# DIRECT REACTION INELASTIC SCATTERING TO THE $2^-$ STATE OF $^{16}O$ VIA A NONLOCAL INTERACTION

By F. RUZZENE* and K. AMOS*

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*Abstract*

A study is made of the effects of a purely nonlocal representation of the reaction mechanism in inelastic scattering. In particular, the inelastic scattering of 30 MeV protons and 65 MeV $\alpha$-particles leading to the $2^-$ state of 8·88 MeV excitation in $^{16}O$ are considered. The reaction mechanisms are represented by separable interactions between the projectile and target nucleon, and a simple spectroscopy for $^{16}O$ is used in the plane wave Born approximation. The derived cross sections are compared with other calculations and the measured data. The asymmetry in proton inelastic scattering is also discussed.

## I. INTRODUCTION

Nonlocal separable two-body interactions have been used extensively in studies of two-nucleon scattering (Signell 1969; Afnan and Read 1972) and in finite and infinite nuclear matter calculations (Kennedy *et al.* 1964; Muthukrishnan and Baranger 1965; Tabakin and Amos 1967). Separable potentials have also been used in three-body calculations of proton–deuteron scattering and the triton binding energy and in calculations of magnetic moments (Aaron and Bahan 1963; Aaron *et al.* 1965; Bhakar and Mitra 1964). In many studies the use of separable interactions has been found to facilitate calculation. However, aside from any mathematical convenience it provides, a separable potential is as acceptable a form of the two-nucleon interaction as any of a variety of other potentials (Tabakin 1964; Haftel and Tabakin 1970).

In more recent work, partially nonlocal interactions in the form of a velocity dependence (Boridy and Pearson 1972) or a two-body spin–orbit operator (Raynal 1971; Love 1972) have been used to study inelastic scattering. Analyses of (p, 2p) data have also been reported by Chatterjee and Deutchman (1972), and similar calculations are being made by I. E. McCarthy (personal communication), in which a nonlocal interaction is used to represent the reaction mechanism. Such studies are interesting since nonlocality in the transition interaction permits orbital angular momentum transfers additional to those allowed by any local form of the transition interaction (Love 1972). Thus, since the magnitude and structure of differential cross sections reflect the allowed values of angular momentum transfer (Amos and Geramb 1971), nonlocality in the transition interaction could yield effects that cannot be produced with calculations involving local interactions. It is interesting therefore to examine the role that a totally nonlocal interaction can play in analyses of inelastic scattering.

* School of Physics, University of Melbourne, Parkville, Vic. 3052.

A study is made here of the inelastic scattering of 30 MeV protons and 65 MeV α-particles leading to excitation of the unnatural parity $2^-$ state in $^{16}O$ at 8·88 MeV. Not only are reliable data available (Harvey *et al.* 1964; Greaves *et al.* 1972) but also these reactions have been analysed using partially nonlocal interactions. Further, excitation of unnatural parity states should most strongly reflect any effect of nonlocality in the transition interactions. The excitation of unnatural parity states by inelastic α-particle scattering is particularly interesting since the reactions are forbidden to occur via a one-step process if the transition interaction is local (Eidson and Cramer 1962; Love 1972), although contributions from multistep processes may be important. A calculation with coupled channels by Tamura (1965) has produced a good fit to inelastic α-particle scattering to the $3^+$ state in $^{24}Mg$. However, such calculations are lengthy and, to date, use the collective model to describe nuclear spectroscopy. With this model, $3^+$ states can be represented as a simple three ($\lambda = 2$) phonon coupling (or as a member of the $\gamma$ vibration band), but $2^-$ states are not so easily described and require phonons of different angular momenta. Also, the data analysed by Tamura are consistent with the Blair (1959) phase rule, indicating that a collective model analysis may be suitable, while the data for the excitation of the $2^-$ state in $^{16}O$ have structure shifted from the positions expected by the phase rule and hence do not assure the success of a coupled channels analysis. It is quite probable then that additional reaction mechanisms are involved in the excitation of the $2^-$ state.

Excitation of unnatural parity states by proton inelastic scattering is not first-order forbidden if the reaction mechanism is local, since conservation of angular momentum can be achieved by a spin-flip process (Reif *et al.* 1968; Amos and Geramb 1971; Love 1972). Further, multiple scattering contributions may again be important and exchange effects, due to the requirement of antisymmetry, cannot be neglected. Both of these effects are embodied in the recent antisymmetrized distorted wave calculations using a core polarization reaction mechanism (Love and Satchler 1971; Geramb 1972*a*). Very good fits to the differential cross sections for proton inelastic scattering to the $2^-$ state in $^{16}O$ were obtained over a wide range of incident energies. However, so far it has not been possible to fit simultaneously the measured asymmetries for this reaction (Smith and Amos 1973). Also, the nuclear structure details implied by the parameters required in the cross section calculations have not been well established (Geramb 1972*a*).

While the effects of multiple scattering processes are important, the significance of other possible processes must be examined. Nonlocal effects in the interactions could contribute significantly, particularly in α-particle scattering, since nonlocality in the interaction permits the excitation of unnatural parity states by a first-order process. Consequently, a detailed study of the contributions to the scattering amplitudes for the excitation of unnatural parity states from different possible types of nonlocal effective interactions must be made using the distorted wave approximation. Previous investigations of inelastic scattering to unnatural parity states using partially nonlocal interactions (Love 1972; Boridy and Pearson 1972) have not been very successful, however, and hence, as a first step in the studies of totally nonlocal interaction effects, we have made calculations incorporating a number of simplifying approximations. In this way, at least, we can assess the merit and practicability

of attempting more "realistic" calculations. Specifically, in the present paper we use the plane wave approximation with simple spectroscopy for the nuclear target states and an s-wave separable interaction for the nonlocal transition. These separable potentials are determined from analyses of the free two-nucleon and free nucleon–$\alpha$-particle systems. The use of such interactions is a major approximation since the transition interaction is, in fact, a complicated two-particle $t$-matrix in a nuclear medium. As a consequence, an effective interaction representing this $t$-matrix should be weaker than the free two-particle interaction and it should be density dependent. That the strength of the effective interaction should be weaker than that of the free two-particle interaction has been demonstrated in analyses of inelastic scattering by Love and Satchler (1970). Hence, our calculations should overestimate the transition strength. Since distortion effects, particularly absorption, upon the projectile wavefunctions are ignored, overestimation of the transition strengths should be enhanced. Details of the present calculations are specified in the next section, while the results are presented in Section III and the conclusions reached are discussed in Section IV.

## II. Calculations

In a microscopic theory of direct reaction inelastic scattering between nuclear target states specified by quantum numbers $J_i, M_i$ and $J_f, M_f$ (Amos and Geramb 1971), the scattering amplitude can be written as

$$T_{fi} = \sum_{j_1 j_2 I N} S(j_1, j_2, J_i, J_f; I)\,[2J_f+1]^{-\frac{1}{2}}\,\langle J_i\, I\, M_i\, N \,|\, J_f\, M_f\rangle \mathscr{M}, \tag{1}$$

where $\mathscr{M}$ is a two-body matrix element given by

$$\mathscr{M} = \sum_{m_1 m_2} (-1)^{j_1 - m_1} \langle j_1 j_2\, m_1 - m_2 \,|\, I - N\rangle \times \langle \chi_f^{(-)}(0)|\langle \phi_{j_2 m_2}(1)|t(0,1)|\chi_i^{(+)}(0)\rangle|\phi_{j_1 m_1}(1)\rangle\,. \tag{2}$$

The present notation is the same as that defined by Amos and Geramb (1971). The total, orbital, and spin angular momentum transfers are taken to have quantum numbers $I$, $L_T$, and $S_T$ respectively, the subscript T being used to differentiate transfer quantum numbers from those of relative motion. The factor $S(j_1, j_2, J_i, J_f; I)$ is the single-particle density for the nucleon transition and contains all the many-particle spectroscopy associated with a single bound state nucleon in states labelled by $j_1\, m_1$ and $j_2\, m_2$ in the initial and final nuclear states respectively.

Antisymmetrization has been excluded from equation (2) for simplicity and the mathematical development that follows is applicable to the case of inelastic $\alpha$-particle scattering. The results are easily generalized for the case of inelastic proton scattering, in which spin and antisymmetrization must be included.

As is evident from equation (1), the scattering amplitude is a multiple sum of all spectroscopic overlaps in which the initial and final states of the target nucleus differ at most in the state specification of a single target nucleon. A simple spectroscopy for the target states facilitates calculations then by reducing these summations.

In particular, if we assume that the $2^-$ state in $^{16}O$ is just a single $1d_{5/2}$ neutron coupled to a $1p_{1/2}$ neutron hole state based upon the ground state of $^{16}O$, the scattering amplitude in equation (1) reduces to a single term in which $j_1$, $j_2$, and $I$ have the values 1/2, 5/2, and 2 respectively and in which the single-particle density is unity. Thus the scattering amplitude is given by equation (2).

Further development of the scattering amplitude requires the transition interaction to be specified. In general, an S state transition interaction can be written as

$$t(0,1) = \delta(\boldsymbol{R}-\boldsymbol{R}')f(r_{01}, r'_{01}), \tag{3}$$

where $\boldsymbol{R}, \boldsymbol{R}'$ and $r_{01}, r'_{01}$ are the two-particle centre of mass and relative coordinates respectively. In most analyses, the scattering amplitudes are formed using a local interaction, that is,

$$f(r_{01}, r'_{01}) = \delta(r_{01}-r'_{01})g(r_{01}). \tag{4}$$

Here we retain nonlocality by using an s-wave separable potential form,

$$f(r_{01}, r'_{01}) = h(r_{01})h(r'_{01})V, \tag{5}$$

whence the two-body matrix elements are given by

$$\begin{aligned}\mathscr{M} = \sum_{m_1 m_2} (-1)^{j_1-m_1} \langle j_1 j_2\, m_1 - m_2 \,|\, I-N\rangle V \\ \times \iint \mathrm{d}\boldsymbol{r}_0\, \mathrm{d}\boldsymbol{r}_1\, \chi_f^{(-)*}(0)\, \phi^*_{j_2 m_2}(1)\, h(r_{01}) \\ \times \iint \mathrm{d}\boldsymbol{r}'_0\, \mathrm{d}\boldsymbol{r}'_1\, \chi_i^{(+)}(0')\, \phi_{j_1 m_1}(1')\, h(r'_{01})\, \delta(\boldsymbol{R}-\boldsymbol{R}').\end{aligned} \tag{6}$$

In the plane wave approximation, and using harmonic oscillator wavefunctions for the single-particle bound states, the integrations in equation (6) are most easily handled by transforming to relative and centre of mass coordinates. However, as we are interested in assessing the practicability of more realistic calculations, we have transformed the integration coordinates to the relative and bound state coordinates $(r_{01}, r_1)$ and $(r'_{01}, r'_1)$. A similar transformation (to relative and continuum particle coordinates) would facilitate distorted wave calculations. The present transformations not only take advantage of the plane wave properties and, if necessary, permit the use of more complicated bound state wavefunctions (Grimm *et al.* 1971) but they also allow us to make an order of magnitude estimate of the computing times to be expected in distorted wave analyses.

With our choice of the transformation of coordinates, and using the expansions

$$\phi_{jm}(1) = R_{nl}(r_1) \sum_{\mu} \langle l\, \tfrac{1}{2}\, m-\mu\, \mu \,|\, j\, m\rangle\, Y_{l\,m-\mu}(\Omega_1)\, X_{\frac{1}{2}\mu}(s_1), \tag{7a}$$

$$\delta(\boldsymbol{R}-\boldsymbol{R}') = (2\pi)^{-3/2} \int \mathrm{d}\boldsymbol{K} \exp\{\mathrm{i}\boldsymbol{K}.(\boldsymbol{R}-\boldsymbol{R}')\}, \tag{7b}$$

where $n$ and $l$ are the bound state principal and orbital quantum numbers, the scattering amplitude is proportional to a factor

$$E_{\mathrm{fi}} = \int \mathrm{d}\boldsymbol{K} \int \mathrm{d}\boldsymbol{r}_1 \exp\{-\mathrm{i}\boldsymbol{r}_1 . (\boldsymbol{k}_{\mathrm{f}} - \boldsymbol{K})\} R_{n_2 l_2}(r_1)\, Y^*_{l_2 m_2 - \mu_2}(\Omega_2)$$
$$\times \int \mathrm{d}\boldsymbol{r}_{01} \exp\{\mathrm{i}\boldsymbol{r}_{01} . (\tfrac{1}{2}\boldsymbol{K} - \boldsymbol{k}_{\mathrm{f}})\} h(r_{01})$$
$$\times \int \mathrm{d}\boldsymbol{r}'_1 \exp\{\mathrm{i}\boldsymbol{r}'_1 . (\boldsymbol{k}_{\mathrm{i}} - \boldsymbol{K})\} R_{n_1 l_1}(r'_1)\, Y_{l_1 m_1 - \mu_1}(\Omega'_1)$$
$$\times \int \mathrm{d}\boldsymbol{r}'_{01} \exp\{\mathrm{i}\boldsymbol{r}'_{01} . (\boldsymbol{k}_{\mathrm{i}} - \tfrac{1}{2}\boldsymbol{K})\} h(r'_{01}) . \tag{8}$$

The plane wave approximation has been used and the centre of mass coordinate has been re-expressed in terms of the relative and bound state coordinates. After multipole expansions of the exponentials with the beam direction specifying the quantization axis, then standard angular momentum algebra can be used to determine that the scattering amplitude is given by

$$T_{\mathrm{fi}} = V(4\pi)^3 \sum (\mathrm{i})^{\lambda_4 - \lambda_3 + \lambda_7 - \lambda_8} Y_{B-N}(\theta_{\mathrm{sc}})$$
$$\times (-1)^{N+1+\lambda_7+H} [H][\lambda_1][\lambda_3][\lambda_4][\lambda_8] \{[\lambda_8][\lambda_7][\lambda_5]/90\}^{\frac{1}{2}}$$
$$\times \langle 1\lambda_7\, 00 | \lambda_8\, 0\rangle \langle \lambda_4\, \lambda_3\, 00 | 20\rangle \langle \lambda_1\, \lambda_4\, 00 | A0\rangle$$
$$\times \langle \lambda_8\, \lambda_5\, 00 | A0\rangle \langle \lambda_1\, \lambda_3\, 00 | B0\rangle \langle H\, 2\, N - N | \lambda_7\, 0\rangle \langle B\, H - N\, N | \lambda_5\, 0\rangle$$
$$\times \begin{Bmatrix} 2 & 2 & 1 \\ \lambda_8 & \lambda_7 & H \end{Bmatrix} \begin{Bmatrix} H & \lambda_8 & 2 \\ A & B & \lambda_5 \end{Bmatrix} \begin{Bmatrix} \lambda_4 & \lambda_3 & 2 \\ B & A & \lambda_1 \end{Bmatrix}$$
$$\times \int K^2\, \mathrm{d}K \left| \int \mathrm{d}r\, r^2\, j_{\lambda_1}(k_{\mathrm{f}} r) j_{\lambda_1}(\tfrac{1}{2}Kr) h(r) \right.$$
$$\times \int \mathrm{d}x\, x^2 j_{\lambda_5}(k_{\mathrm{i}} x) j_{\lambda_5}(\tfrac{1}{2}Kx) h(x)$$
$$\times \int \mathrm{d}y\, y^2 R_{12}(y) j_{\lambda_3}(k_{\mathrm{f}} y) j_{\lambda_4}(Ky)$$
$$\left. \times \int \mathrm{d}z\, z^2 R_{11}(z) j_{\lambda_7}(k_{\mathrm{i}} z) j_{\lambda_8}(Kz) \right| , \tag{9}$$

where $[L] = 2L+1$ and the sum is over the quantum numbers $\lambda_1$, $\lambda_3$, $\lambda_4$, $\lambda_5$, $\lambda_7$, $\lambda_8$, $A$, $B$, and $H$.

## III. Results

The present results from the plane wave approximation were obtained using harmonic oscillator wavefunctions to represent the bound states, with an oscillator energy of 12·0 MeV. The separable interactions were taken from other calculations

involving the α-particle–nucleon interaction (Mitra *et al.* 1962) and the nucleon–nucleon interaction (Yamaguchi 1954). The derived results are compared with other calculations in which both local and nonlocal interactions were used and from these comparisons we can assess the general significance of nonlocality in the transition interaction.

### (*a*) *Inelastic Scattering of α-particles*

Since α-particles are spinless, inelastic scattering to unnatural parity states cannot occur via a spin-flip process, i.e. a process which involves a spin angular momentum transfer quantum number $S_T = 1$. Consequently, the transition interaction must permit components in the transition amplitude for the excitation of unnatural parity states in which $L_T = I$. Such components do not exist if the reaction mechanism for inelastic α-particle scattering is represented by a local interaction

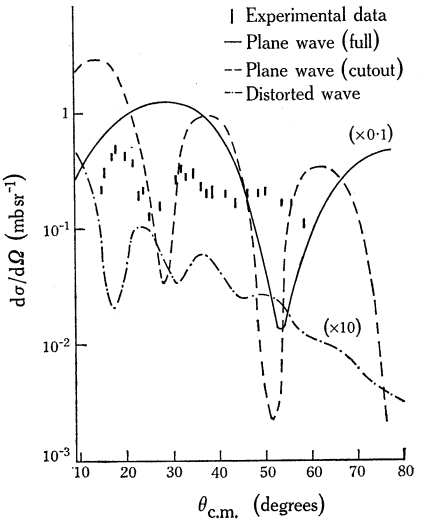


Fig. 1.—Differential cross sections for the inelastic scattering of 65 MeV α-particles leading to the $2^-$ state in $^{16}O$ at 8·88 MeV. The results from both full and cutout plane wave calculations are compared with the curve from a distorted wave calculation in which a spin–orbit potential was assumed for the interaction. The numbers in parentheses are the factors by which the results have been multiplied to produce the curves. The experimental data are from Harvey *et al.* (1964).

since the parity change in the reaction determines that $L_T$ and $I$ will differ. Specifically, excitation of the $2^-$ state in $^{16}O$ by inelastic α-particle scattering determines that $I$ is equal to 2 and, for a local α-particle–nucleon interaction, that $L_T$ is either 1 or 3. However, if the interaction is nonlocal then the allowed $L_T$ values are not subject to such a stringent parity selection rule and, for the reaction of interest, $L_T$ can have the values 1, 2, or 3 (Love 1972). Compound nucleus formation, exchange processes, and non-simultaneous multiple phonon excitation also permit the reaction to occur (Eidson and Cramer 1962). However, as we consider the excitation of the $2^-$ state in $^{16}O$ by the inelastic scattering of 65 MeV α-particles here, significant contributions from the first two processes are unlikely. The effect of the third process is not assessed. In any event, our current interest is to evaluate the significance of nonlocality in the target nucleon–α-particle interaction.

The results of calculations using a separable Yukawa form for the α–nucleon interaction (Mitra *et al.* 1962) are shown in Figure 1. Here the plane wave calculations (solid curve) are compared with the results of a distorted wave calculation in which

a spin–orbit potential for the α–nucleon interaction was used (Love 1972). Clearly spin–orbit interaction effects are unimportant for these reactions. Also included in Figure 1 (dashed curve) are the results obtained from a plane wave calculation using a separable interaction (Mitra *et al.* 1962) but removing all contribution from partial waves for continuum states with orbital quantum numbers less than 7. This "cutout" calculation approximates the results expected from a distorted wave calculation. The experimental data for this reaction are taken from Harvey *et al.* (1964).

The full plane wave calculations (solid curve in Fig. 1) give a transition strength that is much stronger than the experimental data and the structure of the data is not reproduced. However, distortion effects for 65 MeV α-particles essentially require the nuclear medium to be strongly absorbing, and hence a plane wave representation for the projectile wavefunctions is inadequate in that it yields a large contribution to the scattering amplitude from the nuclear interior. If such contributions are removed, the cross section predictions will not only decrease in magnitude but will also exhibit greater structure (Amos and McCarthy 1965). Since the nuclear interior contributions to the scattering amplitude are dominantly associated with low partial wave numbers, the results of the cutout approximation calculations should be a rough estimate of the predictions of a distorted wave calculation. The magnitude that results from the cutout calculation is in good agreement with the experimental data and the structure is a definite improvement upon that predicted by the full plane wave calculation. A better treatment of distortion effects would further improve the structure predictions since the sharp structure of plane wave calculations is known to be smoothed out when distortion effects are properly included. The significance of our results is emphasized by comparing the cutout plane wave predictions with those of the distorted wave approximation in which a spin–orbit interaction between the α-particle and target nucleon was used (Love 1972). This comparison shows that nonlocality in the transition interaction can provide an important contribution to the excitation of unnatural parity states by the inelastic scattering of α-particles. The small effects observed in the calculations using a spin–orbit interaction are due to the limited number of weak terms in which the required orbital angular momentum transfer can be produced (Love 1972). Further studies using nonlocal interactions in distorted wave calculations are necessary.

### (*b*) *Inelastic Scattering of Protons*

Since nucleons have spin, inelastic scattering of protons, unlike that of α-particles, can involve spin-flip processes. As a consequence, the scattering amplitude for excitation of the unnatural parity $2^-$ state in $^{16}O$ will have contributions from terms in which $L_T = 1$ or 3. Hence, the reaction is not first-order forbidden if the transition interaction is local and therefore there is a greater variety of possible interaction forms for inelastic proton scattering than for inelastic α-particle scattering to unnatural parity states. In particular, distorted wave calculations (Geramb 1972*a*) have established that a core polarization component in the reaction mechanism is essential. As a consequence, for inelastic proton scattering we are concerned less with establishing an alternative (or competitive) reaction mechanism than with a possible explanation of the discrepancies between current distorted wave analyses and the observed data.

The results of four calculations of the differential cross sections for the inelastic scattering of 30·4 MeV protons leading to the $2^-$ state in $^{16}O$ are shown together with the experimental data in Figure 2. The solid curve gives the result of a plane wave calculation in which a nonlocal separable two-nucleon interaction (Yamaguchi 1954) was used. For comparison, the dashed curve represents the result of a plane wave calculation made using a local interaction (Blatt–Jackson potential), while also included in Figure 2 are the results of two distorted wave approximations: (1) a calculation in which a simple collective model of the core polarization reaction mechanism (Geramb 1972*a*) was used (the specifics of this calculation (Smith and Amos 1973) are not essential for the present discussion) and (2) a calculation in which a velocity-dependent two-nucleon interaction (Boridy and Pearson 1972) was used. The latter calculation was for an incident energy of 27·3 and not 30·4 MeV but gross features of the predicted form are not expected to vary with a 3 MeV change in incident energy.

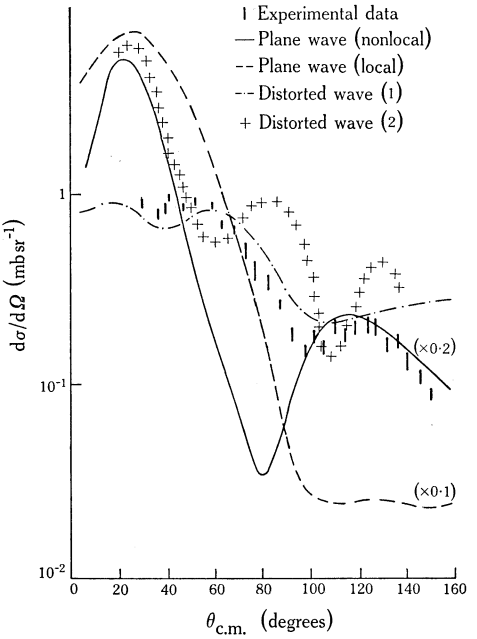


Fig. 2.—Differential cross sections for the inelastic scattering of 30·4 MeV protons leading to the $2^-$ state of $^{16}O$ at 8·88 MeV. The result from a plane wave calculation assuming a nonlocal separable two-nucleon interaction is compared with those from a plane wave, local interaction, calculation and from distorted wave calculations using (1) a core polarization exchange reaction mechanism and (2) a velocity-dependent interaction. The numbers in parentheses on the curves are the multiplication factors for the calculated results. The experimental data are from Greaves *et al.* (1972).

The plane wave results do not reproduce the structure of the data and grossly overestimate the transition strength but, as in the analyses of the inelastic scattering of α-particles, distortion effects greatly influence the predictions. In particular, the magnitude of the results is significantly reduced when more "realistic" calculations are made using a local transition interaction (Amos and Smith, unpublished data), although the structure predicted by these calculations is basically the same as that of the present plane wave calculations, namely a strong forward peak and negligible back angle scattering. Consequently, if we assume that a similar scaling effect will result when distorted wave calculations are made with a nonlocal two-nucleon interaction, nonlocality in the transition interaction should influence the predictions of large angle structure in particular. A careful assessment must be made, however,

as not only can multiple scattering terms and local components of the "proper" transition interaction contribute but also other types of nonlocality can yield large effects. The result of the distorted wave calculations (2), in which a velocity-dependent form of the transition interaction was used, is included in Figure 2 to illustrate this point.

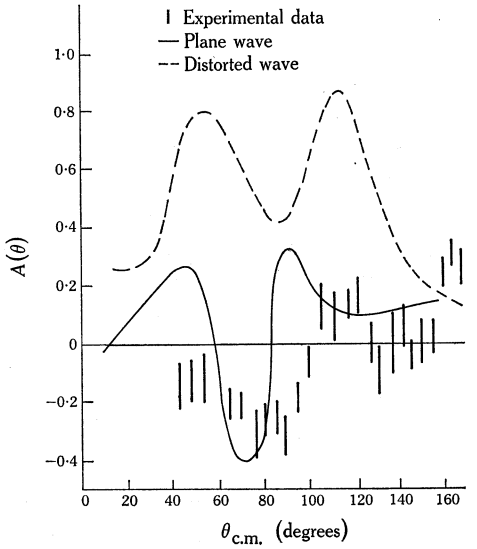


Fig. 3.—Asymmetries for the inelastic scattering of 30·4 MeV protons leading to the $2^-$ state in $^{16}O$ at 8·88 MeV. The plane wave approximation result using an s-wave separable two-nucleon effective interaction is compared with the curve obtained from a distorted wave calculation incorporating a core polarization exchange reaction mechanism. The experimental data are from Greaves *et al.* (1972).

The significance of the effects in inelastic proton scattering so far discussed would not be great if differential cross sections were the only data available. The results of distorted wave calculations of the differential cross sections for inelastic proton scattering populating the $2^-$ state via a core polarization exchange mechanism fit the data very well (Geramb 1972*b*). The result of a similar calculation shown in Figure 2 (distorted wave (1)) does not fit the experimental data as well as the prediction of Geramb because a simpler model of the reaction mechanism has been used, but the curve is close enough to the better analyses for our purposes. One of the problems with calculations in which the core polarization exchange process is assumed to be solely responsible for the transition is the associated prediction of the asymmetry. The dashed curve in Figure 3 shows the predicted asymmetry from the distorted wave calculations using a core polarization mechanism. The prediction from the plane wave calculations using the separable interaction for the reaction mechanism is shown by the solid curve. No results are available for the velocity-dependent interaction while the local (Blatt–Jackson) interaction predicts zero asymmetry. The experimental data in Figure 3 are from Greaves *et al.* (1972). While neither calculation fits the data, the nonlocal interaction results are reasonable at large scattering angles and reflect the gross features of the data. Great reliance cannot be placed on such general agreement, however, since the asymmetry is normalized by the predicted differential cross sections and thus wherever the structure of the cross section is not reproduced any fit to the asymmetry is accidental. The results, therefore, can only imply that the nonlocal interaction components may have a substantial effect at large scattering angles.

## IV. Conclusions

The present plane wave calculations for α-particle and proton inelastic scattering to unnatural parity states via a nonlocal interaction mechanism have yielded significant results and shown that more realistic analyses using a distorted wave approximation are warranted, at least for inelastic α-particle scattering. Although the computational times required and the variety of possible contributing processes make the distorted wave analyses of inelastic proton scattering less desirable, to offset this, inelastic proton scattering has additional measurable quantities that are more sensitive than differential cross sections (e.g. asymmetry).

The analyses of the inelastic scattering of α-particles to the $2^-$ state in $^{16}O$ have shown that strong nonlocality in the effective α–nucleon interaction will give a substantial contribution to the transition amplitude even when distortion effects in the projectile wavefunctions are taken into account. Hence a nonlocal effective interaction represents a reaction mechanism for the excitation of unnatural parity states by inelastic α-particle scattering that may compete strongly with other allowed reaction mechanisms, such as compound nuclear formation, particle exchange processes, and production of non-simultaneous multiple phonons.

The analyses of the inelastic scattering of protons to the $2^-$ state of $^{16}O$ imply that nonlocality effects in the effective two-nucleon interaction will be most significant at large scattering angles. However, as there are many allowed reaction mechanism components it is unlikely that the differential cross sections by themselves will be sufficient to assess nonlocality effects. Spin-dependent data, such as the asymmetries, are more sensitive to details of the reaction mechanism and therefore may permit a quantitative assessment of nonlocality effects.

## V. Acknowledgment

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