Total nuclear reaction probabilities for 2 to 6 MeV/nucleon d and ^{3}He in Si

R. E. Warner,* C. P. Browne, S. E. Darden, J. J. Kolata, and A. Rollefson
University of Notre Dame, Notre Dame, Indiana 46556

P. A. Kimoto
Oberlin College, Oberlin, Ohio 44074

A. Galonsky
Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824
(Received 18 January 1988)

The total nuclear reaction probabilities for 4–13 MeV deuterons and 5–18 MeV ^{3}He ions stopping in Si were measured, in coincidence studies of d+^{3}He elastic scattering. These probabilities are about 3×10^{-3} and 8×10^{-4}, respectively, for the most energetic d and ^{3}He investigated, and are slightly lower than those predicted using total reaction cross sections σ_R calculated with the optical model. Evidence of the DeVries-Peng scaling anomaly (deuterons have larger radii but smaller σ_R than ^{3}He) is presented.

I. INTRODUCTION

In this paper we report measurements of the total probability η for 2 to 6 MeV/nucleon deuterons and ^{3}He projectiles, incident upon Si, to undergo inelastic nuclear interactions before being brought to rest by ionization processes resulting from their electromagnetic interactions. Consider a particle of energy E, at which the total reaction cross section is σ_R, traveling a distance dx in matter with ρ nuclei per unit volume. Its probability $d\eta=\sigma_R dx$ of interacting in this distance may be related to the stopping power dE/dx (Refs. 1 and 2) and the ionization loss dE which it would otherwise experience through the relationship $dx=(dE/dx)^{-1}dE$. Since at such low energies there is negligible probability that the particle will interact inelastically more than once during the stopping process, the total reaction probability η is given by

$$\eta(E_0)=\int_0^{E_0}\sigma_R\rho(dE/dx)^{-1}dE \ , \tag{1}$$

where E_0 is the initial energy. Finally, the cross section at some energy E is proportional to the slope at that energy of the curve $\eta(E_0)$ vs R_0, where R_0 is the range of a projectile of energy E_0.

Few direct measurements of the total reaction cross section, a parameter of several nuclear models, exist at low energies. Often, this important quantity is deduced from optical model analyses of elastic scattering data. The total reaction cross sections for 16 MeV protons have, for example, been measured[3] for several target nuclei. We believe that our data are the lowest-energy measurements of η and σ_R yet reported for composite projectiles.

DeVries and Peng[4] have surveyed the available nucleus-nucleus total reaction cross section data (obtained through both direct measurement and optical model analysis) which they interpret with a two-parameter formula

$$\sigma_R=\pi(R_i+\lambda\!\!\!^{-})^2\left[1-\frac{zZe^2}{(R_i+\lambda\!\!\!^{-})E}\right](1-T) \ , \tag{2}$$

based on the assumption that a projectile following the classical Coulomb trajectory[5] has a probability $(1-T)$ of interacting if the distance of closest approach does not exceed the sum of the effective hard-sphere interaction radius R_i and the reduced wavelength $\lambda\!\!\!^{-}$ of the incident particle. E represents the c.m. energy in Eq. (2), and ze and Ze are the charges of projectile and target, respectively. An effective test of the theory is obtained at low energies where one free parameter, the transparency T, is assumed to vanish. The other free parameter R_i is given by

$$R_i=\sqrt{5/3}(r_p+r_t) \ , \tag{3}$$

where the rms projectile and target radii, r_p and r_t, respectively, are obtained from standard tables.[6]

Such a "broad-brush" theory necessarily omits details related to the structure of individual nuclei. Moreover, it assumes zero cross section below the Coulomb barrier energy [here defined as that energy for which σ_R, as calculated from Eq. (2), vanishes], thus excluding such well-known effects as Coulomb excitation,[7] sub-Coulomb stripping,[8] and reactions initiated by nucleon tunneling[9] or barrier penetration by one cluster of a complex projectile.[10] An important question raised by DeVries and Peng has to do with the scaling of R_i with projectile radius. Even though deuterons have larger radii than ^{3}He, existing cross section data generally require larger interaction radii for ^{3}He than for deuterons incident upon the same nucleus. Our data provide further evidence for this anomaly.

Reaction cross section measurements for Si have particular value since Si crystals often are used as charged particle detectors. Anomalous pulse heights result when the detected particles interact inelastically with the detector nuclei. The counts in the "full energy peak" must be corrected for such losses when absolute cross sections are being measured. Proton loss factors have been measured at 25–50 MeV for Ge (Ref. 11) and other detectors[12] and at 30–150 MeV for NaI(*Tl*).[13] The only previously reported loss factors for composite projectiles are for 35–250 MeV deuterons in Ge.[14,15] Our present measurements show that below 20 MeV, losses in Si will not exceed 1% for deuterons or 0.1% for ^{3}He.

II. THE MEASUREMENTS

Our method for measuring reaction probabilities, previously used by some of us[14] to measure losses of 35–105 MeV deuterons in Ge, is based upon coincidence detection of elastic scattering events. The particle whose reaction probability is not being measured is detected in a "recoil" telescope whose aperture is small enough to determine the effective solid angle for coincidence detection. Similarly, the particle of interest is stopped in a "measuring" telescope whose aperture is large enough to exclude slit-edge energy losses, and whose stopping counter must have large enough transverse dimensions to stop all elastically scattered particles (except those backscattered, as will be discussed later). By changing the scattering angle, particles of different energies can be directed toward the measuring telescope. Moreover, in the present experiments, measurements for both d and ^{3}He were made by interchanging the roles of the two telescopes.

A 2.2 mg/cm^2 CD_2 target was bombarded at the University of Notre Dame tandem accelerator by a ^{3}He beam whose energy at target center was 24.0 MeV. Beam currents of 2–8 nA were utilized.

The recoil telescope had a rectangular (2×4 mm) tantalum aperture to reduce kinematic broadening, immediately followed by Si detectors of 50 and 2000 μm thickness. The measuring telescope used a 5×10 mm aperture followed by Si detectors of 30 and 1000 μm thickness, whose usable areas were 200 and 300 mm^2, respectively. In general, detection of deuterons in a given solid angle constrains the recoil ^{3}He's into a smaller solid angle. Thus, when ^{3}He reaction probabilities were measured, the recoil telescope defining aperture and the measuring telescope aperture were placed at 90 and 112 mm from the target, respectively. When deuterons were measured, the less favorable kinematics required that the recoil telescope aperture be set back to 129 mm, and the measuring telescope aperture be brought forward to 79 mm, from the target. Safety factors (ratio of geometric width of the measuring telescope aperture to the width actually illuminated by particles detected in coincidence) ranged from 2.3 to 4.6 in this experiment. The adequacy of clearance was verified by measurements showing that the elastic coincidence detection ratio remained constant when one telescope was held fixed and the second was moved within the expected angular range.

Conventional fast-slow electronics were used, as in the earlier coincidence measurements,[16] with pileup rejection added to improve the quality of the spectra in the measuring telescope. Pulse height data from the four detectors and the time difference between the passing counter signals were recorded in event mode on magnetic tape. Random coincidence rates in the regions outside the stopped peak were typically 1% of total rates and were subtracted in the usual manner.

The possibilities for detecting contaminant events from reactions other than d + ^{3}He elastic scattering were carefully considered. When deuterons were measured, ^{3}He's which elastically scattered always left at least 2.5 MeV more energy in the recoil telescope than those which caused deuteron breakup. For the ^{3}He reaction probability measurements, a still larger separation between the deuteron groups from elastic scattering and ^{3}He breakup resulted. Although the CD_2 target contained about 1% ordinary hydrogen, opening angles between reaction products from ^{3}He + p elastic scattering and the ^{3}He + p$\rightarrow$d + 2p reaction were too small for such events to be recorded. Finally, runs with a CH_2 target showed that background from all reactions in the ^{3}He + ^{12}C system was negligible. In fact, the only events recorded during such runs were elastic ^{3}He + d scattering from the 0.07% deuterium "contamination" in the CH_2 target.

III. ANALYSIS OF THE DATA

Those events were accepted for which the recoil telescope pulse heights identified a particle of proper type with the energy resulting from d + ^{3}He elastic scattering, the time signal was within either the total or random coincidence window, and the passing counter of the measuring telescope showed normal energy loss for an elastically scattered particle. Nearly always, when the appropriate particle with the correct energy was identified in the recoil telescope, the desired particle passed through the measuring telescope without hitting its slit. However, to identify confidently the very small fraction of particles which interacted in the stopping counter of the measuring telescope, we had to test the energy loss in the passing counter of that telescope, for the following reasons. Multiple scattering in the target caused some particles to hit the edge of the measuring telescope slit before detection. Occasional wandering of the beam also caused abnormal energy losses through slit-edge interactions or, possibly, the illumination of a thick spot on the target. Finally, although pileup rejection was largely effective, some pileup events were noted in the spectra and eliminated by the energy loss test. A fairly tight gate was set on the passing counter signal, accepting only about 80% of the events in the elastic peak. We verified that our results were independent of this gate width in a range where the acceptance varied from about 50% to 90%.

A typical recorded energy spectrum, that from 12.7 MeV deuterons in the 1000 μm detector, is presented in Fig. 1. The maximum energies available from various charged-particle reactions on the principal isotope ^{28}Si (92.2% abundance) are shown, as well as those of two of

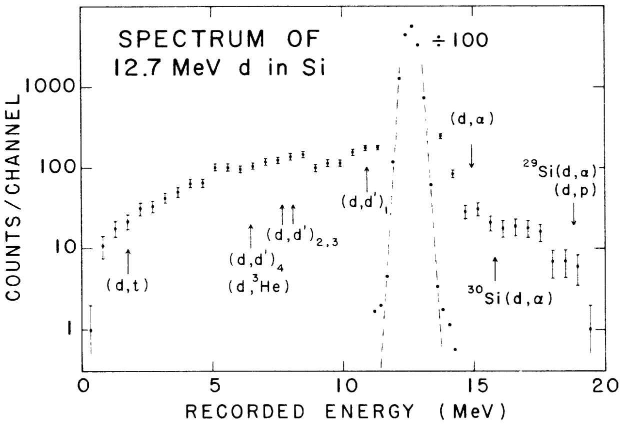

FIG. 1. Gated spectrum of 12.7 MeV deuterons in a 1000 μm Si detector. Dashed lines delineate the peak due to particles stopped entirely by ionization loss. Maximum energies which the ^{29,30}Si(d,α) reactions can deposit are indicated. Other symbols denote maximum energies from charged-particle reactions on the principal isotope ^{28}Si.

the three highest-Q reactions on the other stable isotopes ^{29}Si and ^{30}Si (4.7 and 3.1 %, respectively). [The ^{29}Si(d,p) threshold lies further to the right, but only one count was recorded for energies higher than those shown.] The positive-Q reactions obviously yield some events which deposit more energy than those in the stopped peak. Other notable features of the spectrum are the absence of counts above the ^{28}Si(d,p) ground state threshold and the enhancements due to inelastic scattering to the first three ^{28}Si excited states.[17] Apart from these enhancements, the spectrum is a rather smooth continuum as the result of escape of both protons and neutrons from stripping reactions, stripping into the continuum, deuteron breakup, etc. All observed spectra, including this one, showed more counts per channel below than above the stopped peak.

The experimental conditions for scattering particles into the measuring telescope, and our measured total reaction probabilities for particles of these energies, are given in Table I. The probabilities were calculated by summing the reaction events which lie below, above, and (presumably) under the stopped peak, and dividing these by the counts in the peak. The peak channels were delineated by fitting separate exponential functions to the two sides of the peak, as is shown in Fig. 1. This procedure was preferable to Gaussian fitting, since effects such as kinematic broadening and the Landau effect (more large than small losses in the passing counter) make the peak somewhat asymmetric. The reaction events per channel under the peak were assumed to equal the average of the counts per channel below and above the peak. The uncertainty in this quantity was then increased to encompass the possibilities that it was as large as the average value below, or as small as the average value above, the peak.

Possible systematic errors due to two elastic scattering effects were considered. First, particles may backscatter and then leave the stopping detector, yielding small pulses whose misinterpretation as reaction events would erroneously increase η. To evaluate this effect, the cross section for elastic scattering at angles greater than 90° was calculated for d + Si and ^{3}He + Si elastic scattering using the code PTOLEMY (Ref. 18) and accepted optical parameters[19,20] for these systems as input data. Consideration of the maximum depth from which backscattered particles could escape from the detector leads to escape probabilities of about 10^{-6} and 5×10^{-6} for 12 MeV ^{3}He's and 10 MeV deuterons, respectively. Moreover, some escaping particles would reenter the passing counter, generating a large enough signal to veto the event. Thus the number of misidentified events would be further reduced by a significant, though difficult to calculate, factor.

A second elastic scattering effect[21] could erroneously *reduce* the number of reaction events which are counted. Consider a particle whose energy is reduced by $\Delta E = E_i - E_f$ by elastic scattering, while other particles must travel a distance $\Delta x = (dE/dx)^{-1}\Delta E$ to achieve the same energy loss through ionization. The elastically scattered particle is, in effect, "deprived" of the opportunity to interact inelastically in the distance Δx. Taking into account the dependence of energy loss, available solid angle, and differential cross section (calculated with previously cited optical parameters) on the scattering angle, we estimated that the fractional reduction in the effective range is less than 10^{-3} for both deuterons and ^{3}He. Therefore, systematic errors from both these effects are negligible in this experiment, compared with the statistical uncertainties of about 10%.

TABLE I. Experimental conditions and results. E_c is the energy at target center, immediately after scattering; E_0 is the energy when incident upon stopping counter.

Particle	θ (lab)	E_c (MeV)	E_0 (MeV)	Reaction probability η
d	61.8°	5.1	3.9	$(2.41\pm0.24)\times10^{-4}$
d	56.3°	7.1	6.3	$(5.8\pm0.7)\times10^{-4}$
d	49.1°	9.8	9.3	$(1.67\pm0.10)\times10^{-3}$
d	41.0°	13.1	12.7	$(3.21\pm0.20)\times10^{-3}$
τ	39.0°	8.6	4.6	$(3.6\pm1.1)\times10^{-5}$
τ	30.0°	14.7	12.5	$(3.19\pm0.36)\times10^{-4}$
τ	20.0°	19.7	18.1	$(8.1\pm0.7)\times10^{-4}$

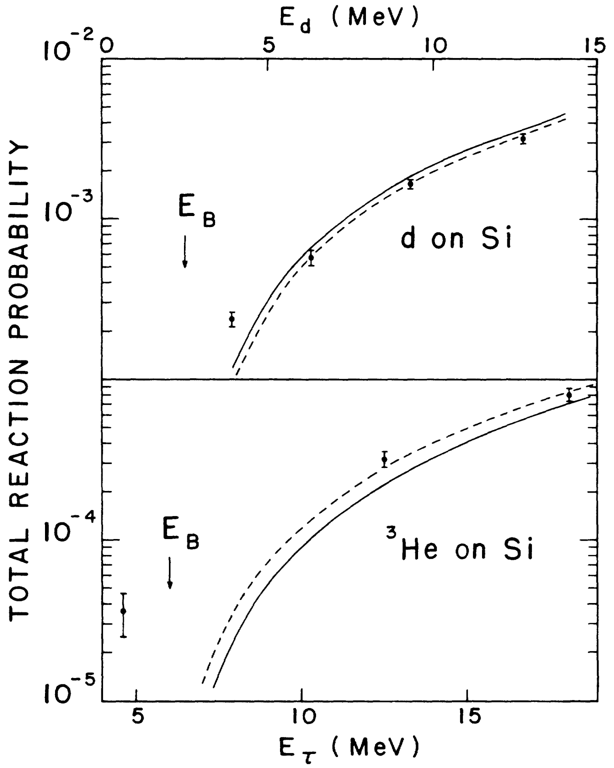

FIG. 2. Total reaction probability vs incident energy for d and ^{3}He on Si. Solid curves show predictions of Eq. (2) using nuclear radii from Ref. 6; dashed curves are for other radii specified in the text. Coulomb barrier energies, where Eq. (1) predicts $\sigma_R = 0$, are indicated by E_B.

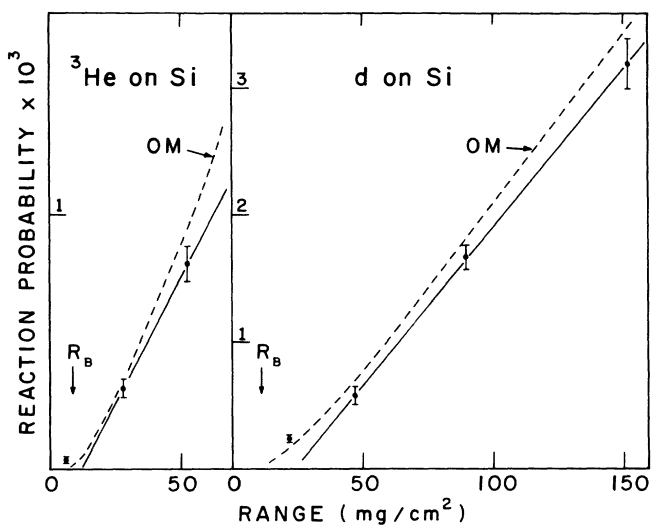

FIG. 3. Total reaction probability vs range of incident particle. Predictions (dashed lines) were obtained by integrating Eq. (1) with σ_R's calculated from the optical model. Ranges of particles at the Coulomb barrier energy are denoted by R_B.

IV. RESULTS AND CONCLUSIONS

Our results for total reaction probability versus particle energy are plotted in Fig. 2, where they are compared with predictions from Eq. (2) with $T = 0$. The solid lines apply when the effective interaction radius is calculated [via Eq. (3)] using the accepted values[6] of the radii of d, ^{3}He, and ^{28}Si: namely, 2.09, 1.88, and 3.11 fm, respectively. Two features are apparent. First, this theory, which makes the cross section vanish at and below the Coulomb barrier, underpredicts the reaction cross section at very low energies where such processes as Coulomb excitation, tunneling, sub-Coulomb stripping, etc., operate. Second, at the higher energies the theory underpredicts the cross section for ^{3}He and overpredicts that for deuterons. Better fits, represented by the dashed lines, were found by lowering the deuteron radius to 1.92 fm and raising that for ^{3}He to 2.16 fm. DeVries and Peng[4] have noted a persistent anomaly in low energy total cross section data: Although deuterons have larger radii than ^{3}He, the effective interaction radius is larger for ^{3}He than for deuterons interacting with the same nucleus. Thus our work provides further evidence for this anomaly.

In Fig. 3 the measured reaction probabilities are plotted versus the range of the incident particle. This presentation is chosen since the slope at any energy is proportional to the total reaction cross section at that energy. The data are compared with predictions (dashed lines) obtained by calculating σ_R from the optical model parameters,[19,20] and then integrating Eq. (1). Stopping powers from the Williamson tables[1] were used. These agree within 1%, for protons and α particles in the energy range of interest to us, with the stopping powers given by Ziegler.[2] Above the Coulomb barrier, our measured probabilities are consistently lower than the predictions by at least one standard deviation per point. Thus they indicate that the total reaction cross sections are at least 10% lower than those inferred from the optical model analyses of the elastic scattering data. The solid lines in Fig. 3 indicate the average slopes of our data just above the Coulomb barrier. They show that the average total reaction cross section is 935 mb for ^{3}He + Si between 12 and 18 MeV, and 1170 mb for d + Si between 6 and 13 MeV.

In conclusion, we find (by extension of our calculations) that reaction losses in Si detectors cannot exceed 0.1 and 1 % for ^{3}He and deuterons, respectively, with energies up to 20 MeV. We agree with DeVries and Peng[4] that the reaction cross sections of these two projectiles on Si scale anomalously with their radii. Finally, our measured total reaction probabilities are somewhat smaller than those obtained by calculating total reaction cross sections from the optical model.

ACKNOWLEDGMENTS

We wish to thank Dr. Mamoru Fujiwara for a helpful discussion of this work, L. Lamm and R. Vojtech for their assistance with the offline computer analysis, and Z. Ayer, M. Gummin, L. van Wormer, and X. Yang for assistance in accelerator operation and data collection. We also thank the National Science Foundation for financial support of this work under Grants PHY-8521042, PHY-8421302, and PHY-861-1120.

*Permanent address: Oberlin College, Oberlin, OH 44074.
†Permanent address: University of Arkansas, Little Rock, AR 72204.

[1]C. F. Williamson, J.-P. Boujot, and J. Picard, Tables of Range and Stopping Power of Chemical Elements for Charged Particles of Energy 0.05 to 500 MeV, Commissariat d'Energie Atomique Report No. R3042, Saclay, 1966.
[2]J. F. Ziegler, *The Stopping and Ranges of Particles in Matter* (Pergamon, New York, 1977), Vols. 3 and 4.
[3]R. E. Pollock and G. Schrank, Phys. Rev. **140**, 575B (1965).
[4]R. M. DeVries and J. C. Peng, Phys. Rev. C **22**, 1055 (1980).
[5]M. M. Shapiro, Phys. Rev. **90**, 171 (1953).
[6]C. W. de Jager, H. de Vries, and C. de Vries, At. Data Nucl. Data Tables **14**, 479 (1974).
[7]D. Cline, Annu. Rev. Nucl. Sci. **36**, 683 (1986).
[8]L. D. Knutson and W. Haeberli, Phys. Rev. Lett. **35**, 558 (1975).
[9]J. D. Cockcroft and E. T. S. Walton, Nature **129**, 649 (1932).
[10]O. Häusser *et al.*, Phys. Lett. **38B**, 75 (1972).
[11]R. F. Carlson *et al.*, Nucl. Instrum. Methods **188**, 465 (1981).
[12]A. M. Sourkes *et al.*, Nucl. Instrum. Methods **143**, 589 (1977).
[13]J. N. Palmieri and J. Wolfe, Nucl. Instrum. Methods **76**, 55 (1969).
[14]D. Friesel *et al.*, Nucl. Instrum. Methods Phys. Res. **B16**, 96 (1986).
[15]R. M. Eisberg *et al.*, Nucl. Instrum. Methods **146**, 487 (1977).
[16]R. E. Warner *et al.*, Nucl. Phys. **A470**, 339 (1987).
[17]P. M. Endt and C. van der Leun, Nucl. Phys. **A310**, 1 (1978).
[18]Program PTOLEMY, M. H. Macfarlane and S. C. Pieper, Argonne National Laboratory Report ANL-76-11, 1976.
[19]C. M. Perey and F. G. Perey, Phys. Rev. **152**, 923 (1966).
[20]K. H. Bray, J. Nurzynski, and G. R. Satchler, Nucl. Phys. **67**, 417 (1965).
[21]M. Fujiwara, private communication.