Light-ion elastic scattering potentials: Energy and projectile-mass dependence

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(Received 15 January 2003; published 29 July 2003)

Volume integrals of the real potentials derived from elastic scattering studies of deuterons, tritons, ^{3}He, and α particles have been calculated for data available from the lowest to the highest energy. These volume integrals have been plotted as a function of energy per nucleon for each projectile. By selecting energy regions where there were least ambiguities in the potentials and averaging the volume integrals in 1 MeV bins, the energy dependences were determined. The volume integrals show a logarithmic dependence on the energy per nucleon. The zero crossing of the potentials is at about the same value of $\sim$650 MeV/nucleon for all projectiles. With increasing projectile mass, the potentials become weaker, possibly due to Pauli blocking effects in the projectile. Neutron-rich projectiles have smaller volume integrals due to the manifestation of the isospin effect. A similar analysis of the imaginary volume integrals shows that they increase from zero at the lowest energies to about 100–150 MeV fm^3 around 10 MeV/nucleon and then remain essentially constant.

DOI: 10.1103/PhysRevC.68.014613 PACS number(s): 25.10.+s, 24.10.−i, 25.55.Ci

I. INTRODUCTION

Elastic scattering of light ions ($A \leqslant 4$) from nuclei has been a subject of study for several decades. The major reason for these studies was to understand the interaction of these composite projectiles with the nucleus. Various methods were attempted to interpret the experimental data. However, the success of the optical model in explaining proton elastic scattering data [1,2] led investigators to apply the optical-model techniques to the analyses of light-ion scattering. It was envisaged that such a model should provide a convenient and consistent parametrization of the data. The resulting optical-model potential parameters that fit the elastic scattering data were expected to provide physical information on the interaction of light ions with the nucleus. The energy and projectile-target-mass dependence of the potential parameters should provide more insight into the effective nuclear mean field that causes the scattering of the light ions.

The most extensive work was carried out with α particles. However, the early investigators of α elastic scattering encountered persistent difficulties in determining unambiguous potential parameters. First was the *continuous* correlation between the strength V_0 and the geometrical parameters of radius and diffuseness, r_0 and a_0, resulting in spurious energy dependences of these individual parameters. A change from the best-fit value of one parameter can be compensated by adjustments of the other two, resulting in an equally good fit to the data. This ambiguity problem was resolved by calculating the volume integral J_R of the potential which is free of these parameter correlations and is considered to be a well-defined quantity for the interaction. A more serious problem encountered in low energy ($E \leqslant 100$ MeV) α elastic scattering investigations was the existence of *discrete* ambiguities in the potentials [3–7]. For each set of scattering data, a number of families of parameters with greatly different volume integrals were obtained. These discrete potentials correspond to different numbers of half wavelengths of the projectile wave function contained within the nuclear potential well [8]. The primary cause of the discrete ambiguity is the limited range of the measured differential cross section angular distribution. At these low energies the Coulomb repulsion and strong absorption prevent the α particle from penetrating the nucleus. Thus it samples only the extreme surface region of the nucleus. The forward angular distribution is characterized by smooth exponential falloffs due to Rutherford scattering followed by the Coulomb rainbow. Then comes the angular region of nuclear Fraunhofer diffraction oscillations. These oscillations are basically due to the interference between the far-side and near-side scattered waves. It is this region that is responsible for the discrete ambiguous potentials. As higher energy beams became available, measurements over sufficiently broad angular ranges [9–16] showed that the diffraction region is followed by another smooth exponential falloff. This is sometimes referred to as the nuclear rainbow scattering region. Because of the deeper penetration of the α particle into the nucleus, the near-side scattered wave is absorbed, resulting in the disappearance of the oscillatory structure. Since the α particle now samples smaller radial regions of the nucleus, unique potentials have been obtained. In their analysis of 40–142 MeV α particle elastic scattering from Zr isotopes, Put and Paans [17] showed the transition from multiple discrete ambiguous potentials to a single unique potential.

The volume integrals for ^{3}He are widely scattered at low energies [18,19]. Discrete ambiguous potentials were obtained for energies between $\sim$30 MeV and $\sim$100 MeV [21,20]. Beyond 100 MeV, unique potentials have been determined [22]. The deuteron volume integrals also display a wide range of values at low energies [23–25], narrowing to a smaller spread beyond 25 MeV. Features of the triton volume integrals are similar, but the maximum energy for which data are available is only 38 MeV.

Very little information is available on the systematics of light-ion scattering potentials. Several attempts were made to determine the energy dependence of composite-projectile potentials. Most of these studies involved a single projectile scattering off one or more target nuclei over some limited energy range. Consequently, different *linear* energy dependences were determined by different investigators, and were often not consistent. Also, no comparison was made between the potentials of different composite projectiles, although it was recognized that the potentials were weaker than those deduced from proton values. It was this paucity of information on the systematic trends of light-ion elastic scattering potentials that has prompted us to carry out a review of light-ion elastic scattering potentials, with the goal of determining both their energy and projectile-mass dependences. Section II discusses the parameter selection and analysis procedure. The energy dependences of the volume integrals are derived in Sec. III. Section IV provides a comparison of the various light-ion potentials. A review of the imaginary potential volume integrals is given in Section V. Sec. VI contains the results and conclusions of our investigations.

II. PARAMETER SELECTION AND ANALYSIS PROCEDURE

The compilation of Perey and Perey [26] listing optical-model potential parameters derived from light-ion elastic scattering studies up to 1975 provided the initial parameter set for the various projectiles. Additional values for α elastic scattering were obtained from the studies of Majka *et al.* [27], Put and Paans [17], Bonin *et al.* [15], and Ingemarsson *et al.* [16]. To obtain the highest-energy potentials, we performed standard optical model analyses with Woods-Saxon form factors (described below) of the data for 1370-MeV α particles scattering from ^{12}C and ^{40,42,44,48}Ca [13,14]. More ^{3}He parameters were obtained from the work of Didelez *et al.* [20], Singh *et al.* [28], and Yamagata *et al.* [29]. Other deuteron parameters were obtained from the work of Sawada [30], Ingermarsson and Tibell [31], Knopfle *et al.* [32], Aspelund *et al.* [33], and Nguyen Van Sen *et al.* [34]. Additional triton potential parameters were obtained from the compilation of Ward and Hayes [35]. Most of the light-ion elastic scattering data were analyzed in terms of the optical model with real and imaginary central potentials. Since these potentials represent the mass distribution of the target nucleus, they are spherically symmetric, and the radial shape is given by the Woods-Saxon form

$$V(r)=V_0/(1+\exp[(r-r_0A_t^{1/3})/a_0]),$$

where the parameters V_0, r_0, and a_0 define the strength and shape of the potential. Since V_0, r_0, and a_0 correlate with each other, it is appropriate to determine the volume integral J_R of the potential. This is the spatial integral of the potential, weighted by the strength. It is free of the continuous parameter ambiguities and defines the total effective potential for the projectile-target interaction. However, J_R is found to be proportional to both the projectile and target masses. Therefore, following common practice, we calculated the real volume integral per nucleon pair, defined as

$$J_R/A_pA_t=[1/A_pA_t]\int V(r)d\mathbf{r},$$

where A_p and A_t are the projectile and target mass numbers. Therefore J_R/A_pA_t is independent of the interacting masses and is expected to be the same for all target/projectile combinations. Thus it provides a basis for comparison of the interaction potentials for targets and projectiles across the periodic table. The derived volume integrals per nucleon pair are plotted as a function of energy per nucleon in Figs. 1, 3, 4, and 5. They will be discussed in the following section.

III. ENERGY DEPENDENCE OF THE REAL VOLUME INTEGRALS

A. α particles

Many investigators attempted to determine the energy dependence of the α-nucleus potential. Lerner *et al.* [37] obtained a linear energy dependence of the strength, V_0, for α particle scattering from ^{40}Ca between 40 and 115 MeV. Smith *et al.* [38] derived a linear energy dependence of the α-^{12}C volume integrals from 104 to 166 MeV of the form $J_R/A_pA_t(E)=J_R/A_pA_t(0)[1-aE]$, with $a=0.003$ MeV^{-1}. Put and Paans [17] obtained a linear energy dependence of the strength V_0 for $\alpha+{}^{90}$Zr from 80 to 142 MeV with a slope of 0.25 ± 0.05. These investigators obtained linear energy dependences because of the fact that the analyses were carried out over narrow energy ranges. The logarithmic energy dependence that we derive over a very wide energy range can be approximated by a linear form over small energy ranges.

In our analysis, we included parameters from all known investigations. Figure 1 presents the calculated volume integrals as a function of energy per nucleon, E/A. The low-energy volume integrals have a large spread, ranging from $\sim$50 to $\sim$1900 MeV fm^3. As the energy increases this spread narrows. For E/A between $\sim$5 MeV and $\sim$25 MeV, one observes groups of volume integrals due to the discrete ambiguous potentials. Beyond 25 MeV/nucleon, unique potentials have been determined. Even these unique potentials have some spread due to different methodologies of analysis and differences in the absolute normalization of the data. We averaged the volume integrals for $E/A\geqslant25$ MeV. These are plotted as a function of energy per nucleon in Fig. 2. A least-squares fit to the data gives a logarithmic energy dependence of the form

$$J_R/A_pA_t(E)=J_R^0/A_pA_t-\beta\ln E$$

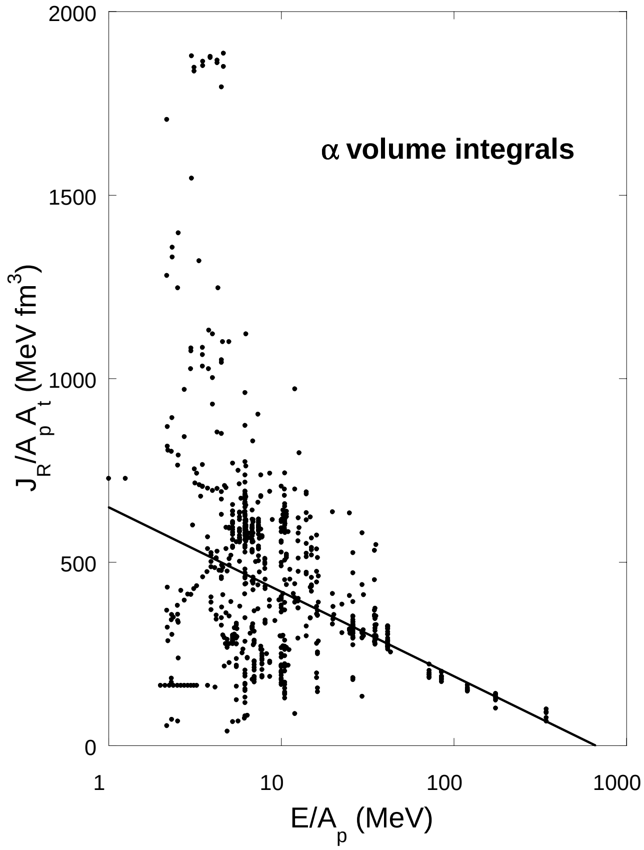

FIG. 1. α volume integrals versus energy per nucleon. The solid line is a logarithmic fit as discussed in the text.

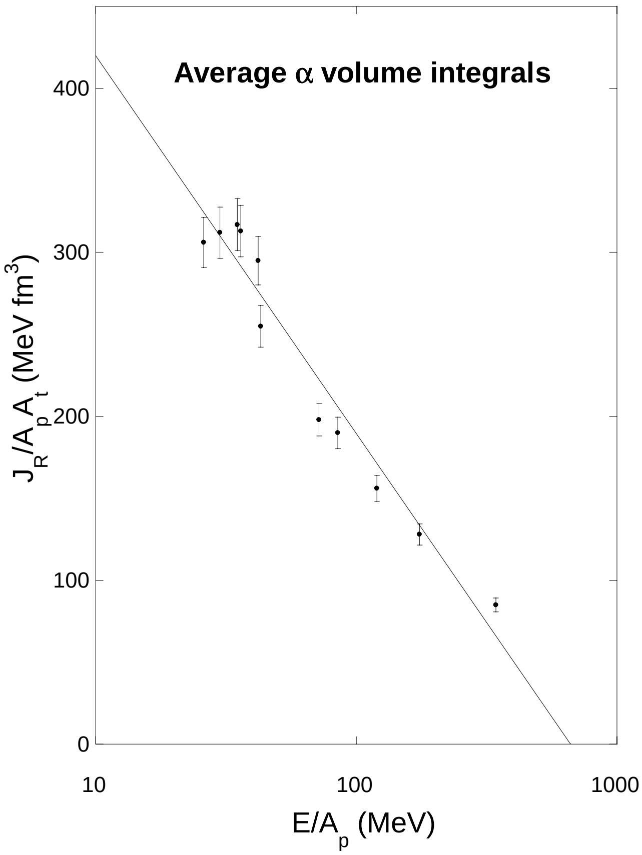

FIG. 2. Average α volume integrals versus energy per nucleon.

with $J_R^0/A_pA_t = 650 \pm 33$ MeV fm^3 and $\beta = 100 \pm 5$ MeV fm^3. This energy dependence is plotted as solid lines in Figs. 1 and 2. The zero crossing of the potential in its transition from attractive to repulsive is found to be at 670 $\pm$70 MeV/nucleon, which is in agreement with proton and neutron values [39].

B. ^{3}He particles

Several attempts were made by investigators to determine the energy dependence of ^{3}He elastic scattering potentials. Fulmer *et al.* [40] obtained a linear energy dependence of the strength, $V_0 = 133.9 - 0.14E$, for $^3\mathrm{He} + ^{60}\mathrm{Ni}$ elastic scattering from 30 to 71 MeV. Chang *et al.* [41] analyzed ^{3}He elastic scattering from ^{40}Ca and ^{58}Ni between 28 and 84 MeV and also obtained a linear energy dependence of the strength. In their analysis of $^3\mathrm{He} + ^{58}\mathrm{Ni}$ in the energy region 90–120 MeV, Hyakutake *et al.* [36] derived a linear energy dependence of the form $V_0 = 121.1 - 0.173E$. By including the results of the 217-MeV studies, they obtained a logarithmic energy dependence of the ^{3}He volume integrals with $J_R^0/3A = 640$ MeV fm^3 and $\beta = 70$ MeV fm^3. From Fig. 4 of Yamagata's paper [29], we deduced a logarithmic energy dependence for ^{3}He with $J_R^0/3A = \sim 930$ MeV fm^3 and $\beta = \sim 150$ MeV fm^3.

As for ^{4}He, the ^{3}He volume integrals that we calculated from available parameters have a large spread at low energies (Fig. 3), and the spread narrows as the energy increases. We averaged the volume integrals for $E/A \geqslant 4$ MeV, because values at lower energies can be distorted by nuclear structure and reaction effects. A least-squares fit of these averaged values gave a logarithmic energy dependence with $J_R^0/3A = 702 \pm 35$ MeV fm^3 and $\beta = 107 \pm 5$ MeV fm^3. This gave the zero crossing at 710 ± 70 MeV per nucleon. The energy dependence is plotted as a solid line in Fig. 3.

C. Deuterons

Most of the deuteron elastic scattering studies were carried out below 100 MeV and the derived volume integrals were widely scattered (see Fig. 4). However, measurements at 125, 156, 157, 200, 400, 420, 698, and 700 MeV provided sufficient high-energy potentials, which allowed us to determine a deuteron energy dependence that was consistent with those of other light ions. Again to avoid nuclear structure and reaction effects, we averaged deuteron volume integrals for energies $E/A \geqslant 6$ MeV. A least-squares fit of these values gave $J_R^0/2A = 804 \pm 40$ MeV fm^3 and $\beta = 125 \pm 6$ MeV fm^3. This dependence is plotted as a solid line in Fig. 4, and it gives the zero crossing at 620 ± 60 MeV/nucleon.

D. Tritons

It is understandable that no major attempt has been made to determine the energy dependence of triton elastic scattering potentials because there are no data beyond 38 MeV.

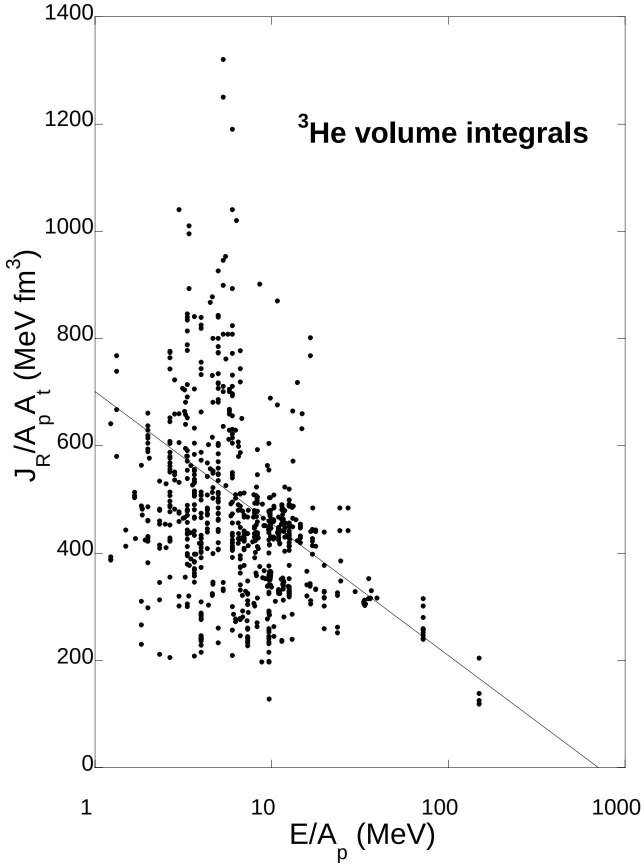

FIG. 3. ^{3}He volume integrals versus energy per nucleon.

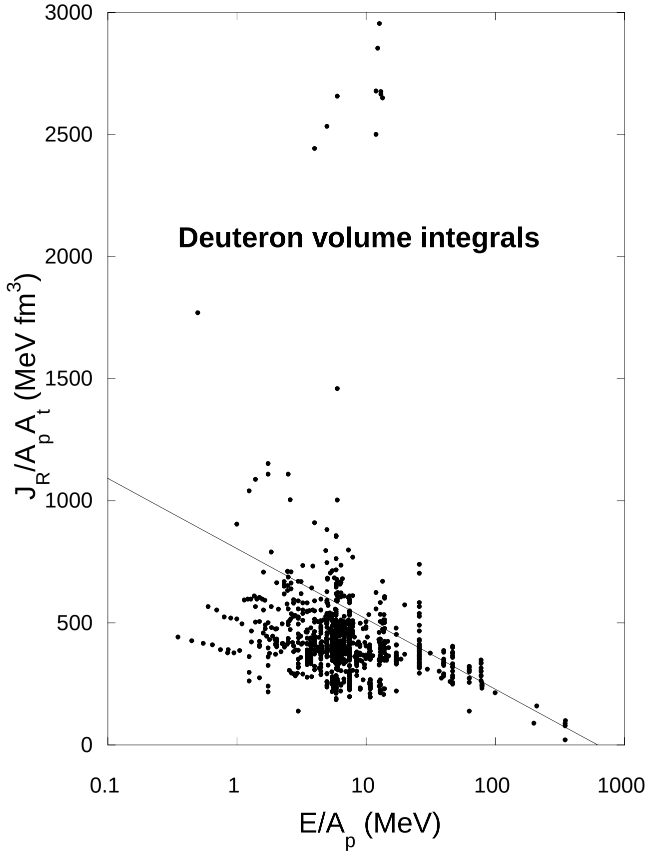

FIG. 4. Deuteron volume integrals versus energy per nucleon.

Since for protons, neutrons, deuterons, ^{3}He, and α particles, the zero crossing of the potential is around 650 MeV/nucleon, it is not unreasonable to assume that all light-ion potentials should change sign from attractive to repulsive at about 650 MeV/nucleon. We averaged all triton volume integrals for $E/A \geqslant 4$ MeV in 1-MeV bins and forced a logarithmic fit with the constraint that it is zero at about 650 MeV/nucleon. This gave us $J_R^0/3A = 672 \pm 34$ MeV fm^3 and $\beta = 104 \pm 5$ MeV fm^3. This result is shown as a solid line in Fig. 5.

IV. SYSTEMATICS OF LIGHT-ION REAL VOLUME INTEGRALS

Figure 6 gives the composite picture of all light-ion volume integrals as a function of the energy per nucleon. Included here are the results of an earlier review of nucleon elastic scattering potentials [39]. In that analysis, a logarithmic dependence of the volume integrals on beam energy was obtained with $J_R^0 = 872 \pm 44$ MeV fm^3 and $\beta = 136 \pm 7$ MeV fm^3 for protons. For neutrons, the corresponding values are 773 ± 39 MeV fm^3 and 120 ± 6 MeV fm^3, respectively.

The most prominent feature of Fig. 6 is that the volume integrals of all light-ion projectiles become zero at about the same energy per nucleon (600–700 MeV/nucleon). This is not surprising because if the interaction of a nucleon goes to zero, then the interaction of a composite projectile, in which the individual nucleons have kinetic energies far in excess of their binding energies, should also go to zero. The result is that all light-ion potentials change sign from attractive to repulsive at the same energy per nucleon. This provides evidence that the composite projectile interaction with the nucleus can be regarded as an incoherent sum of individual nucleon interactions. This result is also confirmed by analyses of ^{6}Li elastic scattering [42], which gave ~600 MeV as the energy for the transition from attractive to repulsive potential.

The rationale of the previous paragraph would be completely true if all the slopes were the same, but the slopes are different. As the mass of the projectile increases, the slope decreases, indicating a quenching of the potential. There are two possible reasons for this effect. First, the Pauli blocking effects in a composite projectile reduce the effective interaction. This can also be explained as the exchange of projectile nucleons with those of the target. The second reason can be that the reduction of the interaction results from the breakup of the projectile. Evidence for this effect is presented by folding-model analyses. Potentials calculated with the folding model are generally too large to fit the experimental data. Investigators have argued that the potential normalization of less than unity required to fit the data is a direct consequence of the breakup of the projectile [43].

It is also observed in Fig. 6 that equal-mass projectiles do not have the same energy dependence. Overall, the neutron

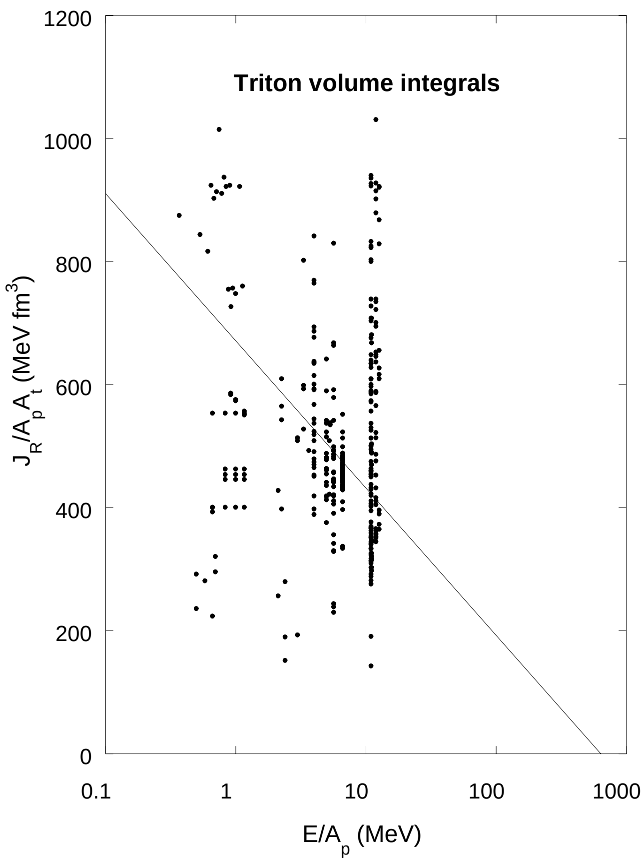

FIG. 5. Triton volume integrals versus energy per nucleon.

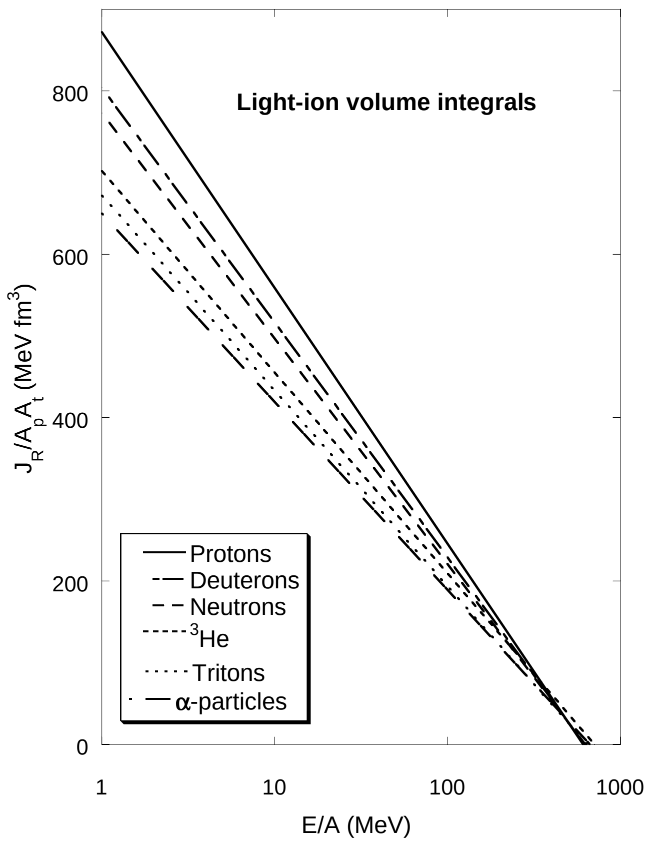

FIG. 6. Light-ion volume integrals versus energy per nucleon.

potential is weaker than the proton potential, and the triton potential is weaker than the ^{3}He potential. This can be understood in terms of the isospin effect. The isospin effect arises basically from the nucleon-nucleon interaction. It is well known that the proton-neutron interaction is about three times as strong as the proton-proton and neutron-neutron interactions. Thus the interaction of a proton (or ^{3}He) with a neutron-rich nucleus will be stronger than the interaction of a neutron (or triton). Most of the lighter nuclei have $N=Z$, but heavier nuclei are generally neutron rich. The potential parameters used in the present study have been derived from elastic scattering from a wide range of nuclei, including both $N=Z$ and the neutron-rich ones. Therefore some average isospin effect is expected to be present in the results. The differences between the neutron (triton) and proton (^{3}He) potentials can thus be attributed to this isospin effect. However, it is not a very drastic effect for the present analysis because the difference is only about 10%.

V. IMAGINARY VOLUME INTEGRALS

The imaginary volume integrals are not as well defined by the data as the real volume integrals. For energies below ~ 10 MeV per nucleon, the absorption is mainly localized in the nuclear surface, so that the interior part of the Woods-Saxon imaginary potential is largely undetermined. Therefore the volume integrals of the imaginary potentials, particularly those with volume form factors, are not well defined. Even at the highest energies there is a significant spread in their values. However, their energy and projectile-mass dependences can still be derived. They show no projectile-mass dependence. In spite of the large spread in the low-energy imaginary volume integrals, they all seem to show an increase with energy up to about 10 MeV per nucleon. After that they show a negligibly weak energy dependence. We carried out least-squares fit to the volume integrals for $E/A \gtrsim 10$ MeV. In this analysis we included only volume integrals between 10 MeV fm^3 and 200 MeV fm^3, because values outside this range are expected to be unreliable. The fits for protons and α particles show a very small increase with energy, while those for neutrons, deuterons, and ^{3}He show a slight decrease. Thus an approximation that the volume integrals for all projectiles remain constant for energies beyond ~ 10 MeV/nucleon seems to be valid. Therefore we carried out a statistical analysis of the volume integrals for $E/A \gtrsim 10$ MeV to derive an average value and standard deviation. The results for α particles is shown in Fig. 7. The low-energy fit (shown as a solid line) indicates that the volume integrals have an energy dependence of the form $J_W/A_pA_t = -33 + 56\ln(E/A)$ for $E/A \leqslant 12$ MeV. For the energy region 12–400 MeV/nucleon, a constant value of 106 ± 26 MeV fm^3 is obtained (shown as a dashed line). The average high-energy values for neutrons, protons, deuterons, and ^{3}He are 91 ± 23, 113 ± 23, 124 ± 30, and 127 ± 25 MeV fm^3, respectively. It is expected that the triton imaginary volume integrals will be similar.

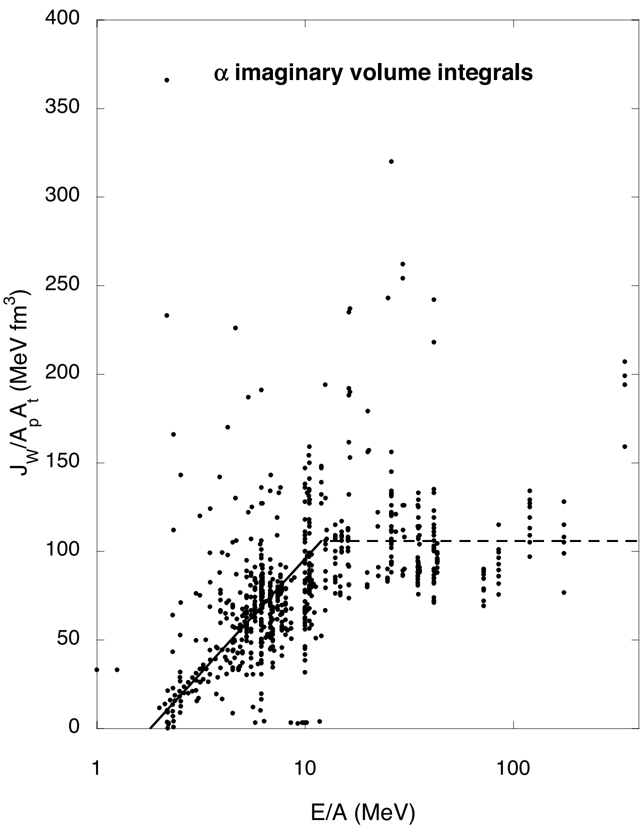

FIG. 7. Imaginary α volume integrals versus energy per nucleon.

VI. SUMMARY AND CONCLUSION

We have carried out a review of all light-ion elastic scattering potentials by calculating the volume integrals per nucleon pair from potential parameters available in the literature. These volume integrals were plotted as a function of energy per nucleon of the projectiles. A logarithmic dependence of the real volume integrals on energy has been derived for all light-ion scatterings. The zero crossing for the transition from attractive to repulsive occurs at the same energy per nucleon of about 650 MeV/nucleon for all the projectiles.

As the mass of the light ion increases, a decrease in the value of the real volume integrals is observed. This can be attributed to either the Pauli blocking effect in the projectile or the breakup of the projectile in the field of the nucleus. Projectiles with the same mass and different isospins have different volume integrals at the same energy. Both $N=Z$ and neutron-rich nuclei were used in the elastic scattering studies. Thus an overall effect of neutron excess of the target nuclei should be manifested in the results. Because the isospin component of the potential for protons and ^{3}He are positive (attractive) while those for neutrons and tritons are negative (repulsive), a trend where the proton (^{3}He) potential is stronger than the neutron (triton) potential is expected. The imaginary volume integrals exhibit the same behavior for all projectiles. They increase from zero at the lowest energies to about 100–150 MeV fm^3 at about 10 MeV per nucleon and remain essentially constant beyond that.

From an utilitarian point of view, this study provides potentials for nuclear reaction calculations involving light ions and nuclei across the periodic table in either the distorted wave Born approximation or impulse approximation. Figure 6 provides the volume integrals for any light ion at any energy up to 1 GeV. By assuming reasonable radius and diffuseness parameters r_0 and a_0, one can calculate the strength V_0 of the potential. This can be done directly for the $N=Z$ projectiles, deuterons, and α's. For nucleons, it is safe to take an average of the proton and neutron volume integrals, viz., $J_R^0/A=822$ MeV fm^3 and $\beta=128$ MeV fm^3. The corresponding average values for $A=3$ projectiles are $J_R^0/3A=687$ MeV fm^3 and $\beta=106$ MeV fm^3. Of course, for these odd-A projectiles one must then add the volume integral of the isospin term, $J_s(N-Z)/A$, where N, Z, and A are the values for the appropriate target nucleus. Results from previous studies [39] seem to suggest a value of 200–400 MeV fm^3 for J_s. For the imaginary potential, one can deduce the parameters by assuming a volume integral of ~ 120 MeV fm^3 for $E/A \geqslant 10$ MeV.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation under Grant Nos. PHY-9971836 (UM-Dearborn), PHY-0140010 (University of Maryland), and PHY-9602872 (IUCF).

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