Elastic scattering of ^{9}Li from protons at 60A MeV

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A microscopic single-scattering model study of elastic scattering of ^{9}Li from protons at 60 MeV/nucleon is reported. Results with two realistic effective nucleon-nucleon interactions, one adopted from the work of Mahaux and collaborators and another from the work of von Geramb and collaborators, bracket the $\sigma(\theta)$ data when a simple Gaussian ground state density with rms radius 2.32 fm is used. [S0556-2813(97)04907-8]

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I. INTRODUCTION

A recent article by Crespo *et al.* [1] presented calculations based on Faddeev wave functions for ^{9}Li$+p$ and ^{11}Li$+p$ elastic scattering data [2] at about 60 MeV/nucleon that did a good job of predicting ^{9}Li-^{11}Li differences but, surprisingly, failed to describe the experimental angular distribution for either nucleus. In contrast, a similar calculation [3] worked well for ^{8}He$+p$ at 72 MeV/nucleon. The calculations in Refs. [1,3] do not include the density-dependent effects that are known [4] to be important when calculating the optical potential at these energies and crucial to a quantitative description of data for nuclei with well-known structure at lower energies [5–7]. We investigate the effects of using a density dependent effective interaction in this paper. Since calculations with plausible interactions, one of which worked well for $p+{}^{6,7}$Li at 50 MeV [8], will be seen to bracket the data for ^{9}Li when we use the same Gaussian wave function as in Ref. [1], we suspect that the ^{8}He results [3] were fortuitous and that there is a need for a study that calibrates the effective interaction at this energy within the chosen reaction model.

II. OVERVIEW OF CALCULATIONS

The calculations shown below follow closely the work in Ref. [8], and so only a summary of the main features will be given here. The scattering potentials [9] are defined by

$$U(c',c)=\left\langle c'\left|\sum_t v_{pt}(1-P_{pt})\right|c\right\rangle, \tag{1}$$

where $c=c'=g$ for this problem (only spherical ground state densities will be considered), v_{pt} is a complex, local, and density- and energy-dependent effective NN interaction whose isoscalar central (C) and spin-orbit (LS) parts will be most important for the calculations shown here, and antisymmetrization between the projectile and struck nucleons (knockon exchange) is included, thereby making the potential nonlocal.

We treat the exchange nonlocality approximately, replacing $v_{pt}(1-P_{pt})$ with a modified quasilocal effective interaction $\overline{v_{pt}}$ via a factorization approximation motivated by forward-scattering and short-range-limit arguments [10,11]. This introduces a dependence on the local wave vector $\vec{Q}_l$, parametrically dependent on r_p, that characterizes the dominant part of the exchange amplitude. The result is conversion of a nonlocal U into a local $\overline{U}$:

$$\overline{U}(c',c)=\left\langle c'\left|\sum_t \overline{v_{pt}}\right|c\right\rangle. \tag{2}$$

The vector $\vec{Q}_l=k_l(\vec{k}_f+\vec{k}_i)/|\vec{k}_f+\vec{k}_i|$, calculated self-consistently from $k_l^2=k_i^2-2\mu\mathrm{Re}U_0/\hbar^2$, is perpendicular to the momentum transfer $\vec{q}=\vec{k}_i-\vec{k}_f$. The density dependence implicit in v_{pt} is evaluated in the local density approximation by using $\rho_g(r_p)$, the spherical ground state density evaluated at the projectile position. The interaction is evaluated at the effective asymptotic ''projectile'' energy of the proton, namely $E_p=60$ MeV.

The integration over target coordinates in Eq. (2) and the multipole expansion required to evaluate the scattering potential for the model described above are most easily performed with momentum-space techniques [12,13] that we implement with the computer code ALLWRLD [14], one version of which was modified to handle the Jeukenne-Lejeune-Mahaux (JLM) interaction as described below.

The central plus spin-orbit spherical optical potential that results can also be written in the more familiar coordinate-space convolution expression

$$U_{\mathrm{opt}}(r_p)\equiv\overline{U_{00}}(g,g)=\int \overline{v^{C}}(r_{pt},Q_l,\rho)\rho_g(r_t)d^3r_t + \frac{1}{4}\int \overline{v^{LS}}(r_{pt},Q_l)\vec{r}_{pt}\rho_g(r_t)d^3r_t\times\vec{p}_p\cdot\vec{\sigma}_p, \tag{3}$$

where Q_l and ρ are parametrically dependent on r_p and isospin indices have been suppressed. Scattering observables are calculated with the elastic part of a standard distorted-wave approximation (DWA) code [15].

We consider two different models for the effective NN interaction at medium energies, one based on the work of Jeukenne, Lejeune, and Mahaux [16,17] and another based on the Paris-Hamburg g matrix [18].

The effective NN interaction used in Ref. [8], which we refer to as the JLM interaction, is a hybrid where the energy- and density-dependent spin-independent central interaction, parametrized as

$$\overline{v}^{C}_{0T}=f^{C}_{0T}(\rho,E)e^{-t^2q^2/4}, \qquad (4)$$

comes from the work described in Refs. [16,17] while the other components come from a sum-of-Yukawas parametrization of the density-independent g matrix developed by the Michigan State group [19]. The density dependence for $\overline{v}^{C}_{0T}$ in Refs. [16,17] was calculated in symmetric and infinite nuclear matter, while Ref. [19] assumed that the bound-state interaction gives a good approximation to the spin-dependent interaction for low scattering energies. We remind the reader that, as in Refs. [6–8], we take $t=1.0$ fm, include the Coulomb correction in evaluating f^{C}_{0T}, and correct the Imf^{C}_{0T} by multiplying by the k mass; we also reduce the Imf^{C}_{0T} by 0.8 as suggested by the results of Ref. [7] and used successfully in Ref. [8]. Other details are specified in Ref. [8]. Systematic studies of this interaction have been done with a range of nuclei for $E_p<30$ MeV; only a few nuclei have been studied up to 65 MeV.

The Paris-Hamburg g matrix of von Geramb [18] was obtained from the Paris potential [20] by using the techniques of Refs. [21,22,18]. Studies of this interaction at ''intermediate'' energies by Kelly and collaborators [23,24] suggest it has too much density dependence and does not reduce to the free scattering values in the limit of zero density. We use it here to provide a point of comparison with the calculations of Ref. [1]. This interaction has not been studied systematically below 135 MeV.

III. RESULTS

The ground state density used for all of the results shown below is the Gaussian density ρ^{I}_{9} with a rms matter radius of 2.32 fm ($b=1.89$ fm) that was used for the calculations shown with a dashed curve in Figs. 4 and 6 of Ref. [1]. Those calculations employed the optimal factorization approximation and free NN amplitudes calculated directly from the Paris potential [20] following Kerman, McManus, and Thaler (KMT) [25].

Figures 1 and 2 show our results for elastic scattering cross section and analyzing power angular distributions, respectively. The cross section data are from Moon *et al.* [2]. The solid curves were calculated with the JLM interaction while the dash-dotted curves employ the density-dependent Paris-Hamburg interaction. The $\sigma(\theta)$ data fall between the extremes defined by these two calculations. Since the ground state (g.s.) density being used is quite crude (its size is set only by total reaction cross sections), we hesitate to conclude much more than that it should be possible to describe the data with either interaction after moderate adjustments of ρ_g. A choice between the interactions must be made based on data for nuclei whose structure is well known. The $A_y(\theta)$ results show a pronounced difference between the two interactions; it is unfortunate that polarization data are quite difficult to obtain with radioactive beam experiments. However, as we note below, data for other Li isotopes suggest a preference for the JLM interaction, which worked well for polarization data available at 50 MeV [8].

The short dashed curve labeled ''P-H free'' illustrates the effect of turning off the density dependence in the Paris-Hamburg interaction and using the asymptotic wave number in the exchange approximation. This is not the same as using the free amplitudes in a nonlocal calculation within the optimal factorization approximation as was done by Crespo *et al.* [1], but it does give a rough indication of how density dependent (Pauli blocking) effects in the optical potential [4] affect the cross section and $A_y(\theta)$. Note that the interaction choice leads to larger changes than including density-dependence in the Paris-Hamburg interaction.

We have also done calculations (not shown in the figures) with the free t matrix of Franey and Love [26] in the zero-range exchange approximation. These results are low at forward angles and in the minimum, like the ''free'' calculation in Fig. 1, but are higher at 60°. In summary, the effective interaction employed, inclusion of density dependence in that interaction, and the exchange approximations each significantly affect the q dependence of the scattering, illustrating the importance of calibrating the reaction model by examining data for well-understood nuclei before proceeding to use it to study other nuclei.

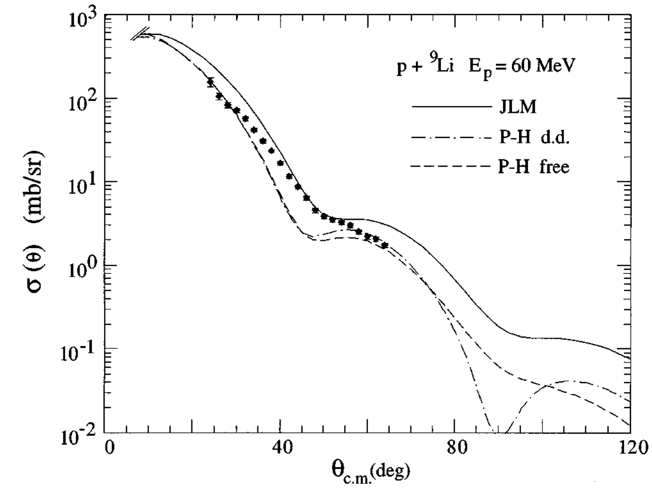

FIG. 1. Experimental [2] and calculated $\sigma(\theta)$ angular distributions for ^{9}Li$+p$ at 60 MeV/nucleon. The solid curve shows the JLM result, while the dash-dotted (dashed) curves show the Paris-Hamburg result with (without) density dependence. The ''P-H free'' calculations also use the asymptotic wave number for the exchange approximation.

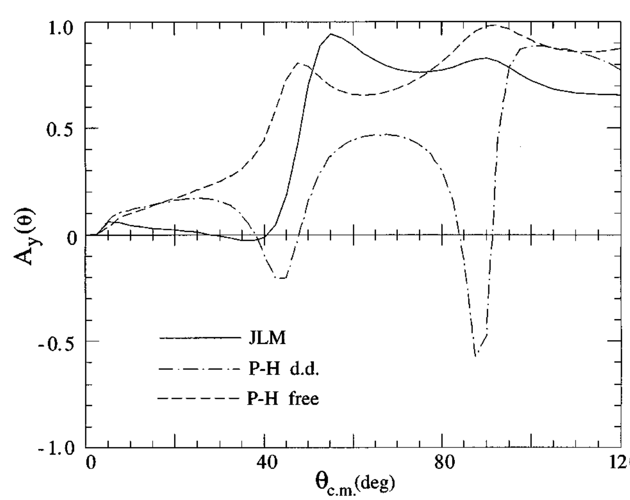

FIG. 2. Calculated $A_y(\theta)$ angular distributions for ^{9}Li$+p$ at 60 MeV/nucleon. Line codes are the same as in Fig. 1.

As a check on our preference for the JLM interaction at these energies, we have performed similar calculations for $p+{}^{6,7}$Li scattering at 65 MeV, where there are unpublished data [27] that were shown in Ref. [2]. These calculations used the carefully calibrated ground state densities used in Ref. [8]. Results based on the JLM interaction are in generally good agreement with the (unpublished) cross section data, although there seems to be a preference for more absorption — that is, not scaling the imaginary central potential by 0.8 as required at lower energies. The Paris-Hamburg interaction produces results that are consistently below those data. The JLM interaction is clearly preferred when one looks at the $A_y(\theta)$ data for ^{6}Li, less so for ^{7}Li. Nonspherical (quadrupole) terms in the $p+{}^7$Li potential contribute in the minimum around 50° and cannot be ignored. Those results will be reported in a future, more detailed, study.

IV. CONCLUSIONS

We find that a density-dependent effective interaction that works well at lower energy, the one based on the JLM interaction, is above the data when the proposed density is used, while similar calculations based on the Paris-Hamburg interaction are low. Eliminating the density dependence from the Paris-based calculations (the zero density limit) and shifting to the asymptotic wave number for exchange lowers the result further, but not quite as low as the results shown in Ref. [1]. Clearly the inclusion of density dependence (Pauli effects) is important at this energy, although the effect of density dependence is not as large as the difference between the two effective interactions examined here. There are other differences between our calculations and those of Ref. [1]; the way we treat exchange (local energy vs optimal factorization vs full folding [28,29]) could also be relevant. In any case, with both the wave function of ^{9}Li and the interaction at this energy poorly known, one can learn little from a straight comparison to the ^{9}Li data.

The next step should be to study the effective interaction and reaction model at this energy with nuclei whose densities are known from other work. Extensive studies of this type have been made at low energy ($E_p<30$ MeV) but not at the energies between 50 and 100 MeV where the ^{9}Li$+p$ cross sections were measured and where other radioactive beam experiments are planned. A microscopic analysis of cross section and polarization data for stable nuclei is needed that would explore the interactions and other physical effects (exchange and nonspherical potentials, for example) known to be important in this energy region. With such a calibrated interaction, energies around 60 MeV are well suited [30] to the determination of nuclear density distributions, particularly neutron-proton differences.

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