstad, J. Gomez del Campo,† J. A. Biggerstaff,
A. H. Snell, and P. H. Stelson
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

The cross section for the fusion of heavy ions at high energies is of interest because it can depend on the properties of the entrance channel[1] and may also give information on the highly-excited compound nucleus. Extensive experimental data for very light systems (i.e. $A \lesssim 30$) have not been available, however, possibly because the evaporation residues produced at higher bombarding energies have masses comparable to or even less than the projectile. In this case the separation of the products of inelastic direct reactions and of fusion presents an additional difficulty. Fusion measurements at high energies and for light systems, however, are of particular interest, because systems having fewer nucleons might exhibit phenomena qualitatively different from those observed for heavy systems. Possible differences are a dependence of σ_{fus} on microscopic properties of the entrance channel,[2] or a limitation on σ_{fus} imposed by angular momentum restrictions in the compound nucleus rather than by the entrance channel.

Beams of ^{14}N at seven energies over the range 43.8 to 178.1 MeV were used to bombard a 272 $\mu gm/cm^2$ carbon foil. Reaction products with $Z = 3$ to 12 were identified with a ΔE-E counter telescope in which the ΔE detector was an ionization chamber 9.5 cm long and filled with methane at a typical pressure of 20 Torr. Angular distributions were measured over the range of 4° to 40° (lab). In some measurements, an ionization chamber incorporating a position-sensitive solid-state detector was used.[3]

The yields of neon, sodium and magnesium nuclei are clearly the residues of compound nucleus formation followed by evaporation of light particles. These residues have a velocity distribution centered about the velocity of the compound nucleus and broadened by the recoil imparted by light-particle emission. The yields of lighter elements, however, may contain contributions from two-body reactions in which one or more nucleons are transferred. These contributions appear with a velocity

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characteristic of that of the projectile, and thus have an energy typically higher than that for an evaporation-residue of the same mass.

We believe that it is possible in the present case to separate these two components with sufficient confidence to enable the extraction of fusion cross sections. The separation relies on the expectation that the energy distributions for the evaporation-residues change in a consistent way from element to element. As the Z of the residue decreases, the centroid of the energy distribution decreases and the width increases. These considerations have been quantified by developing a Monte-Carlo computer code[4] which uses the Hauser-Feshbach prescription, including angular momentum, for the statistical decay of the compound system. In this way, the relative intensities, energy distributions and angular distributions of the evaporation residues may be predicted in the laboratory system. We emphasize, however, that our analysis of the reaction products is not directly dependent on this model; the calculations serve only to give confidence that the peak-shapes assumed in the analyses of the energy spectra correspond to those expected for evaporation residues.

The foregoing remarks are illustrated in Fig. 1a which shows measured and calculated energy spectra for sodium and nitrogen nuclei produced at bombarding energies of 86.3 and 167.1 MeV, respectively. Similar agreement has also been obtained at other bombarding energies from 43-178 MeV for the energy spectra and for angular distributions of other elements. The change in the elemental distribution of the evaporation residues with bombarding energy is as would be expected from the decay of a compound nucleus formed with increasing excitation energy and angular momentum. A comparison of measured and predicted relative yields for evaporation residues at two energies is shown in Fig. 1b.

We have considered whether processes analogous to deeply inelastic scattering might produce significant contributions to the yields which we identify as evaporation-residues. If one makes the reasonable assumption that the deeply inelastic process should excite the target or the projectile with approximately equal likelihood considering their nearly equal masses, then one would expect to observe nearly equal intensities of the unexcited parameters for the "deep-inelastic" yields of Z=6 and Z=7. This prediction is not observed. On the other hand the relative evaporation-residue yields

for Z=6 and Z=7 (indeed, the relative yields, energy spectra, and angular distributions for other values of Z also) change dramatically with bombarding energy in the range 43-178 MeV in a manner which is reproduced with remarkable precision by our evaporation calculation (see Fig. 1b). It thus seems reasonable to conclude in this case that processes analogous to deep-inelastic scattering do not contribute significantly to the yields which we identify as evaporation residues. However, one cannot rule out, a priori, small contributions from such processes, particularly at higher energies.

The experimental results are presented in Fig. 2a. Figure 2a also includes measurements by Kuehner et al.[5] of the fusion cross section at lower energies. Remarkably, above 40 MeV σ_{fus} is nearly constant. The average value is 812 ± 27 mb which, after inclusion of a systematic error of ± 7%, corresponds to a critical radius parameter r_{cr} = 1.08 ± 0.04 fm. A good fit to the low- and high-energy data is given by the model of Glas and Mosel[6] with the parameters r_{cr} = 1.06, $V(R_{cr})$ = 0.0, r_B = 1.47, $V(R_B)$ = 6.3 and is shown in Fig. 2a. (Considering the large spacing of the data points and relative errors of ± 7%, the present results do not rule out the possibility of small oscillations in σ_{fus} such as have been observed for $^{12}C + {}^{16}O$ at lower energies.[5,7])

The values of σ_{fus} at high energies therefore may be explained by an entrance-channel requirement that the colliding ions penetrate to a critical radius. In the present case this radius corresponds to a combined nuclear density ρ_c in the overlap region of $\rho_c = (0.6 - 0.9)\rho_o$ where ρ_o is the central density. This value is comparable to the value $\rho_c \sim \rho_o$ obtained for heavier systems,[8] ($r_{cr} \sim 1.03 \pm .08$).

A possible alternative explanation of the limitation on σ_{fus} involves the maximum angular momentum of the compound nucleus ^{26}Al for a given excitation energy (the yrast line). In Fig. 2b, the values of $J_c(J_c+1)$ defined by $\sigma_{fus} = \pi\lambda\!\!\!^{-2}(J_c+1)^2$ are plotted versus excitation energy in ^{26}Al. The data determine a straight line on a $J_c(J_c+1)$ scale which, in a rotational model, indicates a moment-of-inertia $\frac{2\mathcal{J}}{\hbar^2} = 7.7 \pm 0.7\ \mathrm{MeV}^{-1}$ and a band-head excitation energy of ∿ 15 MeV. The above moment-of-inertia is equivalent to that given by a deformed ^{26}Al nucleus ($\beta \sim 0.5$ for a prolate rigid rotor) or to that given by the factor $\frac{2\mu R^2}{\hbar^2}$ in the centrifugal potential for a ^{12}C nucleus and ^{14}N nucleus at a separation of $R = (1.06 \pm .05)(A_1^{1/3} + A_2^{1/3})$ fm. The band-head is located, perhaps not coincidentally, at the separation energy

for $^{26}Al \rightarrow {}^{12}C + {}^{14}N$. Thus, the observed values of σ_{fus} at energies greater than 40 MeV may be explained by postulating a compound nucleus which, for excitation energy E_x, has a maximum angular momentum J_c given by

$$E_x = (7.7\ \mathrm{MeV}^{-1})^{-1}\ J_c(J_c+1) + 15\ \mathrm{MeV}. \qquad (1)$$

The present experimental results by themselves cannot distinguish between these alternative origins for the limitation on σ_{fus} (entrance channel or compound nucleus). However, assuming only that an equilibrated compound nucleus is formed in this reaction (regardless of the origin on the limitation on σ_{fus}), the experimental data suggest that the ^{26}Al nucleus (*i*) is deformed for excitation energies E_x and angular momenta J_c similar to those given by Eq. (1) and (*ii*) has been formed at the highest bombarding energy with an angular momentum nearly equal to the limit for a rotating liquid drop,[9] $\sim$ 25.5 ħ.

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†Research supported by the U.S. Energy Research and Development Administration under contract with the Union Carbide Corporation.
+On sabbatical leave from Instituto de Fisica, University of Mexico.
[1]A. M. Zebelman and J. M. Miller, Phys. Rev. Letts. 30, 27 (1973).
[2]D. Glas and U. Mosel, Phys. Letts. 49B, 301 (1974).
[3]R. G. Stokstad, D. C. Hensley and A. H. Snell, to be published.
[4]J. Gomez del Campo, computer code LILITA, unpublished.
[5]J. A. Kuehner and E. Almqvist, Phys. Rev. 134B, 1229 (1964).
[6]D. Glas and U. Mosel, Nucl. Phys. A237, 429-440 (1975).
[7]P. Sperr, S. Vigdor, Y. Eisen, W. Henning, D. G. Kovar, T. R. Ophel and and B. Zeidman, Phys. Rev. Letts. 36, 405 (1976).
[8]J. Galin, D. Guerreau, M. Lefort and X. Tarrago, Phys. Rev. C 9, 1018 (1974); B. Tamain, C. Ngô, J. Peter, and F. Hanappe, Nucl. Phys. A252, 187 (1975).
[9]S. Cohen, F. Plasil and W. J. Swiatecki, Ann. Phys. 82, 557 (1974).

FIGURE CAPTIONS

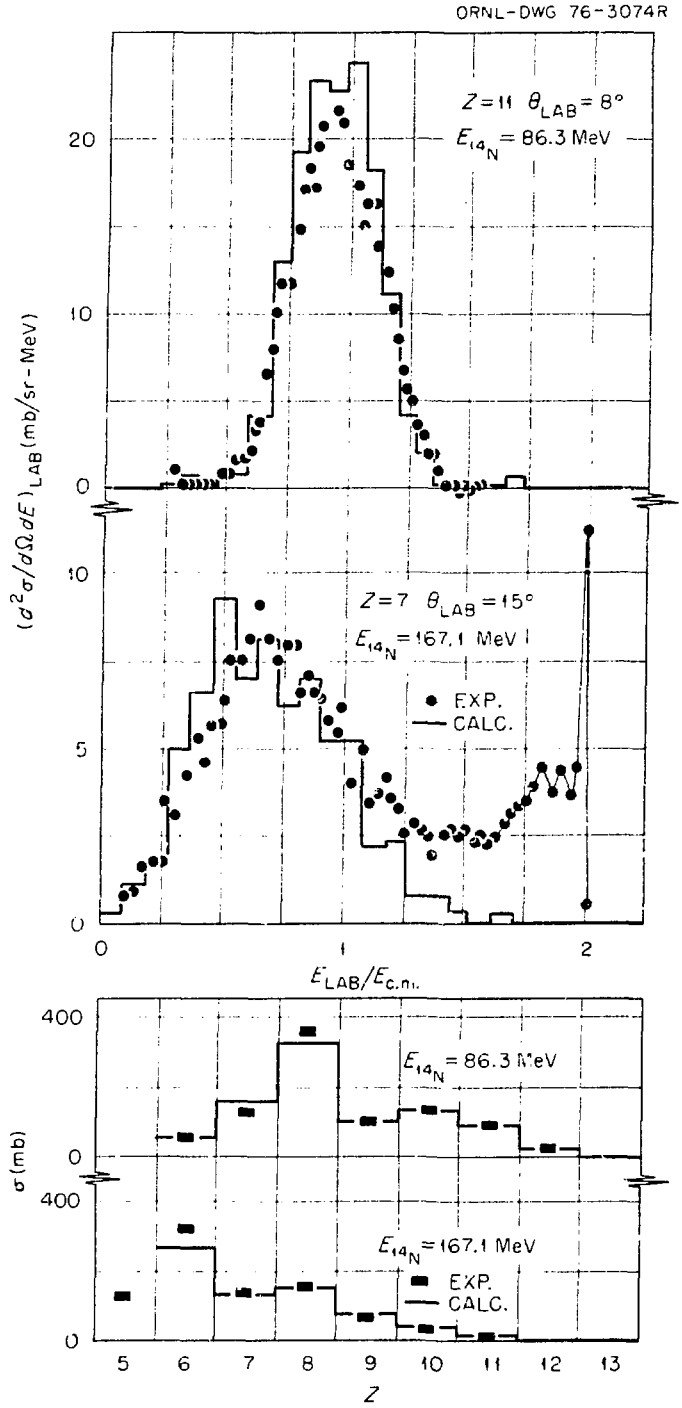
Fig. 1. (a) Energy spectrum of sodium ions at $\theta_{lab} = 8°$ ($E_{^{14}N} = 86.3$ MeV). The histogram is the result of a Monte-Carlo calculation, normalized to the total yield of all evaporation residues, Z = 6-12.

(b) Energy spectrum of nitrogen ions at $\theta_{lab} = 15°$ ($E_{^{14}N} = 167.1$ MeV). Again, the calculation of the evaporation residue component (histogram) is normalized to the total angle-integrated yield of all residues, Z = 5-12.

(c) and (d) Comparison of measured and predicted evaporation-residue cross sections. The predicted values have only a relative significance, having been normalized to the total yield.

Fig. 2. (a) The measured fusion cross sections (solid points) as a function of bombarding energy (lab). The data shown as crosses are from Ref. 5. The dashed line is a theoretical[6] fit discussed in the text.

(b) The measured critical angular momenta as a function of excitation energy in ^{26}Al. The dotted line corresponds to a moment of inertia $\mathcal{J} = 0.55\ \mathcal{J}_r$, where $\mathcal{J}_r$ is the rigid-body value, and is an estimate for the ground-state moment-of-inertia.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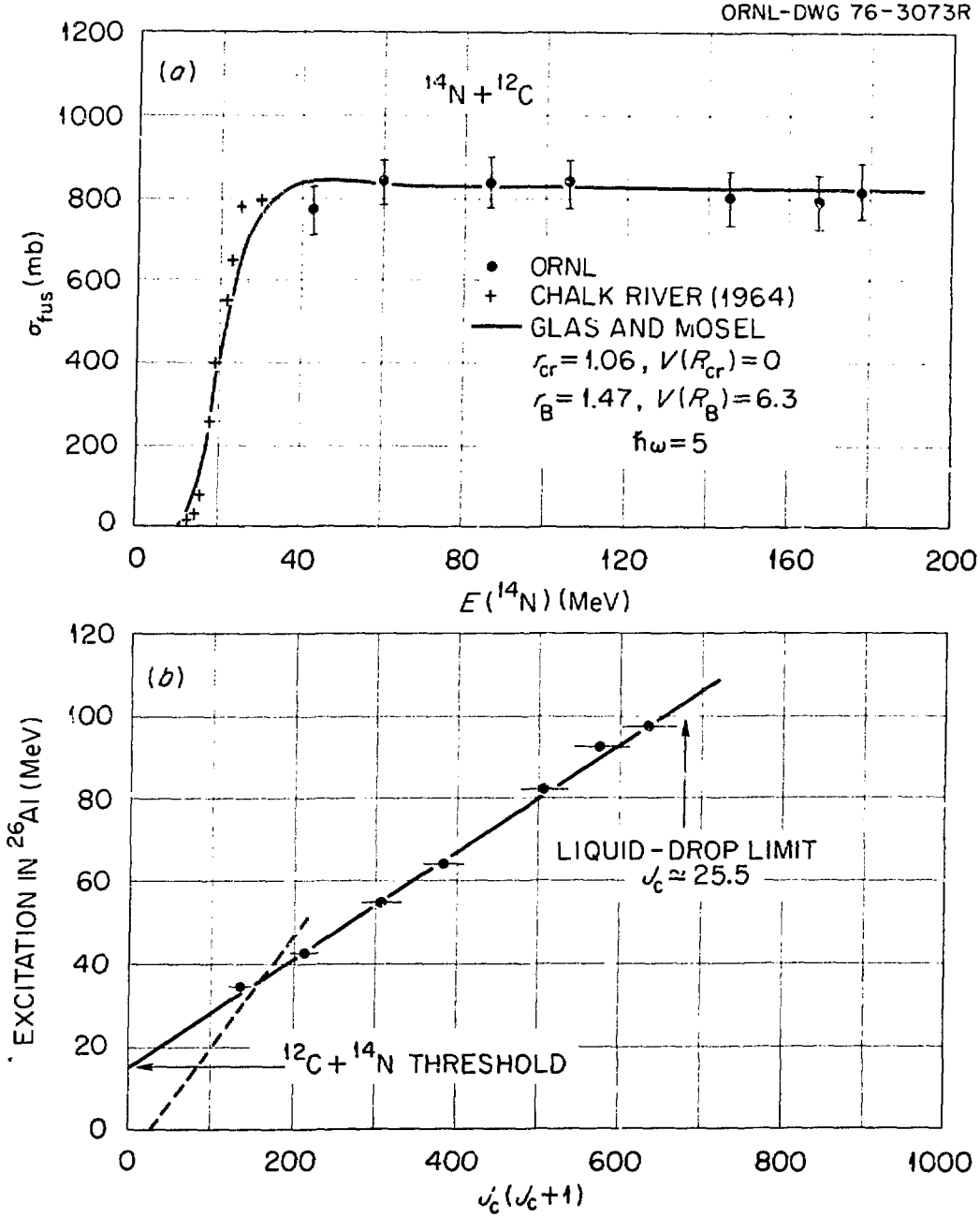
Z=11 θLAB=8°
E14N=86.3 MeV
Z=7 θLAB=15°
E14N=167.1 MeV
EXP.
CALC.
(d²σ/dΩdE)LAB (mb/sr-MeV)
ELAB/Ec.m.
E14N=86.3 MeV
E14N=167.1 MeV
EXP.
CALC.
σ(mb)
Z

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