Detailed Study of the Lane Potential: Multichannel and Polarization Constraints

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A Lane-model analysis of the ^{9}Be + nucleon system has provided a detailed description of both cross-section and polarization data for (p,p) elastic, (n,n) elastic, and (p,n) quasi-elastic scattering over a range of energies. Emphasis is placed on consistency in isospin conservation, data-set completeness, and multichannel constraints. Results favor a symmetry potential which is energy dependent with volume and surface form factors for the real and imaginary wells, respectively. A symmetry spin-orbit $(\vec{1}\cdot\vec{\sigma})(\vec{t}\cdot\vec{T})$ interaction was found to be unnecessary.

The simple, appealing model first suggested by Lane[1] to relate the quasielastic (p,n) reaction to elastic (p,p) and (n,n) scattering has been quite successful in explaining global cross-section trends and features.[2] For an individual nucleus, however, it has been unable to predict correctly all related cross sections[3] and the (p,n) polarization observables.[4] Although such difficulties have been ascribed to inherent model limitations, ambiguities in the multichannel optical potentials suggest that only a consistent, simultaneous search on all available data for the three channels can provide sufficient constraints to obtain a detailed description. Because of the practical and conceptual appeal of the Lane model, it is important to determine whether such an exhaustive approach can indeed overcome the difficulties of previous analyses in explaining the polarization and multichannel effects for an individual nucleus. As such, the approach presented in this Letter emphasizes consistency and completeness in an isospin-conserving, coupled-channels calculation. The results shown below provide a good simultaneous description of all available observables for the ^{9}Be + nucleon system and reaffirm the significance of isospin conservation as expressed in the original Lane model.[1]

The present analysis is based on an expansion of the computer code[5] TWAVE into a multichannel search program which extends the constraint of isospin conservation to the simultaneous description of a complete data set. Our basic isospin potential can be represented by an isoscalar term U_0 and a symmetry term U_1, both complex and containing spin-orbit interactions:

$$U(r) = -[U_0(r) + 4U_1(r)(\vec{t}\cdot\vec{T})/A],$$

$$U_0(r) = V_0 f_R(r) - i4a_I W_0 \frac{df_I(r)}{dr} - \lambda_\pi^2(\vec{1}\cdot\vec{\sigma})V_{\text{s.o.}}{}^0 \frac{1}{r}\frac{df_{\text{s.o.}}(r)}{dr},$$

$$U_1(r) = V_1{}^v f_R(r) - 4a_R V_1{}^s \frac{df_R(r)}{dr} - i4a_I W_1 \frac{df_I(r)}{dr} - \lambda_\pi^2(\vec{1}\cdot\vec{\sigma})V_{\text{s.o.}}{}^1 \frac{1}{r}\frac{df_{\text{s.o.}}(r)}{dr},$$

$$f_i(r) = \{1 + \exp[(r - R_i)/a_i]\}^{-1}.$$

Note that this formulation of the symmetry potential permits explicit evaluation of the effects of different V_1 shapes and different spin-orbit strengths $V_{\text{s.o.}}{}^1$. The search procedure is designed especially for a multichannel Lane calculation and exploits the relationships between isospin potential representations and the types of data to be described. For example, the independent potentials may be transformed with strict isospin consistency from the "elastic" U_0 and "quasielastic" U_1 form (U_0, U_1) to the familiar "proton" U_p and "neutron" U_n form (U_p, U_n). Because of the extensive literature concerning proton optical models and the critical sensitivity of the symmetry potential, in this study the (U_p, U_1) representation was a logical choice for the independent potentials.

The ^{9}Be + nucleon system provides a unique opportunity for this analysis, since the primary requirement of data-set completeness and consistency is satisfied because of extensive experimental and theoretical studies at this laboratory.[6-9] Although optical models are traditionally associated with heavier targets, their successful application to elastic scattering in light nuclei has been previously demonstrated.[10] The smoothness of parameters in standard elastic-scattering optical potentials for ^{9}Be supports their validity above at least 12 MeV for (p,p) and 9 MeV for (n,n). Use of such spherical potentials for the deformed ^{9}Be nucleus is reinforced by successful comparisons[6,7] with inelastic, coupled-channels, direct-reaction analyses and by the small calculated compound-nucleus contributions[11] to the (p,p) cross section at energies as low as 8 MeV. As for the (p,n) channel, a nonresonant analysis is suggested by the gradual energy dependence of the Legendre polynomial coefficients[9] which represent $\sigma(\theta)$ and $A_y(\theta)$, by the equality of experimental results[8] for the polarization $P^y(\theta)$ and analyzing power $A_y(\theta)$, and by the constancy[12] of the zero-degree polarization-transfer coefficient above 12 MeV.

Examination of previous proton-elastic-scattering potentials suggested a trial U_p parameter set based primarily on that of Werby, Edwards, and Thompson.[11] This energy-dependent potential spans the constant-geometry solutions of Loyd and Haeberli[13] at lower energies and of Votava *et al.*[6] at higher energies. The latter set[6] is comparable to the global parameters of Watson, Singh, and Segel,[10] from which a trial U_1 symmetry potential was also inferred for the present analysis.

The U_p and U_1 potentials resulting from the search are shown in Fig. 1; representative values are given in Table I. In Fig. 2 the calculated distributions are compared to experimental results for energies above 11 MeV, the region where data from this laboratory predominate. The highlights of the calculations are the energy dependence of the $\sigma_{pn}(\theta)$ cross section, correctly produced by an essentially energy-independent U_1 potential; the forward-angle $\sigma_{nn}(\theta)$ cross-section results, well described even in the representation where the U_n potential is generated from U_p and U_1; and the sensitive elastic and quasielastic analyzing powers, well predicted for the first time. In fact, the simultaneous Lane-model description of each data set is fully comparable to those based on separate single-channel models.

The symmetry potential obtained in the search is essentially constant with energy, but the proton parameters retain the energy dependence of the trial set. Solutions for fixed-geometry potentials based on constant-volume-integral conditions were limited to the higher-energy region of our study but may be applicable also in the region above 15 MeV. In any case, energy-dependent potentials are not uncommon in models for light nuclei which span a sizable energy range.

Although theoretical arguments[15] have proposed a symmetry spin-orbit term, previous analyses[4] have not convincingly proven the need for such a term in the Lane model. Initially, we expected that a good description of a complete set of cross-section and polarization data might

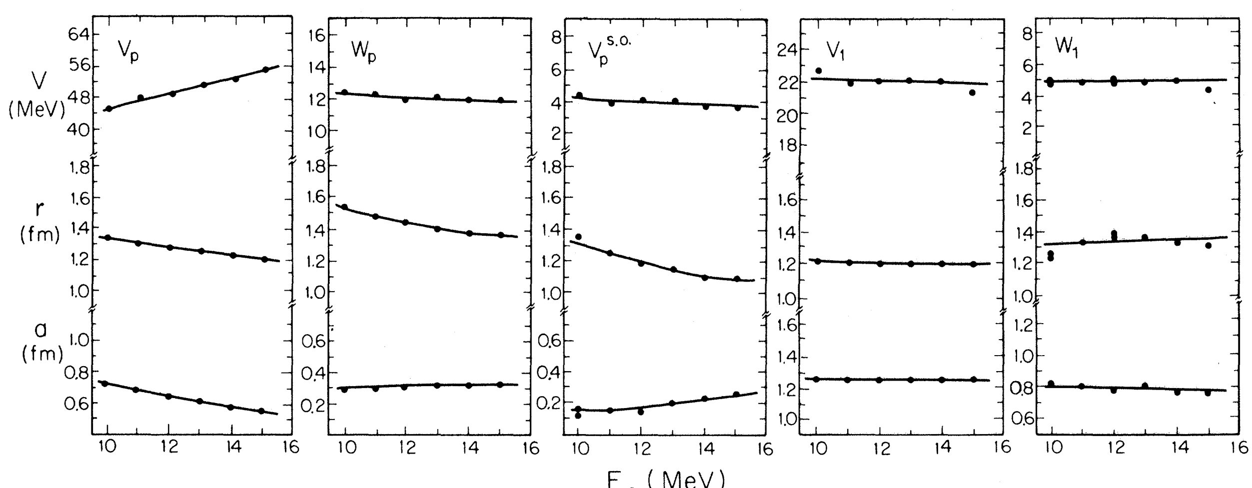

FIG. 1. Lane potential for the ^{9}Be + nucleon system.

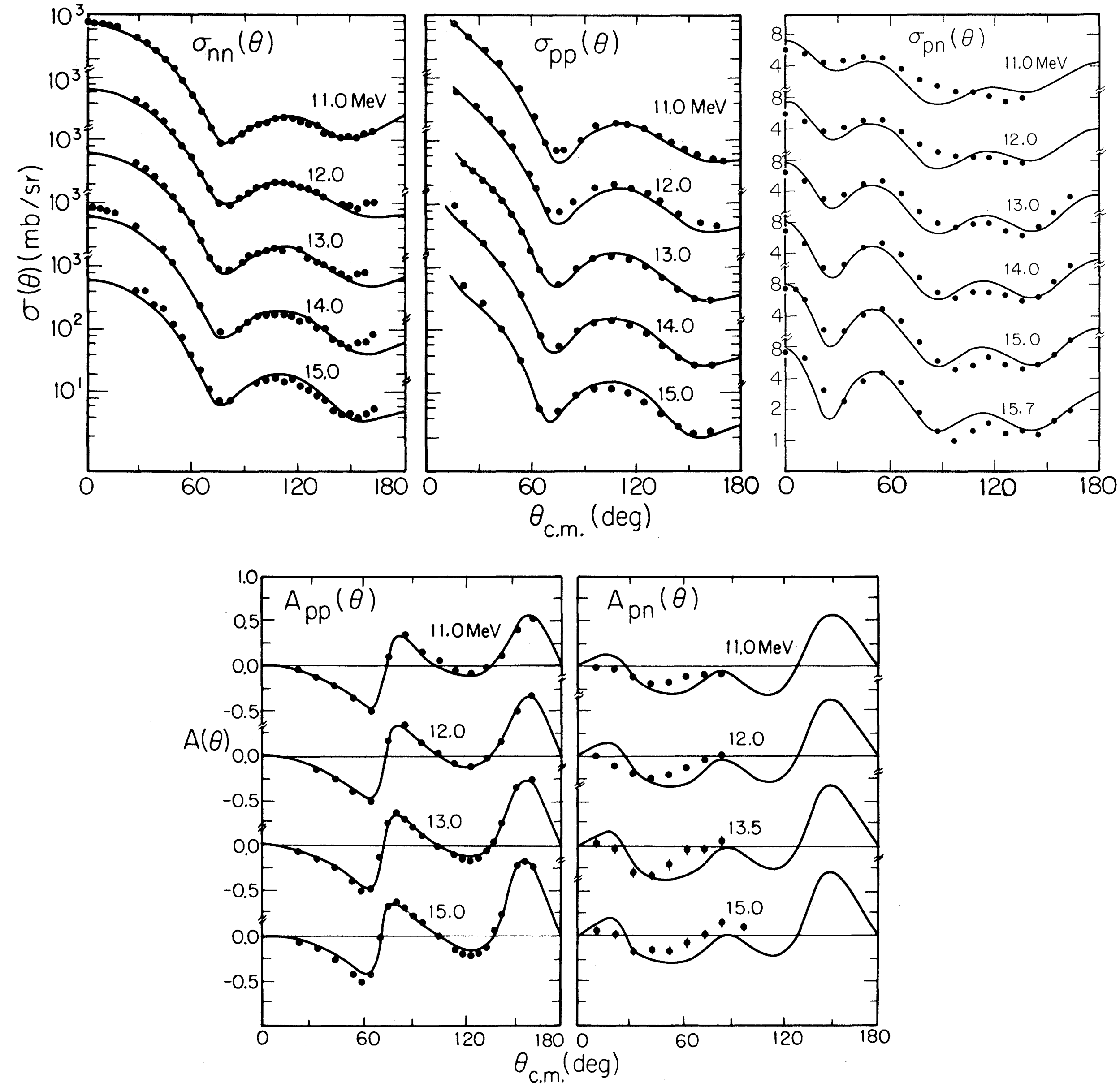

FIG. 2. Lane-model description of the ^{9}Be + nucleon data set using the parameters of Fig. 1.

establish the existence and magnitude of this term. However, the optimum symmetry spin-orbit strength of about + 1.0 MeV could be set equal to zero with negligible effects on the predictions. We therefore conclude that even within the comprehensive analysis reported here a complete description of the data is possible without evoking such an $(\vec{l}\cdot\vec{\sigma})(\vec{t}\cdot\vec{T})$ interaction. In addition, a reasonable Coulomb correction ΔV_C was added to the proton potential, but its exact value for the low-Z nucleus ^{9}Be was not critical in the search and a value of zero also gives a satisfactory solution. We simply point out that our method of a simultaneous analysis of all three channels should in general provide the most reliable measure of Coulomb and symmetry spin-orbit effects.

The choice of a volume form factor for the real symmetry potential was motivated phenomenologically. Hartree-Fock[14] calculations of the optical symmetry potential, however, suggest that its real part is peaked at the nuclear surface and that a spin-orbit interaction may be important. We have obtained a surface-peaked, energy-

TABLE I. Representative values of the energy-dependent Lane model in terms of parameters for the $U_p(r)$ proton and $U_1(r)$ symmetry potentials. Strengths are in MeV; radii and diffusenesses are in femtometers. For all cases $\Delta V_C = 0.75Z/A^{1/3}$ and $r_C = 1.30$ fm.

E_p	V_p	r	a	W_p	r_i	a_i	$V_{s.o.}$	$r_{s.o.}$	$a_{s.o.}$	V_1	r_1	a_1	W_1	$r_1{}^i$	$a_1{}^i$
11.0	47.2	1.30	0.68	12.3	1.48	0.30	4.2	1.25	0.16	22.2	1.19	1.26	4.9	1.33	0.80
13.0	51.3	1.26	0.61	12.1	1.40	0.32	4.0	1.14	0.21	22.0	1.19	1.25	4.8	1.34	0.79
15.0	55.0	1.21	0.55	12.1	1.37	0.33	3.8	1.10	0.27	21.7	1.19	1.25	4.8	1.36	0.77

dependent symmetry potential which provides a good description of all above data except the (p,n) analyzing powers. Addition of a symmetry spin-orbit term did allow fair description of this last observable, but only near $E_p = 13.5$ MeV. Although this potential set is similar to that of the Hartree-Fock study, we favor the simpler volume potential since fewer degrees of freedom are required to satisfactorily describe the data set.

Our final comments concern the energy and radial dependence of our Lane potential. The extracted parameters, especially those governing the proton potential, are possibly more a reflection of the particular ^{9}Be case than a global description for light nuclei. If this is so, our potential may actually be regarded as a convenient specification of an effective interaction for the ^{9}Be + nucleon system which is still consistent with the Lane equations and therefore connects the corresponding interactians in different channels. This constraint is the important point in our multichannel analysis: The combination of isospin conservation with data-set completeness transcends the details of specific nuclei and may be the most important consideration in obtaining proper detailed descriptions of individual systems.

In summary, we emphasize that good descriptions are obtained for the available cross-section and polarization results in all three channels of the ^{9}Be + nucleon system. This has been achieved by using a new computer code which searches for an isospin-conserving potential that simultaneously describes the complete data set for a single target nucleus. Results favor a symmetry potential with a volume real term, a surface imaginary term, and a small spin-orbit term. Lastly, since the data set was also well described with this spin-orbit term set equal to zero, even the inclusion of polarization data for two of the channels yields no solid evidence for the addition of an $(\vec{l}\cdot\vec{\sigma})(\vec{t}\cdot\vec{T})$ interaction to the optical potential.

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