same way for four heavy-ion reactions. The slope of the energy dissipation as a function of $\sigma_z{}^2$ is largest for small values of the variance and decreases as the variance increases. Under the assumption of the time scale discussed earlier, the initial energy loss rate is approximately 4×10^{23} MeV/sec, whereas this rate is decreased by a factor of 25 at a much later time when the total kinetic energy loss is 300 MeV (see Fig. 1). These results are consistent with the view that there is some type of rapid energy dissipation mechanism during the early stages of the collision (e.g., as proposed by Broglia, Dasso, and Winther[9]). However, the results may be consistent also with a statistical model where most of the energy loss goes into the production of particles and holes and transfer of nucleons. A more detailed presentation of the data in terms of the angle dependence of the variables will be submitted for publication.

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Measurements of Fusion Cross Sections for Heavy-Ion Systems at Very Low Energies*

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Measurements of the fusion cross sections for ^{10,11}B + ^{12}C, ^{12}C + ^{13}C, ^{12}C + ^{14}N, ^{14}N + ^{14}N, and ^{14}N + ^{16}O at sub-Coulomb-barrier energies, together with earlier results for ^{12}C + ^{12}C, ^{12}C + ^{16}O, and ^{16}O + ^{16}O, show that the average energy dependence of the fusion cross section can change dramatically with only small variations in the mass and charge of the interacting nuclei.

The measurement of heavy-ion reaction cross sections for systems such as ^{12}C + ^{12}C[1-3] at energies well below the Coulomb barrier has been a rich source of information on nuclear structure in the continuum. Perhaps because of their astrophysical significance,[4] the reactions which have been studied at the lowest possible bombarding energies until recently have involved only the α-conjugate nuclei ^{12}C and ^{16}O.[5-7] The discovery of "quasi-molecular" resonances in the fusion cross sections, σ_{fus}, for the reactions ^{12}C + ^{12}C (Refs. 1 and 2) and ^{12}C + ^{16}O (Ref. 5) has prompted measurements in many other systems near the Coulomb barrier.[8] However, in the search for narrow resonances in these other systems, the significance of the gross energy dependence of

$\sigma_{\rm fus}$ often has been neglected. Michaud and Vogt,[9] through their analyses of the reactions mentioned above, have drawn attention to the importance for nuclear structure physics of the average energy dependence of $\sigma_{\rm fus}$ at low energies. Certainly, the qualitative features shown by the three α-conjugate systems provide a strong motivation for similar studies of other heavy-ion systems at very low energies. We present, in this Letter, a brief description of the results of new measurements on six other heavy-ion systems in this mass region. The new feature which emerges from the present comparison of the various systems is that the average energy dependence of the fusion cross section at subbarrier energies may vary markedly from one system to the next even though differences of only one or two nucleons are involved. This is in sharp contrast to the situation usually encountered at energies above the barrier and in heavier systems.[10] Future articles will describe in more detail the experimental procedures, analyses, and results for the individual reactions.[11]

The experiments were performed with beams of ^{12}C, ^{14}N, and ^{16}O ions from the ONR–California Institute of Technology tandem accelerator. The present experimental method differs from previous measurements[1-3,5-7] of reaction cross sections at very low energies in that absolute fusion cross sections have been deduced from the observation with a Ge(Li) detector of discrete γ-ray transitions de-exciting low-lying states in heavy residual nuclei produced by p, n, or α-particle evaporation from the compound nucleus. The main advantage of this method is the high resolution of the Ge(Li) detector, which enables a discrimination against the radiation produced by contaminants in the target. The Hauser-Feshbach model is used to estimate the relative fraction of compound nuclear decays which contribute to the observed γ-ray transitions. In cases for which the γ-rays produced by primary p, n, and α emission to bound states are observed and may be effectively summed, the deduced absolute cross sections are very insensitive to the parameters entering into the Hauser-Feshbach calculations. In other cases, where only two of these three decay modes are observed, the ratio of the absolute cross sections deduced independently from each mode constitutes a partial check on the procudure and accompanying assumptions. A study of the ^{12}C + ^{16}O reaction,[11] for which measurements using other techniques exist,[5-7] was undertaken as a check on the reliability of the present method. The results agreed within the accuracy of the respective measurements. We estimate that the absolute normalizations for the deduced fusion cross sections are accurate to ± 30%. The data points at the lowest bombarding energy for each system have a statistical uncertainty of typically ± 30%.

Because of the large variation in cross section with bombarding energy (typically six to eight decades from the lowest to the highest energy), we express the results in the form of the nuclear S factor[4] defined by $S(E) = \sigma_{\rm fus} E \exp(2\pi\eta)$, where E is the effective bombarding energy in the center of mass and $\eta = Z_1 Z_2 e^2/\hbar v$ is the Sommerfeld parameter. In order to compare in one figure the S factors for a number of reactions having quite different Coulomb barriers we shift each energy scale by an amount $E_c = Z_1 Z_2 e^2/R_c$, where $R_c = 1.70 \times (A_1^{1/3} + A_2^{1/3})$ fm. The energy dependence of the experimental S factors is presented in Fig. 1. The S factors for ^{12}C + ^{12}C, ^{12}C + ^{16}O, and ^{16}O + ^{16}O are from Refs. 2, 3, 6, and 7.

This Letter consists mainly of a comparison of the *average or gross energy dependence* of the S factors over the region extending from 1 MeV above the barrier to ~ 4 MeV below the barrier. In order to facilitate a relative comparison of the observed experimental energy dependence, the results of a standard optical model calculation[9] ($V = 50$ MeV, $W = 10$ MeV, $r = 1.27$ fm, $a = 0.40$ fm) are shown for each case. The essential and new feature revealed by a comparison of the results shown in Fig. 1 is that the shape of the energy-averaged S factor for different systems may vary substantially, even though changes of only one or two nucleons are involved. The results for ^{10,11}B + ^{12}C and ^{13}C + ^{12}C illustrate this particularly well. At $E - E_c = -1$ MeV the measured S factor for ^{12}C + ^{13}C exceeds the standard optical-model prediction by a factor of ~ 2; at $E - E_c = -3.5$ MeV, it is smaller by a factor of ~ 2. The results for ^{10,11}B + ^{12}C however, agree rather well with the standard prediction over the entire energy region. The energy-averaged S factor for ^{12}C + ^{12}C (as would be given, for example, by a 1-MeV wide running average of the data shown in Fig. 1) has a shape which is strikingly different[12] from those for either ^{10,11}B + ^{12}C or for ^{12}C + ^{13}C. The three nitrogen-induced fusion reactions have a qualitatively similar energy dependence which differs, at the lowest energies, from that observed for ^{12}C + ^{16}O or ^{12}C + ^{13}C.

No simple qualitative explanation is immediately apparent for the sometimes different, some-

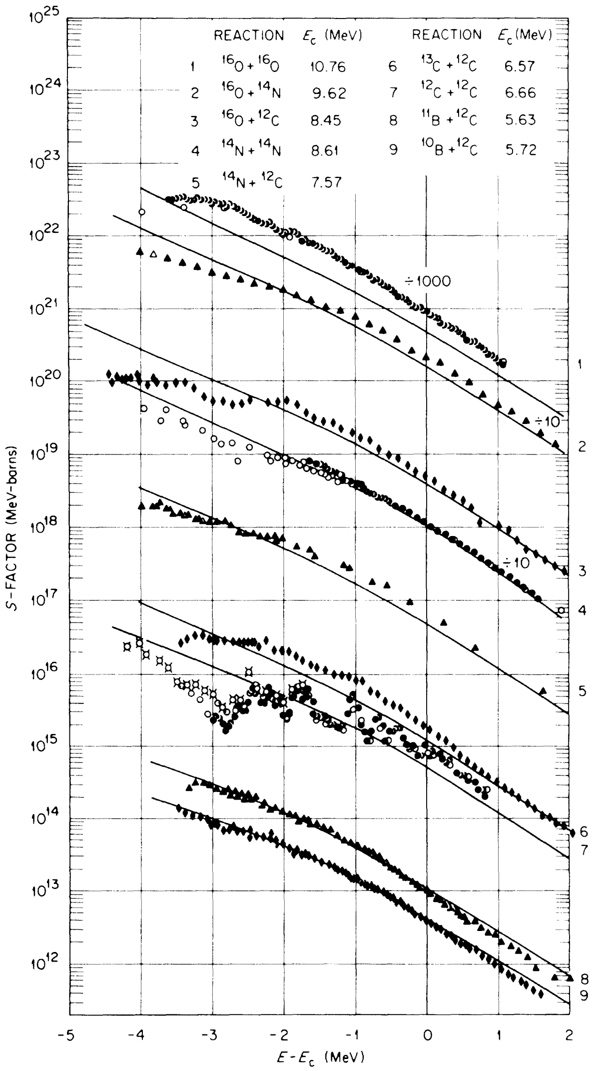

FIG. 1. Experimental fusion cross sections presented in terms of the nuclear structure S factor for nine heavy-ion reactions. The solid curves are the results of optical-model calculations as described in the text. Different symbols used for the same reaction indicate data taken at different laboratories or with different techniques (Refs. 2, 3, 5, 7, and 11).

times similar behavior exhibited at very low energies by the different systems shown in Fig. 1. Considerations of the possible roles played by coupling to low-lying excited states[13] of the target and projectile (polarization effects), α-particle degrees of freedom,[9] the density of states in the compound nucleus,[8,14] and the influence of valence nucleons on the tail of the potential may enter into the search for a complete theoretical explanation. One conclusion however seems firm—a marked change in the energy dependence of the S factor with a change of one or two nucleons in the colliding nuclei must reflect an importance individual nucleons have in the fusion process which goes beyond their obvious contribution to changes in macroscopic variables such as the Coulomb barrier and the $A^{1/3}$ dependence of the rms radius. Thus, the present experimental data present a new example of the emergence of microscopic effects in heavy-ion fusion,[15] a process which, in most cases, is analyzed and understood in terms of macroscopic quantities.[10]

In all cases considered here except $^{10,11}B+^{12}C$, the optical-model prediction based on the standard parameters[9] exceeds the measured S factor at the lowest energies.[16,17] It is true that the agreement with experiment could be improved in some individual cases by an *ad hoc* variation of the parameters entering into the optical model.[18] In this case, the essential feature of the experimental data for the nine systems shown in Fig. 1 would be restated in terms of a variation of the optical-model parameters for some systems which exceeds the smooth variation expected in the absence of microscopic effects. It is likely that this irregular variation of parameters will be necessary for any particular choice of macroscopic barrier-penetration model used to fit the data.

In conclusion, the average energy dependence of the fusion cross section at low energies can exhibit a marked sensitivity to small variations in the proton- and neutron-number of the interacting nuclei. It appears, therefore, that a satisfactory explanation of the experimental results presented here will require a microscopic treatment of the fusion and barrier-penetration processes.

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High Resolution Threshold Photofragment Spectroscopy of $O_2^+(a\,^4\Pi_u \to f\,^4\Pi_g)$†

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A new technique of laser photofragment spectroscopy is introduced and applied to a study of transitions from the $v = 4$ level of the $a\,^4\Pi_u$ state of O_2^+ to predissociating levels of the $f\,^4\Pi_g$ state near the dissociation limit. A resolution of 0.5 MeV is obtained, and specific (Ω, J) levels of the a state are identified. Much higher resolution is possible.

Laser photofragment spectroscopy[1-5] has recently become an established technique for the study of the potential curves of molecular ions. With this technique, one crosses a fast beam of ions (1–10 keV) with polarized photons from a laser and measures the energy spectrum of the photofragment ions produced in photodissociation processes. By rotating the laser polarization, one obtains the angular distribution of these photofragments. There are well-established methods[1-6] with which one can use this information to determine the vibrational spacings of ground, metastable, and predissociative excited states, transition symmetries, molecular bond energies, and potential curves of dissociative states. This technique is limited, however, by the available resolution in the kinetic energy of the ejected photofragments. Even though the center-of-mass en-