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Effects of singlet breakup on deuteron elastic scattering at intermediate energies

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The effects of breakup to singlet spin states on elastic scattering observables for the ^{58}Ni($\vec{d}$, d)^{58}Ni reaction at 400 MeV is studied. The singlet breakup contribution to the elastic amplitude is estimated through an approximate two-step calculation, in which we exploit an adiabatic approximation and closure over the intermediate continuum states. The inclusion of the singlet channel coupling has a large effect on the reaction tensor analyzing power A_{yy} originating from a dynamically induced T_L tensor interaction.

Over the past few years there has been considerable interest in the study of the reaction mechanism in polarized deuteron elastic scattering from medium mass nuclei at intermediate energies.[1-5] The high precision differential cross section, vector (A_y) and tensor (A_{yy}) analyzing power angular distributions from Saclay,[6] at deuteron energies of 200, 400, and 700 MeV, provide a very stringent test of the various reaction model calculations.

In this Rapid Communication we will closely follow the approach of Yahiro and co-workers,[1,7] based on a three-body description of the neutron, proton, and target system. That is, we assume the three-body Hamiltonian

$$H=H_{np}+T_R+V_p(\mathbf{r}_p)+V_n(\mathbf{r}_n)+V_C(r_p)\,, \qquad (1)$$

where H_{np} is the Hamiltonian for the n-p relative motion, T_R is the n-p center-of-mass kinetic energy operator, V_p and V_n are the strong nucleon-target effective interactions, and V_C is the proton-target Coulomb interaction. Relativistic kinematics are included fully[8] in the implementation of this Hamiltonian and the nucleon-target interactions are obtained from phenomenological fits to nucleon-nucleus elastic scattering at half the incident deuteron energy. The (Coulomb) breakup of the deuteron, due to V_C, can reasonably be neglected in the ^{58}Ni($\vec{d}$,d) reaction at 400 MeV to be studied here.

The three-body model is very attractive since it makes a direct connection between the more complex deuteron-nucleus system and the underlying, better understood, and intrinsically simpler nucleon-nucleus phenomenology. In its simplest form, i.e., when breakup effects are neglected, the deuteron-target interaction $U_d(\mathbf{R})$ is of single folding model[9] form

$$U_d(\mathbf{R})=\langle\phi_d\,|\,V_p+V_n\,|\,\phi_d\rangle\,, \qquad (2)$$

where ϕ_d is the deuteron ground-state wave function. This interaction reproduces all major features of the measured elastic scattering observables; however, a detailed fit to the data, and in particular discrepancies with the measured A_{yy}, suggest some important and spin-dependent mechanism is missing from this lowest order treatment.

Relativistic dynamical[10] (Lorentz contraction and Thomas-precession effects) and Pauli blocking corrections to the model Hamiltonian have been studied quantitatively[11] and shown to produce only very minor effects on observables at 700 MeV, and in the latter case 400 MeV, incident deuteron energies. The inclusion of the n-p spin triplet breakup corrections, on the other hand, studied in detail[7] using the method of coupled discretized continuum channels (CDCC), produces significant effects leading to a marked improvement in the agreement with the measured cross section. These triplet breakup corrections do not, however, improve the agreement with the measured A_{yy}; in fact, the calculations indicate very little triplet breakup induced spin dependence. We investigate the role and the importance of contributions from deuteron breakup to intermediate n-p configurations in a singlet spin state, neglected in these earlier calculations.

Whereas breakup to spin triplet configurations can take place through the central and the spin-orbit parts of the nucleon-target interactions V_p and V_n, singlet spin coupling requires a nucleon spin-flip and can thus proceed only through the spin-orbit components of these interactions. At lower energies the central terms dominate these interactions. This is not the case at intermediate energies. We write the sum of the neutron- and proton-target spin-orbit forces[7]

$$V^{so}(\mathbf{r},\mathbf{R})=V_p^{so}(\mathbf{r}_p)\mathbf{l}_p\cdot\boldsymbol{\sigma}_p+V_n^{so}(\mathbf{r}_n)\mathbf{l}_n\cdot\boldsymbol{\sigma}_n$$
$$=\tfrac{1}{2}\bar{V}_+^{so}(\mathbf{L}+\mathbf{l})\cdot\mathbf{S}-i\bar{V}_-^{so}(\mathbf{R}\times\nabla_r+\mathbf{r}\times\nabla_R/4)\cdot\mathbf{S}+\tfrac{1}{2}\bar{V}_-^{so}(\mathbf{L}+\mathbf{l})\cdot\mathbf{S}'-i\bar{V}_+^{so}(\mathbf{R}\times\nabla_r+\mathbf{r}\times\nabla_R/4)\cdot\mathbf{S}'\,, \qquad (3)$$

where

$$\bar{V}_\pm^{so}=V_p^{so}(\mathbf{r}_p)\pm V_n(\mathbf{r}_n),\quad \mathbf{S}=(\boldsymbol{\sigma}_p+\boldsymbol{\sigma}_n)/2\,,$$
$$\mathbf{S}'=(\boldsymbol{\sigma}_p-\boldsymbol{\sigma}_n)/2\,,$$

and $\mathbf{L}$ and $\mathbf{l}$ are the n-p center of mass and relative orbital angular momenta. In this form it is clear that the first two terms, involving $\mathbf{S}$, couple the spin triplet incident deuteron only to triplet breakup configurations, whereas the latter pair of terms, containing $\mathbf{S}'$, will introduce singlet spin ($S=0$) admixtures. We will assume that the underlying V_p^{so} and V_n^{so} have the same strength and geometry and thus the coupling to the singlet channel must be associated with a corresponding parity change in the *n-p* relative motion. The second of the $\mathbf{S}'$ terms in Eq. (3) is responsible for this coupling. Its strength, the sum of the nucleon spin-orbit interactions, is large and the $^{2S+1}l_J = {}^1P_1$ and $^1F_3$ *n-p* configurations are expected to dominate. Our use of closure over the *n-p* intermediate states means that we automatically include all the appropriate relative orbital angular momentum states l in the singlet spin states. In transfer reactions, or at lower energies, where relative S waves dominate, then it is the first of the $\mathbf{S}'$ terms, involving the difference, or isovector component, of the nucleon spin-orbit interactions which is involved, with the result that spin singlet coupling effects were found to be small.[12]

The contribution of the singlet breakup states to the elastic amplitude is studied within a two-step calculation. An exact expression for the elastic amplitude is written as

$$\langle \mathbf{K}'\sigma' | t | \mathbf{K}\sigma \rangle = \langle \mathbf{K}'\sigma' | t_0 | \mathbf{K}\sigma \rangle + \langle \chi_{\sigma'}^{(-)}(\mathbf{K}') | V_p + V_n - U_d | \psi_\sigma^{(+)}(\mathbf{K}) \rangle , \quad (4)$$

where $\langle \mathbf{K}'\sigma' | t_0 | \mathbf{K}\sigma \rangle$ and $\chi_{\sigma'}^{(-)}(\mathbf{K}')$ are the elastic amplitude and final-state distorted-wave function due to the folded interaction $U_d(\mathbf{R})$ and $\mathbf{K}$, $\mathbf{K}'$, σ, and σ' are the initial and final-state momenta and spin projections of the deuteron. The full three-body wave function $\psi_\sigma^{(+)}(\mathbf{K})$ can be written

$$\psi_\sigma^{(+)}(\mathbf{K}) = [1 + G^{(+)}(E)(V_p + V_n - U_d)]\chi_\sigma^{(+)}(\mathbf{K}) , \quad (5)$$

where $G^{(+)}(E) = (E - H)^{-1}$ is the exact three-body propagator. Thus the second term in the elastic amplitude, Eq. (4), can be written

$$\langle \mathbf{K}'\sigma' | \Delta t | \mathbf{K}\sigma \rangle = \langle \chi_{\sigma'}^{(-)}(\mathbf{K}') | (V_p + V_n) Q_d G^{(+)}(E)(V_p + V_n) | \chi_\sigma^{(+)}(\mathbf{K}) \rangle , \quad (6)$$

where Q_d projects off the deuteron ground state and $U_d(\mathbf{R})$ no longer appears due to the orthogonality of the deuteron and the *n-p* intermediate breakup states.

The folded potential, Eq. (2), required for the evaluation of the amplitude $\langle \mathbf{K}'\sigma' | t_0 | \mathbf{K}\sigma \rangle$, was calculated using the soft core ($S+D$-state) deuteron wave function of Reid.[13] For deuteron scattering at 400 MeV, the nucleon-target interactions are required to reproduce the appropriate nucleon-target scattering at 200 MeV. Unfortunately, for a ^{58}Ni target, data do not exist at this energy; however, Dirac phenomenological fits to nucleon elastic scattering data derive potential parameters with very little energy and target mass dependence, and which can therefore be reliably interpolated to the target and energy required. For this reason V_p and V_n were taken as Schrödinger equivalent reductions[14] of a global Dirac optical potential fit[15] to available nucleon scattering data, which included energies from 200 to 1000 MeV and targets of mass range 40–208. The corresponding folded deuteron potentials, evaluated in coordinate space using the techniques of Keaton and co-workers,[16] are shown in Fig. 1. The amplitude $\langle \mathbf{K}'\sigma' | t_0 | \mathbf{K}\sigma \rangle$ was calculated using a version of the spin-1 optical model program DDTP,[17] which makes a conventional partial wave decomposition of the Schrödinger equation, modified to use relativistic kinematics.[8,18]

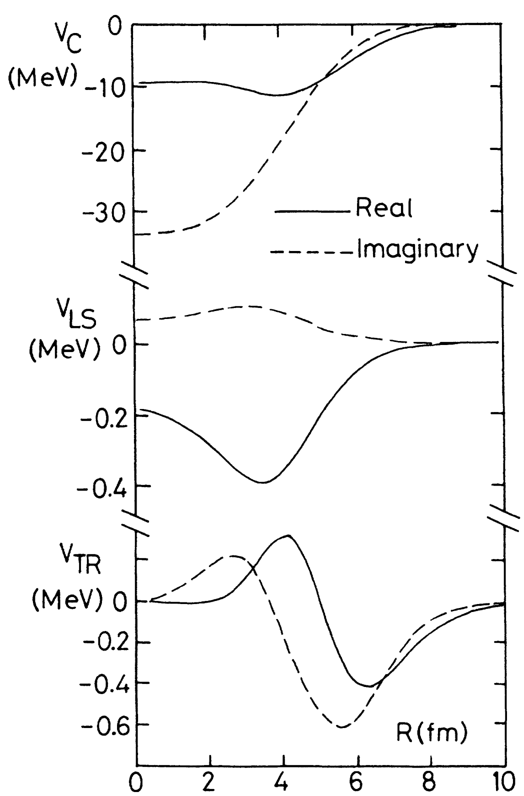

FIG. 1. Folded central, spin-orbit, and tensor (T_R) components of the deuteron-^{58}Ni interaction at 400 MeV incident deuteron energy.

To obtain a quantitative estimate of the importance of singlet breakup, several approximations are now made. In view of the shallow nature of the nucleon- and deuteron-target interactions (Fig. 1), in the entrance, exit, and intermediate states, when compared with the incident deuteron energy, we replace the distorted waves $\chi^{(\pm)}$ by plane waves. Similarly, the full Green's function $G^{(+)}(E)$ is replaced by the corresponding propagator $G_0^{(+)}(E)$, free with respect to the center-of-mass motion of the neutron and proton, i.e.,

$$G^{(+)}(E) \approx G_0^{(+)}(E) = \sum_{\sigma''} \int d\mathbf{k} \int \frac{d\mathbf{K}''}{(2\pi)^3} \frac{|\mathbf{K}''\phi_\mathbf{k}^{\sigma''}\rangle\langle \mathbf{K}''\phi_\mathbf{k}^{\sigma''}|}{E - E_k - E_{K''} + i\epsilon} , \quad (7)$$

where the $\phi_\mathbf{k}$ are *n-p* scattering states of relative momentum k and energy E_k, and $E_{K''}$ and K'' are related by the relativistic energy-momentum relationship.

A further important and reasonable simplification is to assume that the *n-p* relative energies E_k, strongly coupled by V_p+V_n, are small in comparison with the incident deuteron energy E. That is, we assume that the spectrum of breakup states is effectively localized and set $E-E_k$ =const $=\tilde{E}$, an adiabatic approximation. Calculations of the matrix elements $\langle\phi_k^{\sigma''}|V_p+V_n|\phi_d^{\sigma}\rangle$, appearing in Eq. (6), justify this step and suggest the value $\tilde{E}\approx E-10.0$ MeV.

Making these approximations in Eq. (6), the second-order plane-wave estimate of the contribution to the elastic amplitude arising from spin singlet breakup is

$$\langle\mathbf{K}'\sigma'|\Delta t|\mathbf{K}\sigma\rangle=\sum_{lm}\int k^2dk\int\frac{d\mathbf{K}''}{(2\pi)^3}\langle\mathbf{K}'\phi_d^{\sigma'}|V^{so}|\mathbf{K}''\phi_{kl}^{m}\rangle(\tilde{E}-E_{K''}+i\epsilon)^{-1}\langle\mathbf{K}''\phi_{kl}^{m}|V^{so}|\mathbf{K}\phi_d^{\sigma}\rangle\,, \tag{8}$$

where

$$\phi_{kl}^{m}(\mathbf{r})=u_l(k,r)Y_l^m(\hat{r})\chi_0^0(n,p) \tag{9}$$

is the *n-p* wave function in the intermediate state with $\chi_0^0(n,p)$ as the *n-p* singlet state spinor. As detailed above, in the case of singlet breakup the matrix elements in Eq. (8) select odd-*l* intermediate states. The adiabatic approximation allows the intermediate states sum to be carried out by closure, namely

$$\sum_{lm}\int k^2dk[1-(-)^l]u_l^*(k,r)u_l(k,r')Y_l^m(\hat{r})^*Y_l^m(\hat{r}')=\delta(\mathbf{r}-\mathbf{r}')-\delta(\mathbf{r}+\mathbf{r}')\,. \tag{10}$$

When substituted in Eq. (8) the resulting expression can be evaluated without approximation to the spin algebra, vital in our consideration of the induced spin dependence of the mechanism. The deuteron *D* state is, however, neglected in this evaluation. The details of this reduction are presented elsewhere.[18] Similar techniques are applicable to the treatment of triplet breakup effects, for comparison with the earlier analyses.[1,7]

Both triplet and singlet breakup cases were carried through in detail. The calculated second-order elastic contributions $\langle\mathbf{K}'\sigma'|\Delta t|\mathbf{K}\sigma\rangle$ were added to the leading elastic amplitude $\langle\mathbf{K}'\sigma'|t_0|\mathbf{K}\sigma\rangle$ and the observables calculated. The effects of triplet breakup, Fig. 2, agree qualitatively with those of the CDCC calculations.[7] Relatively large contributions to the cross-section angular distributions are observed but little additional spin dependence is apparent. By contrast, the singlet results, Fig. 3, show only small effects on the cross section and A_y, whereas the effect on A_{yy} is considerable, indicating a significant dynamically induced tensor interaction. By use of the invariant amplitude method,[19] one can show[18] that the presence of an induced T_L-type tensor interaction[20] will give rise to large contributions to the off-diagonal elements of the elastic amplitude with $|\sigma-\sigma'|=2$. These matrix elements were indeed found to be considerable in the case of the singlet breakup amplitude.

In this Rapid Communication we present the first quantitative estimate of the importance of coupling to spin singlet states in deuteron elastic scattering at intermediate energies. We conclude that the singlet breakup mechanism leads to a dynamically induced tensor interaction of T_L form. This interaction is of a magnitude that is able to

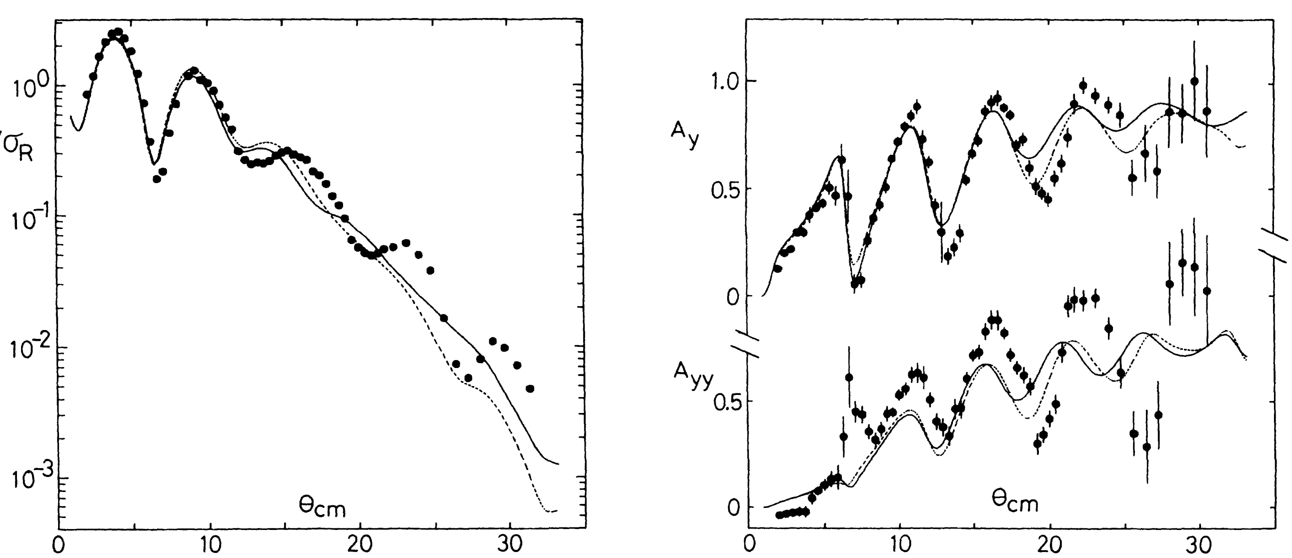

FIG. 2. Calculated elastic cross section, vector, and tensor analyzing power A_{yy} for d-^{58}Ni at 400 MeV. The dashed curves show the no breakup (folding model) calculations and the solid curves include triplet breakup effects. The data are from Ref. 6.

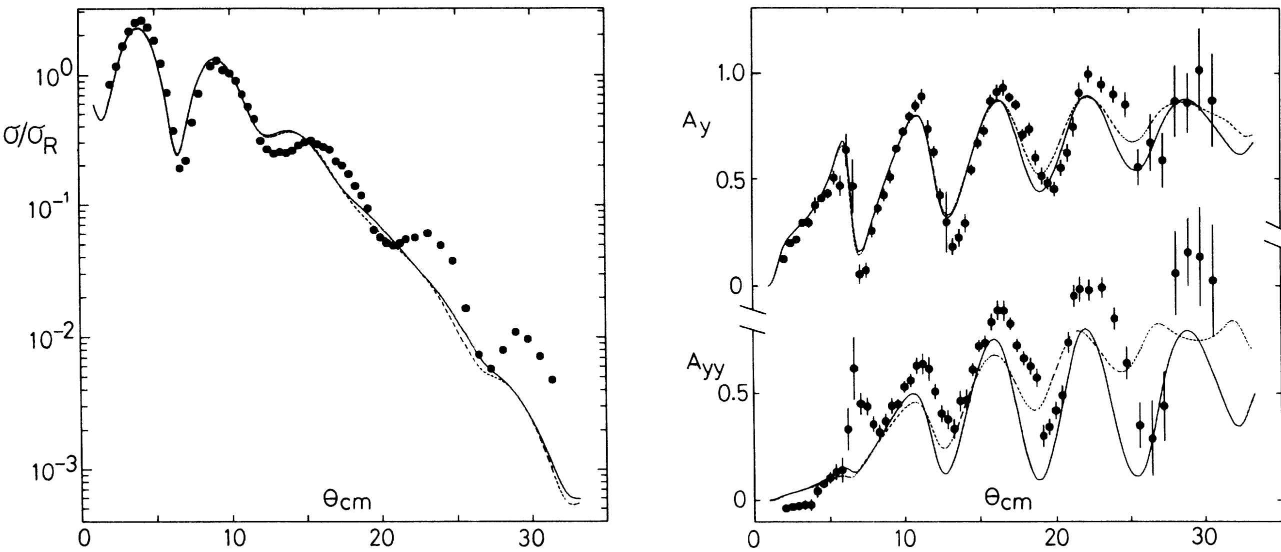

FIG. 3. As for Fig. 2, but now the solid curves result from the inclusion of spin singlet breakup effects. The data are from Ref. 6.

produce very significant effects on the calculated A_{yy} angular distributions but very little effect on the cross section and vector analyzing power A_y. We have evidence that the calculations at large angles show a sensitivity to the underlying nucleon-target interactions entering the three-body Hamiltonian. For example, if these interactions are taken from the work of Yahiro *et al.*[7] the cross section beyond 13° becomes more oscillatory. From the point of view of this communication however, it is important that the calculations show the same enhanced effects on A_{yy} when the singlet channel is included.

In concluding, we note that our calculations are based on a second-order expression for breakup contributions. We have performed calculations using Glauber theory[18,21] which confirm that this is a good approximation at the energies of interest here. In particular, the effects of continuum-continuum coupling in the intermediate states are not important. More significantly, the Glauber calculations showed that the effects of center-of-mass distortion in the entrance, exit, and intermediate states, due primarily to the strong imaginary central part of the folded deuteron interaction, were significant and must be included in order to obtain accurate quantitative results. In no way, however, does this diminish the importance of the large qualitative and quantitative differences obtained here, between the breakup induced spin dependences in the spin triplet and spin singlet modes. It is hoped that the present work will stimulate the inclusion of these singlet breakup effects into future CDCC calculations.

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[1]M. Yahiro, H. Kameyama, Y. Iseri, M. Kamimura, and M. Kawai, in *Proceedings of the Sixth International Symposium on Polarization Phenomena in Nuclear Physics, Osaka, 1985* [J. Phys. Soc. Jpn. Suppl. **55**, 322 (1985)].

[2]F. D. Santos and A. Amorim, Phys. Rev. C **37**, 1188 (1988); F. D. Santos and H. van Dam, Phys. Rev. C **34**, 250 (1986); F. D. Santos, Phys. Lett. B **175**, 110 (1986).

[3]J. R. Shepard, E. Rost, and D. Murdock, Phys. Rev. Lett. **49**, 14 (1982).

[4]R. E. Kozak, B. C. Clark, S. Hama, V. K. Mishra, G. Kalbermann, R. L. Mercer, and L. Ray, Phys. Rev. C **37**, 2898 (1988).

[5]L. Ray, Phys. Rev. C **38**, 2743 (1988).

[6]N. van Sen, J. Arvieux, Ye. Yanlin, G. Gaillard, B. Bonin, A. Boudard, G. Bruge, J. C. Lugol, R. Babinet, T. Hasegawa, F. Soga, J. M. Cameron, G. C. Neilson, and D. M. Sheppard, Phys. Lett. **156B**, 185 (1985); N. van Sen (private communication).

[7]M. Yahiro, Y. Iseri, H. Kameyama, M. Kamimura, and M. Kawai, Prog. Theor. Phys. Suppl. **89**, 32 (1986); Phys. Lett. B **182**, 135 (1986).

[8]W. R. Coker, L. Ray, and G. W. Hoffmann, Phys. Lett. **64B**, 403 (1976).

[9]S. Watanabe, Nucl. Phys. **8**, 484 (1958).

[10]H. Kameyama and M. Yahiro, Phys. Lett. B **199**, 21 (1987).

[11]J. S. Al-Khalili, J. A. Tostevin, R. C. Johnson, and M. Kawai, J. Phys. G **14**, L103 (1988).

[12]J. D. Harvey and R. C. Johnson, J. Phys. A **7**, 2017 (1974).

[13]R. V. Reid, Ann. Phys. (N.Y.) **50**, 411 (1968).

[14]L. G. Arnold, B. C. Clark, R. L. Mercer, and P. Schwandt, Phys. Rev. C **23**, 1949 (1981).

[15]S. Hama, B. C. Clark, E. D. Cooper, H. S. Sherif, and R. L. Mercer, *Global Dirac Optical Potentials for Elastic Proton*

Scattering from Heavy Nulcei, Ohio State University Report, 1989; E. D. Cooper (private communication).

[16]P. W. Keaton, Jr., E. Aufdembrink, and L. R. Veeser, Los Alamos National Laboratory Report No. LA-4379-MS, 1970 (unpublished); P. W. Keaton, Jr. and D. D. Armstrong, Phys. Rev. C **8**, 1692 (1973).

[17]R. P. Goddard, Program DDTP, University of Wisconsin-Madison, 1977 (unpublished).

[18]J. S. Al-Khalili, Ph.D. thesis, University of Surrey, 1989; J. S. Al-Khalili, J. A. Tostevin, and R. C. Johnson (unpublished).

[19]Y. Iseri, H. Kameyama, M. Kamimura, M. Yahiro, and M. Tanifuji, Nucl. Phys. **A490**, 383 (1988).

[20]G. R. Satchler, Nucl. Phys. **21**, 116 (1960).

[21]R. J. Glauber, in *Lectures in Theoretical Physics,* edited by W. E. Brittin and L. G. Dunham (University of Colorado Press, Boulder, 1959), Vol. 1.