Effects of the in-medium *NN* interaction on total reaction and neutron removal cross sections

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We discuss calculations of total reaction cross sections between complex nuclei, σ_R, using optical limit and few-body Glauber models in which the free nucleon-nucleon cross sections σ_{NN} are replaced by their (reduced) values in the nuclear medium. This replacement lowers σ_R by at most a few percent when σ_{NN} is determined from the local matter density in each overlapping volume element of the significant projectile-target trajectories. This relatively small effect contrasts with reductions of about 10% in σ_R reported by Xiangzhou *et al.*, who assume a global value for the matter density throughout the interaction region. For two-neutron halo nuclei, we investigate the significance of these in-medium effects for the neutron-removal cross sections, σ_{-2n}. We show that use of an in-medium σ_{NN} raises σ_{-2n} for ^{6}He but lowers it for ^{11}Li, because of their different halo sizes.

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I. INTRODUCTION

Glauber calculations of reaction cross sections σ_R between complex nuclei begin by considering nucleon-pair collisions, each in fixed spatial positions with respect to the centers of mass of the colliding nuclei—the adiabatic or sudden approximation. Integration over the nuclear wave functions of the projectile and target and all projectile-target impact parameters then combines all such pairwise collisions with the appropriate weights to find σ_R. Thus, the three ingredients of the model are the wave functions of the target and the projectile, and an effective nucleon-nucleon (*NN*) interaction. For calculations at high energies, the latter is usually parametrized in terms of the forward scattering free *NN* amplitude, and in turn in terms of the free *NN* reaction cross section σ_{NN}. For strongly bound and localized nuclei it is then reasonable to make additional approximations to Glauber theory, the so-called optical limit. Here the projectile and target wave functions, more specifically their many-body densities, are replaced by their corresponding one-body densities ρ_p and ρ_t, the assumption being that explicit consideration of *NN* correlations in the projectile and target can be neglected. While accurate for normal, localized systems, this approximation is not appropriate for spatially extended and loosely bound systems, such as halo nuclei. In such cases the core- and halo-neutron-target systems are appropriately treated in the optical limit but the few-body degrees of freedom (correlations) of the neutrons and core in the projectile need to be treated explicitly. These few-body correlation effects reduce σ_R significantly [1] compared with optical limit calculations, thereby leading to larger deduced halo nucleus matter radii than optical limit calculations would indicate. Further, Johnson and Goebel [2] have shown quite generally that, when the effective interaction is purely absorptive, neglect of the correlation effects always leads to an overestimate of σ_R.

Whichever of these above calculation schemes is used, the effective *NN* interaction or cross section is usually taken to be that for *NN* collisions in free space. In a recent study Xiangzhou *et al.* [3] calculated σ_R using instead a parametrized form for σ_{NN} suggested to be applicable within nuclear matter. They adopted a revised but constant σ_{NN} determined for a matter density ρ_0 typical of that at the center of the nucleus, i.e., $\rho_0 = 0.17$ nucleons/fm^3. With this choice they predicted reductions of σ_R of more than 10%. If true, such a strong dependence of σ_R on in-medium effects would have exciting implications. It could allow the in-medium σ_{NN} to be determined from precise σ_R measurements. These σ_{NN} should be less ambiguous than those obtained from the balance energy [4] (i.e., the energy at which transverse flow disappears in nuclear collisions), since the balance energy becomes insensitive to σ_{NN} for large *A*, and also depends on the nuclear compressibility. An additional signature of the in-medium effects would be their different effects on reaction and neutron-removal cross sections, since neutron removal is a more peripheral process.

In this paper we point out that, since the contributions to the reaction cross sections from the impact parameter integrals are dominated by surface and more peripheral collisions, one should, more appropriately, use a *local* density description for σ_{NN} in the collision of complex nuclei. Thus σ_{NN} should be calculated separately for each volume element of the nuclear overlaps, according to the matter density in that element. Doing so we find much smaller reductions of σ_R than those reported earlier [3]. In this paper we apply such a local density approach to normal nuclei, in the optical limit approximation, and also reconsider the implications of such a medium dependence for the reaction and neutron-removal cross sections of two-neutron halo nuclei, calculated using the few-body Glauber approach [1].

II. σ_R FOR THE ^{12}C+^{12}C SYSTEM

Within the semiclassical Glauber theory, calculations of σ_R require knowledge of the nuclear transparency $T(b)$, the probability that the projectile with impact parameter b will be transmitted through or past the target. We assume a purely absorptive, zero-range approximation for the forward scatter-

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ing NN amplitude. This is given, for instance, in [5], by

$$T(b)=\exp\left[-\int_{-\infty}^{\infty}dZ\int d\boldsymbol{r}\,\sigma_{NN}\rho_p(r)\rho_t(|\boldsymbol{R}+\boldsymbol{r}|)\right], \quad (1)$$

where $\boldsymbol{R}$ is the displacement from the target center to the projectile center, and $\boldsymbol{r}$ is the displacement of each volume element from the projectile center. The integration over dZ extends over the straight line trajectory of the center of mass of the projectile, and, for a given b, the integral over $\boldsymbol{r}$ samples those regions where the projectile and target overlap. The σ_{NN} used in Eq. (1) are obtained by appropriate weighting of the $nn(=pp)$ and np intrinsic cross sections which, for the ^{12}C target, is their mean value. The reaction cross section is obtained after integration over all impact parameters as

$$\sigma_R=2\pi\int_0^{\infty}[1-T(b)]b\,db. \quad (2)$$

Here, the nuclear matter density $\rho(r)$ for ^{12}C is taken to be a spherically symmetric Gaussian function. Within the local density model, this density appears not only directly in the overlap integral of Eq. (1), but it also influences σ_{NN}, as we now describe. Hereafter, subscripts f and m will be used to denote the free and in-medium cross sections, respectively.

An accurate parametrization of the free-space NN cross sections is given by Charagi and Gupta [6]. To allow direct comparison with the results of the work of Xiangzhou *et al.* [3] we will first use the in-medium $\sigma_{nn,m}$ and $\sigma_{np,m}$ parametrizations proposed there, and comment later on the form of this parametrization. The medium modifications are applied to the free-space cross sections as multiplicative factors, $\sigma_{nn,m}=x_{nn}\sigma_{nn,f}$, etc., where

$$x_{nn}=(1+7.772E^{0.06}\rho^{1.48})/(1+18.01\rho^{1.46}), \quad (3)$$

$$x_{np}=(1+20.88E^{0.04}\rho^{2.02})/(1+35.86\rho^{1.9}). \quad (4)$$

These factors have very weak dependence on E, the projectile laboratory energy in MeV/nucleon. When using Eqs. (3) and (4), we take ρ to be the sum of the target and projectile densities in each volume element being considered; i.e., the local density at each point along the trajectory. We will see that for trajectories most significant for the calculation of reaction cross sections, this local density is smaller than the global central density used in Ref. [3].

Figure 1 shows the results of several calculations of σ_R for the ^{12}C+^{12}C system. The two solid curves use free cross sections $\sigma_{NN,f}$ and Gaussian matter densities. The lower curve is for an rms matter radius of 2.32 fm, obtained by unfolding the proton charge radius of 0.8 fm from the known rms charge radius of 2.45 fm [7]. The upper curve uses a ^{12}C rms radius of 2.45 fm, and was chosen to fit the available data between 100 and 1000 MeV/nucleon [8,9]. The dashed and dotted curves also use Gaussian matter densities but employ the in-medium $\sigma_{NN,m}$ discussed above. The dashed curve is calculated using the local density prescription, while the dotted curve uses a constant global ρ of

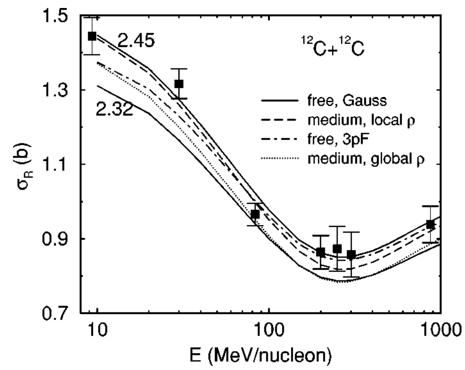

FIG. 1. Total reaction cross sections vs energy for the ^{12}C + ^{12}C system, computed for both free and in-medium σ_{NN}, and compared with data from Refs. [8,9]. All curves, but the lower solid curve, are for ^{12}C rms radii of 2.45 fm. All but the dot-dash curve use Gaussian matter densities.

0.17 nucleons/fm^3, as did Xiangzhou *et al.* [3]. The maximum deviation from the $\sigma_{R,f}$, calculated from $\sigma_{NN,f}$, is now only about 3% at 300 MeV/nucleon when the local densities are used to compute $\sigma_{NN,m}$. The deviations are of the order of 8% for a global density of 0.17 nucleons/fm^3. In Ref. [3], where approximate, surface-normalized density distributions [10] were used to describe the projectile and target densities, the same global modification to $\sigma_{NN,m}$ gave a difference of about 10%.

In the remaining calculation, the dot-dashed curve in Fig. 1, the free $\sigma_{NN,f}$ were used together with three-parameter Fermi (3pF) density distributions for the ^{12}C, to test the sensitivity of our results to the form factors used. The 3pF parameters for ^{12}C given by de Jager *et al.* [7] give a 2.45 fm radius. Figure 1 shows that the difference between the free $\sigma_{R,f}$ calculated with the 3pF form factor and the Gauss form factor with this same matter rms radius, is comparable to, and at some energies larger than, the reduction due to the medium. Nearly identical reductions, as a function of incident energy, were found with these two form factors. We note also that finite range effects associated with the effective NN interaction will have significantly larger effects on the calculated σ_R [11] than the in-medium effects obtained here.

It is instructive to clarify why this effect is so small. Decomposing

$$\sigma_{NN,m}(\rho)=\sigma_{NN,f}-\delta\sigma_{NN}(\rho), \quad (5)$$

it follows from Eqs. (1) and (2) that

$$\Delta\sigma_R=\sigma_{R,f}-\sigma_{R,m}=2\pi\int_0^{\infty}T_f(b)[C(b)-1]b\,db, \quad (6)$$

where

$$C(b)=\exp\left[\int_{-\infty}^{\infty}dZ\int d\boldsymbol{r}\,\delta\sigma_{NN}(\rho)\rho_p(r)\rho_t(|\boldsymbol{R}+\boldsymbol{r}|)\right] \quad (7)$$

and $T_f(b)$ is the transmission for a free-space interaction. The factors in the integrand of Eq. (6) are shown in Fig. 2, for the ^{12}C+^{12}C system at 30 and 300 MeV/nucleon. In-

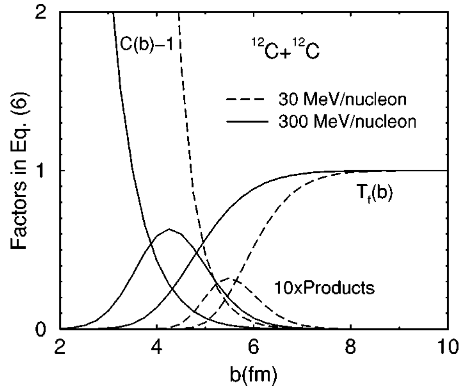

FIG. 2. Factors in the integrand of Eq. (6), which determine the difference of free and in-medium σ_R's for the $^{12}C+^{12}C$ system, at two bombarding energies.

medium reductions of σ_{NN} increase the transmission $T(b)$ by the factor $C(b)$, which reduces σ_R. We note that this effect is not important at very small impact parameters, where $T(b)$ is negligible for both choices of force, and also at large b where the overlap vanishes. Therefore the difference of $\sigma_{R,m}$ from $\sigma_{R,f}$ arises almost entirely from peripheral collisions in the low density tail regions of the projectile and target densities.

Figure 2 also demonstrates why, with this density and energy dependence, the effect is greatest at intermediate energies. At 30 MeV/nucleon the transmission remains very small out to impact parameters of at least 5 fm, and is everywhere reduced by the large $\sigma_{NN,f}$ at that energy. Since $\sigma_{NN,f}$ reaches its minimum near 300 MeV/nucleon, its further reduction in the medium has maximum effect. The figure strongly supports our argument for using the local, not central, density to determine the correct effective $\sigma_{NN,m}$. At 30 MeV/nucleon, the largest contribution to $\Delta\sigma_R$ comes from impact parameters near 5.6 fm. Thus, at the closest approach the midpoint between the two nuclear centers is 2.8 fm from each, at which point the summed local density is only 0.072 nucleons/fm^3.

A simpler, linear dependence of $\sigma_{NN,m}$ on ρ was found satisfactory for interpreting balance-energy data [4] measured primarily below 100 MeV/nucleon, i.e.,

$$\sigma_{NN,m}=\sigma_{NN,f}(1+\alpha\rho/\rho_0). \tag{8}$$

With this energy-independent prescription nearly identical results to those of Eqs. (3) and (4) were obtained, using $\alpha=-0.21$ and $\rho_0=0.17$ nucleons/fm^3, for bombarding energies from 100 to 1000 MeV/nucleon; the in-medium reductions obtained with the two prescriptions differed by less than 5% of their values.

III. σ_R FOR ^{A}Li+^{12}C

Optical-limit calculations of σ_R using both free (solid curve) and in-medium (dashed curve) σ_{NN}'s for the $A=6$ through $A=9$ Li isotopes, on a ^{12}C target at 800 MeV/nucleon, are shown in Fig. 3 together with the data from RIKEN [12,13]. The ^{12}C matter density was once again assumed Gaussian with rms radius 2.32 fm. For ^{6}Li through ^{9}Li the densities were also assumed to be Gaussian. Their rms matter radii were adjusted individually, in the case of the free interaction, to fit the data and ranged from 2.21 fm through 2.30 fm, somewhat less than those reported by the RIKEN group [14]. Our inclusion of in-medium forces once again lowers σ_R by just over 3% for the four isotopes. These effects should be compared with the reductions of about 11% for all isotopes reported in Ref. [3].

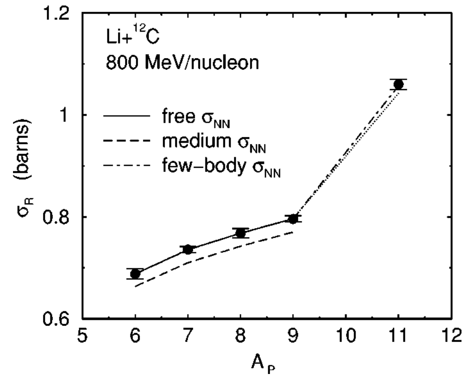

FIG. 3. Predicted total reaction cross sections vs A for ^{A}Li $+^{12}$C at 800 MeV/nucleon, compared with data from Refs. [12,13]. The solid and dashed curves show optical-limit calculations. The dot-dash (dotted) curves show few-body calculations using free (in-medium) σ_{NN}'s where $A=9$ S matrices have been fitted to the $A=9$ reaction cross section data point.

As was pointed out earlier, for the ^{11}Li two-neutron halo system we now know [1] that optical-limit calculations are inadequate for detailed quantitative studies. The real question for ^{11}Li is, therefore, whether in-medium corrections of the type discussed here have any implication for the deduced size of the halo nucleus calculated, more precisely, using the few-body Glauber description. For the structure of ^{11}Li we use the mixed sp model ($P3$) as advocated by Thompson and Zhukov [15]. This model contains a superposition of $(0p_{1/2})^2$ and $(1s_{1/2})^2$ two-neutron configurations. The s-wave admixture arises from intruder levels from the sd shell in ^{10}Li and this has been shown to have a profound effect on the ^{11}Li structure [15,16]. The observed narrow momentum distributions and the electromagnetic response, $dB(E1)/dE$, were found to strongly support the presence of the s-state intruder; see Ref. [16] and references therein. In the $P3$ model the ground state is a mixture of 51% $(p_{1/2})^2$ and 45% $(s_{1/2})^2$ components, in good agreement with the values extracted in Ref. [17]. The rms matter radius of ^{11}Li computed with this wave function is 3.51 fm.

We note that in the free case, and even if the in-medium effects are applied, the optical-limit calculations overestimate the measured reaction cross section for ^{11}Li (1060 ± 10 mb [13]), in line with the expectations of Ref. [1]. The results of the free and in-medium optical-limit calculations are collected in Table I.

Calculations of σ_R using the few-body Glauber model proceed by calculating the ^{11}Li-target elastic S matrix [1] as

$$S(b)=\langle\Phi_0|\mathcal{S}_9(b_9)\mathcal{S}_{n1}(b_1)\mathcal{S}_{n2}(b_2)|\Phi_0\rangle, \tag{9}$$

TABLE I. σ_R and σ_{-2n} (in mb) for $^{11}\text{Li}+^{12}\text{C}$ at 800 MeV/nucleon predicted by optical-limit Glauber (OL) and few-body (FB) models using both free and in-medium σ_{NN}'s, the latter from the prescription of [3]. Pauli-blocking in-medium corrections are described in the text, and the experimental data are from Ref. [13].

	Measurement	OL, $\sigma_{NN,f}$	OL, $\sigma_{NN,m}$	FB, $\sigma_{NN,f}$	FB, $\sigma_{NN,m}$	Pauli
σ_R	1060 ± 10	1172.9	1119.5	1056.7	1043.0	1051.0
σ_{-2n}	220 ± 10	307.3	286.5	260.8	247.8	256.1

which is the expectation value in the ^{11}Li ground state wave function of the elastic S-matrix elements of the ^{9}Li core and the two neutrons with the target, all expressed as a function of their individual impact parameters. Then, $T(b)=|S(b)|^2$. Now each $\mathcal{S}_i(b_i)$ is calculated within the optical limit, cf. Eq. (1), and

$$\mathcal{S}_i(b)=\exp\left[-\frac{1}{2}\int_{-\infty}^{\infty}dZ\int d\boldsymbol{r}\,\sigma_{NN}\rho_i(r)\rho_t(|\boldsymbol{R}+\boldsymbol{r}|)\right]. \tag{10}$$

These can be calculated using either free or in-medium prescriptions for the σ_{NN}.

In the earlier analysis of Al-Khalili and Tostevin [1], the core S-matrix $\mathcal{S}_9$ was chosen, by adjustment of the ^{9}Li matter radius, so as to reproduce the experimental σ_R datum for the core-target system (796 ± 6 mb). In doing so, several theoretical simplifications, such as the effects of in-medium and finite range effects, which were not treated explicitly, were included (approximately) implicitly in this physical input. With the $\sigma_{NN,f}$ this required a ^{9}Li Gaussian density with a rms matter radius of 2.30 fm [1]. With the neutron S matrices also calculated using $\sigma_{NN,f}$ and the $P3$ wave function, this generated a $\sigma_{R,f}$ of 1056.7 mb for ^{11}Li in agreement with the datum 1060 ± 10 mb [13]. We now consider the sensitivity of these earlier results to in-medium corrections and indeed to the in-medium prescription used.

As has been mentioned already, e.g., Fig. 3, prescriptions for in-medium corrections modify (reduce) the calculated core-target reaction cross section. Since in-medium effects are now included approximately to make a fair comparison with the earlier few-body results, we require the in-medium core-target S-matrix input to be fine tuned once again to reproduce the measured core-target σ_R prior to its use in Eq. (9). This has been carried out. Use of Eqs. (3) and (4), requires a ^{9}Li Gaussian density with a rms matter radius of 2.41 fm to make $\sigma_{R,m}$ agree with the experimental value of 796 mb. The in-medium $\mathcal{S}_n$ are also computed from the $\sigma_{NN,m}$ of Eqs. (3) and (4). The resulting ^{9}Li and neutron S matrices for these free (solid curves) and in-medium few-body calculations (dashed curves) are shown in Fig. 4. The increased transparency for impact parameters in the nuclear surface and the interior resulting from the reduced intrinsic NN cross sections in the medium are evident. The calculated few-body reaction cross section $\sigma_{R,m}$ for the $P3$ wave function is now 1043.0 mb, showing once again the $P3$ wave function to be essentially consistent with the experimental cross section for ^{11}Li. The difference in few-body reaction cross sections between the free and in-medium calculations is therefore only 14 mb, i.e., a change of 1.3%. This must be compared with the cross section change of 116 mb, a 10% effect, between the free optical-limit and few-body calculations due to the inclusion of the neutron and core correlations.

Although these medium effects appear small, we should, however, also question the origin of the in-medium parametrization proposed by Xiangzhou *et al.* The parametrization, suggested to be motivated by the Li and Machleidt [18] medium modifications for the energy range 50 to 300 MeV/nucleon, does not agree with that analysis. The factors defined in Eqs. (3) and (4) also have a very slow approach toward the free values at a higher energy. The role of the in-medium corrections resulting from the Pauli-blocking mechanism in nucleon-ion and ion-ion collisions has been discussed by several authors [19,20]. The relevant formulas are collected in Appendix C of Ref. [20]. There, in the nucleon-target problem for energies E in excess of say 300 MeV, where first order multiple scattering theory is on a sound footing, medium dependence of the NN cross section is expressed as

$$\sigma_{NN,m}=\sigma_{NN,f}P(E_F^t/E),\quad P(X)=1-7X/5. \tag{11}$$

Here E_F^t is the Fermi energy of the target, which, in the local density approximation, is related to the target density through the local Fermi momentum $k_F^t(r)=[3\pi^2\rho_t(r)/2]^{1/3}$. While at 300 MeV/nucleon the medium effects of Eq. (11) are very similar to those of Eqs. (3) and (4), at 800 MeV/nucleon the effects are already significantly smaller. To in-

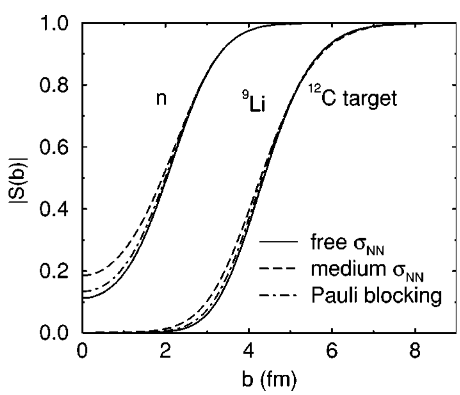

FIG. 4. Free and in-medium elastic S matrices for ^{9}Li and a neutron on a ^{12}C target at 800 MeV/nucleon, used for few-body calculations of σ_R for $^{11}\text{Li}+^{12}\text{C}$. All ^{9}Li S matrices have been chosen to reproduce the measured ^{9}Li-target reaction cross section. The dashed curves use the in-medium corrections of Xiangzhou *et al.* [3] and the dot-dashed curves use the Pauli-blocking corrections discussed in Sec. III.

corporate these simply at 800 MeV/nucleon, where we are in a perturbative regime, we assume that in the ion-ion (^{9}Li+target) case we can write $\sigma_{NN,m} = \sigma_{NN,f} P(E_F^t/E) P(E_F^c/E)$ with E_F^c the Fermi energy of the ^{9}Li core. Using these in-medium (Pauli-blocking) corrections the ^{9}Li and neutron in-medium *S* matrices are shown by the dot-dashed curves in Fig. 4. The reduced medium effects in this case are evident. Using this prescription requires a ^{9}Li Gaussian density with a 2.34 fm rms matter radius to obtain a $\sigma_{R,m}$ of 796 mb. Few-body calculations based on this Pauli-blocking parametrization now generate a $\sigma_{R,m}$ of 1051.0 mb for ^{11}Li, reflecting once again a significantly smaller in-medium reduction, and agreement with the experiment. Our results for σ_R and σ_{-2n} (see the following section) are summarized in Table I.

IV. CALCULATIONS AND RESULTS FOR σ_{-2n}

In this section we consider neutron removal from the $2n$-halo nuclei ^{6}He and ^{11}Li, beginning with optical-limit Glauber calculations of σ_{-2n}. While we will show that these optical-limit calculations differ in detail, quantitatively, from those of the few-body model, they nevertheless reveal an interesting qualitative difference between the medium effects in the ^{6}He and ^{11}Li cases. Two-term harmonic oscillator functions [21] are used for the core and valence nucleon densities ρ_c and ρ_v of ^{6}He, and $P3$ densities [15] are taken for ^{11}Li. The corresponding transparencies $T_c(b)$ and $T_v(b)$ are found using Eq. (1). For heavy targets especially, electromagnetic dissociation is important. To find the Coulomb breakup probability $P_{Coul}(b)$ at impact parameter *b*, we find virtual photon densities with the Weizsacker-Williams method [22], and take electric dipole response functions from Danilin *et al.* [23] for ^{6}He and from [16] for ^{11}Li. It is instructive to have a new expression for σ_R showing the separate roles of the two projectile nucleon groups,

$$\sigma_R = 2\pi \int [1 - T_c(b) T_v(b) + P_{Coul}(b) T_c(b) T_v(b)] b\, db. \tag{12}$$

The term $T_c(b)T_v(b)$ is the combined probability for neither group to have a nuclear reaction; the final term counts Coulomb breakup only when both groups avoid reactions with the target. For $2n$ removal we have

$$\sigma_{-2n} = 2\pi \int \{T_c(b)[1 - T_v(b)] + P_{Coul}(b) T_c(b) T_v(b)\} b\, db. \tag{13}$$

Pure $2n$ removal requires the core to survive, which leads to the factor $T_c(b)$ in the first term. Both previous equations contain the implicit assumption that the Coulomb breakup affects only the valence neutrons.

Calculations were made for several targets from $A = 12$–238, using 2pF or 3pF target densities [7]. In-medium forces always decreased σ_{-2n} for ^{11}Li, typically by about 5%, but *increased* it for ^{6}He by as much as 1%. To show the physical basis of this small but surprising increase for ^{6}He, we plot in Fig. 5 the factors $1 - T_v(b)$ and $T_c(b)$ which determine the nuclear part of the integrand of Eq. (13), and also

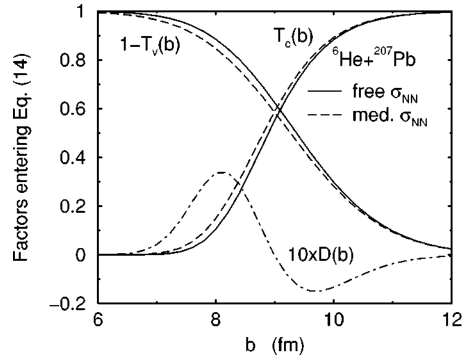

FIG. 5. The difference function $D(b)$, defined in Eq. (14), plotted against the impact parameter for ^{6}He+Pb at 800 MeV/nucleon. This function determines the difference of nuclear σ_{-2n}'s computed for free and in-medium σ_{NN}'s. Also shown are the four factors that combine to determine $D(b)$.

$$D(b) = [T_c(b)\{1 - T_v(b)\}]_m - [T_c(b)\{1 - T_v(b)\}]_f. \tag{14}$$

At the smallest impact parameters *b*, core disruption is certain, precluding simple $2n$ removal. For somewhat larger *b* (here, 7–9 fm), the in-medium nuclear forces allow greater core transmission $T_c(b)$ while the valence-*n* removal probability remains near 100%; thus the weaker in-medium forces are favored here for nuclear $2n$ removal. Further out, (9–12 fm) core transmission is nearly certain but the stronger free *NN* forces will more likely remove the valence neutrons; this region favors free σ_{-2n}. For the compact ^{6}He halo, the outer region is contracted, and the in-medium σ_{-2n} is 1% greater. However, the very extended ^{11}Li halo favors the outer region, reducing the in-medium σ_{-2n} by 5%. Since in-medium forces favor the joint survival probability of both core and valence neutrons, $T_c(b)T_v(b)$, the Coulomb term always favors the in-medium σ_{-2n}.

Finally, to compare with these density-based calculations, few-body calculations of σ_{-2n}, taken as the sum of elastic breakup and $1n$ and $2n$ stripping were carried out for 800 MeV/nucleon ^{11}Li incident upon a ^{12}C target. The cross section was found to be 260.8 mb for free nucleon-nucleon forces, 247.8 mb with in-medium forces using local densities and the Xiangzhou prescription [3], and 256.1 mb considering the Pauli-blocking medium effects discussed in Sec. III. The 5% reduction using the Xiangzhou method is very close to that obtained with the simpler optical-limit calculations, where 307 and 286 mb were obtained with free and in-medium forces, respectively. The σ_{-2n}'s found with optical-limit and few-body calculations differ more than the σ_R's due to the more peripheral nature of *n* removal. All of our predictions are somewhat larger than the measurement of 220 ± 10 mb reported by Kobayashi *et al.* [13], and are collected in Table I.

The much smaller reduction of σ_{-2n} obtained by considering the Pauli-blocking mechanism underscores the importance of the asymptotic behavior of σ_{NN} at high energies, and the rate at which these medium effects disappear. For example, De Jong *et al.* [24] have shown that, at moderate densities and energies approaching 1000 MeV/nucleon, pion polarization in the nuclear environment could even increase σ_{NN} above its free value.

V. CONCLUSIONS

We have shown that changes in both σ_R and σ_{-2n} caused by in-medium effects should be, at most, a few percent at intermediate energies. The maximum effect occurs where σ_{NN}, and consequently the opacity, are at a minimum. These effects can be qualitatively understood since the *difference* of the cross sections comes mainly from the surface. At small impact parameters the nuclei are so nearly black that they are insensitive to σ_{NN}, while for large impact parameters the densities are so low that reactions are rare. An especially interesting effect is the occasional *increase* of σ_{-2n}, especially for ^{6}He+Pb, where at small impact parameters the weaker in-medium forces increase the core survivability before the *n*-removal probability drops significantly. The opposite effect, occurring in the extended halo of ^{11}Li, shows the dependence on projectile structure.

We conclude that the earlier predictions [3] overestimate significantly the reduction of σ_R at high energies for several reasons. These include the use of a global density and an incorrect high energy behavior of the assumed σ_{NN}, even in the absence of effects that might arise from modification of the free pion properties (polarization) in the medium.

The consequences of in-medium effects are therefore significantly smaller than those of other physical corrections that we know to be present. We have not explicitly considered here the finite range of the *NN* force, nor the experimental uncertainties in the density distributions, but we have considered the in-medium effects within the few-body Glauber model. The few-body approach naturally allows one to fit the constituent cross sections before addressing the scattering of the composite system, and, with this philosophy, changes in reaction cross sections arising from few-body effects are found to be almost an order of magnitude larger than in-medium effects. These in-medium effects are too small to determine through reaction cross section measurements; consequently, experimental determination of these processes will have to come from elsewhere.

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