Existence of a nonlocality in the nucleon-^{16}O optical potential and its physical origin

George H. Rawitscher
Department of Physics, University of Connecticut, Storrs, Connecticut 06269-3046, USA

D. Lukaszek
Department of Physics and Earth Science, Central Connecticut State University, New Britain, Connecticut 06050, USA

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The cross section and polarization for nucleon elastic scattering from ^{16}O has a minimum at large angles and low energies that cannot be fitted with phenomenological or microscopic local optical potentials. Inclusion of exchange terms, e.g., knock-on and heavy-ion exchange, also failed to reproduce this minimum. However, it has been well fitted previously with a parity dependent (local) optical potential. It is shown here that this parity dependence simulates, at least in part, the nonlocality due to channel coupling.

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The elastic cross section for neutron or proton scattering from the nucleus of ^{16}O exhibits a minimum near 120° at incident energies between 10 and 60 MeV, which cannot be fitted by a local optical model, in spite of many attempts [1].[1] Elaborate microscopic optical potentials, based on folding a nucleon-nucleon (NN) G matrix over the ground state wave function of the nucleons in the target nucleus, that give excellent parameter-free fits to the elastic cross sections and polarizations for most nuclei [2–4] also fail to fit the backward angular distribution for closed shell nuclei, such as ^{16}O, ^{40}Ca, and ^{48}Ca. Explicit inclusion of the exchange or Fock term for neutron-oxygen (n-^{16}O) scattering was also considered [5], but the effect of these nonlocal Fock terms could be simulated [5] by a smooth angular momentum independent local potential, and also provided no better fit to the cross section than the optical model ones. These poor fits are illustrated in Fig. 1.

However, a parity dependent potential was found [6] that produced an excellent fit to the whole angular and energy range of the differential cross section and polarization of proton-oxygen (p-^{16}O) scattering. This potential is of the form

$$V(r) = U_1(r) + (-1)^L U_2(r), \tag{1}$$

where L is the orbital angular momentum of the incident nucleon relative to the center of mass of the target nucleus, and the potentials $U_j = V_j + iW_j, j=1,2$, are complex functions of the radial distance r. These potentials were obtained [6] phenomenologically by an "inversion" procedure especially developed for such fits [7]. The existence of parity dependence has been found previously [8,9] and has been found necessary to fit the back-angle scattering cross sections for α-particle neon (α-^{20}Ne) collisions [10], but has not before been brought out in as clear a form as in the work of Cooper and Mackintosh [6,9].

[1]The author is grateful to Dr. Daniel Horen for performing many searches of optical potentials to fit the p-^{16}O data, achieving no reasonable results.

Since ^{16}O could contain substantial α-particle clustering in its ground state, and since the nucleon–α-particle ($N\alpha$) scattering cross section has a strong minimum at backward angles, the possibility exists that the poor fit of N-^{16}O scattering theory to experiment could be due to α clustering in ^{16}O. This α-clustering feature was also mentioned in a study [11] of 96 MeV elastic neutron-nucleus (nA) scattering as a possible mechanism for explaining the discrepancy between conventional theories and experiment of the n-^{12}C cross section near 40°. However, for the case of n-^{16}O scattering at low energies this clustering mechanism was ruled out [12] as follows. The scattering of nucleons from a He nucleus was analyzed with a parity dependent potential of the form of Eq. (1), and large values for the potentials $V_2^{(\alpha)}$ and $W_2^{(\alpha)}$ were found [13]. It could thus be possible that the L-dependent potentials for ^{16}O arise from a remnant of the parity dependent N-α potentials, due to α-clustering in ^{16}O. The $V_j^{(\alpha)}$ and $W_j^{(\alpha)}$ potentials of Ref. [13], with $j=1,2$, were folded over a harmonic oscillator distribution of α particles in the nucleus of ^{16}O, and the result is denoted as V_j' and W_j', $j=1,2$ [12]. The result shows that neither $W_1'(r)$ nor $W_2'(r)$ has a positive

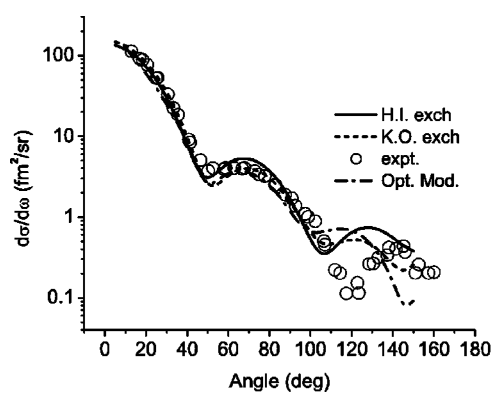

FIG. 1. Various unsuccessful fits to the elastic differential cross section for 20 MeV neutrons scattering from ^{16}O. The solid line includes heavy-ion exchange [15]; the dashed line includes knock-on exchange [5]; the circles represent the experimental results of Petler *et al.* [1]; and the dotted line is a conventional optical fit from Ref. [1].

value at small distances, contrary to what is the case for the parity dependent p-^{16}O potentials of Ref. [6]. In spite of the fact that the parity dependent potentials $V_2'(r)$ and $W_2'(r)$ have a large effect on the cross section, in that they shift the second minimum to somewhat larger angles, the fit to the experimental cross section is nevertheless inadequate [12] regardless of whether the strength of the imaginary central potential $W_1^{(16)}(r)$ is artificially increased, or whether the spread of the α-particle distribution is artificially reduced to smaller distances in an attempt to shift the second cross section minimum to the larger angles where it occurs experimentally.

What physical processes give rise to the L dependence of Eq. (1), found in Ref. [6]? It is known that this type of dependence does occur as a result of heavy-ion (or core) exchange in the resonating group model [14] description of heavy-ion scattering, but its effect is large only when the mass difference between the projectile and target nuclei is small. This is not the case for N-^{16}O scattering, and indeed, explicit inclusion of heavy-ion exchange for n-^{16}O scattering at the low incident energies envisaged here (20–60 MeV) did not lead to an improved fit to the experimental data [15]. It is the purpose of the present paper to show that a process that can give rise to potentials of the form of Eq. (1) is virtual excitation of states of the target nucleus during the scattering process. This dynamic polarization of the target nucleus by the incident nucleon is described by the occurrence of coupled channels in the Schrödinger equation. This is the first time that a connection between channel coupling and a potential of the type (1) could be established, since the mechanisms normally held responsible for giving rise to $(-)^L$-type potentials, such as heavy-ion exchange, and possibly α-particle clustering, were ruled out for this n-^{16}O case.

As is well known [16], optical potentials which are equivalent to coupling to (virtual) excited states are nonlocal, and the local equivalent potentials (LEP) which are equivalent to the nonlocal ones are both angular momentum and energy dependent. The calculation of the polarization potentials [17] involves complicated projection operators, and is difficult to carry out other than in special cases [18]. A closed form expression for the polarization potential due to virtual Coulomb excitation of low-lying 2^+ states for scattering of heavy ions has been given before [19], and a L dependence of such a potential has also been found [20]. A direct calculation of the elastic scattering in the presence of channel coupling to giant quadrupole resonances did produce significant corrections to the scattering at large angles in nuclei such as ^{16}O, ^{40}Ca, and ^{24}Mg [21], as well as in ^{208}Pb [22], that resulted in improved fits. A calculation of the polarization potential in n-^{16}O scattering by means of dispersion relations [23] also provided improved fits to the data. These results give an indication that the source of the parity dependence found in Ref. [6] might be due to channel coupling. However, coupled channel calculations are difficult to perform, because there are too many excited states which participate in the scattering that should be, but cannot be, included. Procedures that replace the left-out channels by an appropriate complex potential are being developed [24,25]. Particularly the work of Ref. [25] shows that channel coupling has a crucial effect on elastic scattering, even though that study is focused mainly on the low energy resonances. The theories mentioned above will ultimately lead to reliable inclusion of the various many-body effects on the optical model potential. Nevertheless, a parity dependence of the form of Eq. (1) is a simple phenomenological way to include coupled channel effects, as will now be justified.

A "toy-model" calculation of channel coupling was performed [26] several years ago for the purpose of explicitly exhibiting the corresponding nonlocal optical potentials in the elastic channel. It consists of between six and ten channels coupled to each other and to the elastic channel. The diagonal potentials are of a Gaussian form, and the coupling potentials are described as derivatives of Woods-Saxon potentials restricted to the surface of the nucleus. All potentials are real. A basis set of positive energy Sturmian functions [27] was used to expand the wave functions in all channels, since such a basis enables one to avoid the use of the complicated projection operators and permits one to calculate the optical potential that replaces the effect of channel coupling [27,25]. Three-dimensional plots of the resulting nonlocal optical potentials indeed revealed an L dependence and the imaginary parts exhibited a positive (emissive) "collar" around the main negative (absorptive) pieces. The latter occur in the radial region where the coupling between channels is largest (at the nuclear surface in the toy example). The emissive collar is due to the reinjection of flux into the elastic channel (a portion of that flux had been previously diverted into the inelastic channels). A reduction of the absorption from the incident channel in the presence of coupling to other channels was also observed in deuteron-nucleus elastic scattering calculations [28], in which the coupling to and among breakup channels was explicitly included.

A method developed by Fiedeldey and collaborators [29] to obtain local potentials equivalent to nonlocal ones (LEP), such that the nodes of the nonlocal and local wave functions coincide (but not their magnitudes), was applied to the toy-model channel-coupling case [30]. In this method the LEPs are obtained from radial derivatives of the Wronskian of two independent solutions (in the elastic channel) of the coupled equations for each incident angular momentum L. Several of the resulting LEPs [30] are reproduced here in Figs. 2 and 3. They oscillate around an average smooth potential, and the maxima for a particular value of L fall on top of the minima for the neighboring L. This shows that the radial dependence of the LEPs is very well approximated by parity dependent expression of the form of Eq. (1) for the low values of L. The description of the LEPs in terms of Eq. (1) is not perfect, however, because the deviation of the LEPs from the average potential is more pronounced for the high values of L than for the low values. In other words, the parity dependent potentials U_1 and U_2 should themselves be L dependent. Another shortcoming of the toy model is that it does not include the coupling between exchange amplitudes that account for the Pauli exclusion principle. These also have non-negligible effects [21,25]. Nevertheless, the indication from the toy model, together with the excellent fits obtained in Ref. [6], is that the parity dependence given by Eq. (1) should be a viable first approximation to coupled channel effects.

The imaginary components of the LEPs shown in the figures have positive values in certain radial regions, a feature

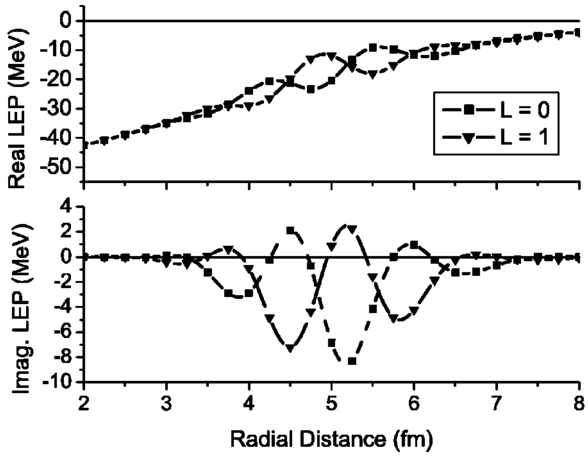

FIG. 2. Angular momentum dependent local equivalent potentials derived in Ref. [30] from a "toy" coupled channels calculation for $L=0$ and 1. The maxima for the $L=0$ case occur near the minima of the $L=1$ case, showing that these LEPs can be well represented by the parity dependent Eq. (1).

that also occurs for the potentials W_1 and W_2 obtained [6] for p-^{16}O scattering. This is a good indication that the effects of channel coupling are present, and hence provide further support for the channel-coupling source for the nonlocality. The LEP potentials shown in Figs. 2 and 3 are different from zero only in the surface region, between 2 and 8 fm, because the coupling potentials in the toy model vanish outside that region. Since there are no imaginary potentials explicitly present in the toy model, the imaginary parts of the LEP potentials also vanish outside of the surface region.

It could be asked how general is Eq. (1) for the various nuclear scattering situations, and why is not a term of this form needed for all optical potentials? A rigorous answer to this question has as yet not been given, although a qualitative answer is provided below. It can be argued that in the case of nuclei away from closed shells, the excited states occur at much lower energies above the ground state than for the "magic" nuclei, and their energy density is generally very high, the more so the further away from a closed shell the nucleus resides. Hence the oscillations in the LEPs should average themselves away more readily for these cases. Further, since there are a larger number of excited states available to absorb flux from the incident channel, the nuclei away from shell closures become less transparent, and the probability of flux returning to the elastic channel should decrease. These points deserve further study, as indicated below.

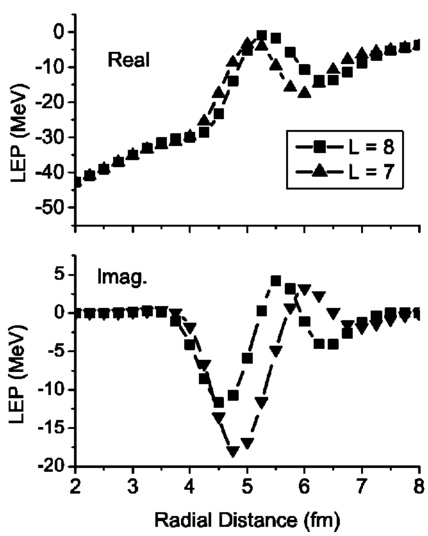

FIG. 3. LEPs similar to those in Fig. 1 for $L=7$ and 8.

A qualitative justification for the parity dependence in the channel-coupling nonlocality will now be attempted. The LEPs illustrated in Figs. 2 and 3 are based on a complicated expression involving the derivative of the Wronskian, $W_L(r)=v_L du_L/dr - u_L dv_L/dr$, of two independent solutions $u_L(r)$ and $v_L(r)$ of the coupled equations in the elastic channel for each incident angular momentum L, as given by Eq. (6) of Ref. [30]. Of course, if there are no nonlocal potentials the Wronskian is a constant and there is no LEP. However, in the presence of a nonlocal potential $K(r,r')$ in the Schrödinger equation

$$\left(-\frac{d^2}{dr^2}+\frac{L(L+1)}{r^2}V(r)-k_0^2\right)u_L(r) = -\int_0^\infty K(r,r')u_L(r')dr' \tag{2}$$

one finds

$$\frac{dW_L(r)}{dr} = \int_0^\infty K(r,r')[v_L(r)u_L(r') - u_L(r)v_L(r')]dr'. \tag{3}$$

If one now assumes that the kernel K is peaked near the surface of the interaction, so that for low values of L the functions u and v can be roughly approximated by their asymptotic expressions

$$u_L(r) \sim \sin(k_0 r + \phi_L), \quad v_L(r) \sim \cos(k_0 r + \phi_L), \tag{4}$$

where $\phi_L = -(\pi/2)L + \delta_L$, then the square bracket in Eq. (3) becomes of the L-independent form $\sim\sin\{k_0(r'-r)\}$. In the above, δ_L is the elastic scattering phase shift for partial wave L. In this case the L dependence of $dW_L(r)/dr$ hinges on the L dependence of the nonlocal kernel K. For example, the Hartree-Fock expression for the exchange nonlocality $K(r,r') \propto \Phi_a(r)v(r,r')\Phi_a(r')$ is independent of the value of L of the incident particle, and indeed, a search for an L dependence in the equivalent LEP for n-^{16}O scattering proved fruitless [31]. In the above, $\Phi_a(r)$ is the wave function of a target particle in bound state a, and $v(r,r')$ is the interaction potential between the two indistinguishable particles within the target.

We now show that the nonlocal potential K has a parity dependent component if it represents the effect of channel coupling. In this case the optical potential for the elastic channel (call it No. 1) is given by [27]

$$K_1(r,r') \propto \sum_{i,i'\neq 1} V_{1i}(r)\mathcal{G}_{i,i'}(r,r')V_{i'1}(r'), \tag{5}$$

where i and i' denote virtually excited inelastic states and $\mathcal{G}_{i,i'}(r,r')$ is the matrix channel Green's function [25,27]. If one particular inelastic excitation $i=n$ is dominant then the sum in Eq. (5) reduces to one term only, and $\mathcal{G}_{n,n}$ can be approximated by the conventional single-channel Green's function $\propto(1/k_n)F_{L'}(k_n r_<)G_{L'}(k_n r_>)$. Here F and G are the regular and irregular solutions of the uncoupled equations in the inelastic channel n with wave number k' and angular momentum L'. The latter tracks with L, differing from it by the angular momentum of the excited state. For the present qualitative discussion we will set $L'=L$. Further, assuming low values of L, so that in the surface region where the coupling potential V_{1n} is large, F and G can be approximated by their asymptotic expressions $F_L(r)\sim\sin(k'r+\phi_L')$, $G_L(r)\sim\cos(k'r+\phi_L')$ one can show

$$\frac{dW_L(r)}{dr}\propto V_{1n}(r)\Bigg\{-\int_0^r V_{n1}(r')\sin[k_n(r-r')]\times\sin[k_0(r-r')]dr'+\frac{1}{2}\int_0^\infty V_{n1}(r')\sin[k_n(r-r')]\times\sin[k_0(r-r')]dr'+(-)^L\frac{1}{2}\int_0^\infty V_{n1}(r')\times\sin[k_n(r+r')+2\delta_n]\sin[k_0(r-r')]dr'\Bigg\}. \qquad (6)$$

The parity dependence in the last term of Eq. (6) arises from the occurrence of $2\phi_n=-(\pi)L+2\delta_n$ in the argument of the first sin function in that term. Thus, the parity dependence of $dW_L(r)/dr$ is due to the L dependence of the Green's function in Eq. (5), and hence the corresponding LEP will also acquire a parity dependence.

An interesting question is whether an inelastic or transfer cross section, calculated by means of the distorted wave Born approximation (DWBA), is strongly affected by the type of optical model potential used to describe the elastic channel: a) a conventional local potential that fits only the forward part of the elastic cross section, or b) a parity dependent potential of the form of Eq. (1), that fits the whole angular distribution, or c) a formalism based on coupled channel calculations? The answer cannot be given without actually comparing the results of two such DWBA calculations, which is beyond the aim of the present investigation. However, a rough indication of what might be the difference between two DWBA calculations, one based on a local optical model and the other on a $(-)^L$ optical model, can be obtained by comparing the behavior with L of the respective elastic scattering S-matrix elements, since the latter give an indication of the behavior of the corresponding radial wave functions. This comparison is illustrated in Figs. 4 and 5 for the case of n-^{16}O scattering at 20 MeV. The corresponding elastic cross sections are compared with the data in Fig. 6. The L-dependent potential gives the back-angle cross section minimum at the right place, while the optical model result misses this angle completely. The L-dependent potential was obtained as follows. The potentials U_1 and U_2 were read off from Fig. 4 of Ref. [6] for the 27.3 MeV curves. These values were then fitted by means of combinations of Gaussian and Woods-Saxon potentials as described in the Appendix. In

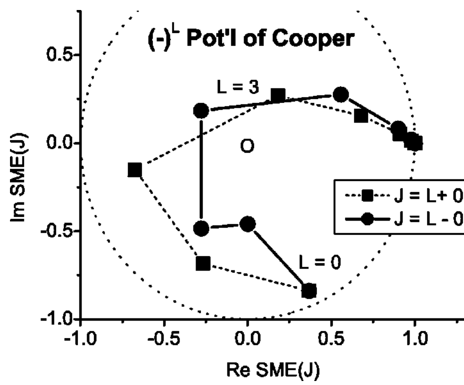

FIG. 4. The S-matrix elements for n-^{16}O scattering at 20 MeV, calculated with a parity dependent optical potential of the form of Eq. (1), based on an approximation to the potentials shown in Fig. 4 of Ref. [6], as is described in the Appendix. The latter fit elastic p-^{16}O scattering at 22.7 MeV, and include a L-independent spin orbit potential.

order to produce the cross section fit shown in Fig. 6 the range of V_1 had to be decreased slightly, as is described in the Appendix. It could have been of interest to seek further changes in the potentials, so as to improve the fit to the minimum at 120° as well. However, in view of the excellent fits obtained in Ref. [6] to p-^{16}O scattering, such a search appears to be superfluous, and would detract from the main point of the present study, namely, the realization that under certain circumstances channel coupling can be simulated by potentials of the $(-)^L$ type.

The large differences of the S-matrix elements of the two potentials, Figs. 4 and 5, imply that the radial wave functions should also be quite different. Hence, the $(-)^L$ dependent polarization potentials of Ref. [6] might serve as a first approximation to include the effect of channel coupling in the optical potential. However, in view of the substantial effect that channel coupling has on the elastic cross sections (particularly of "magic nuclei") and hence on the optical model potentials, it is likely that inelastic or rearrangement reactions might also involve virtual excitation processes. Hence, instead of using L-dependent optical potentials in DWBA calculations for the inelastic or rearrangement processes for a nucleus such as ^{16}O, a better approximation would be to

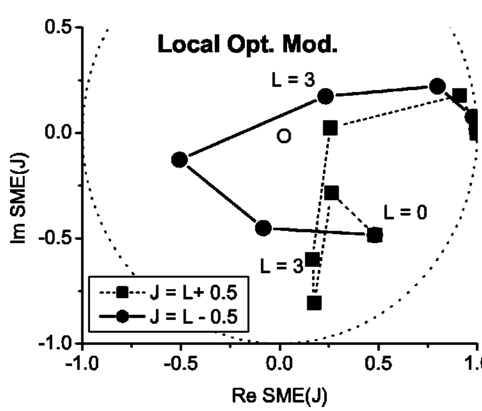

FIG. 5. Same as Fig. 4 calculated with a conventional local optical potential taken from Ref. [32].

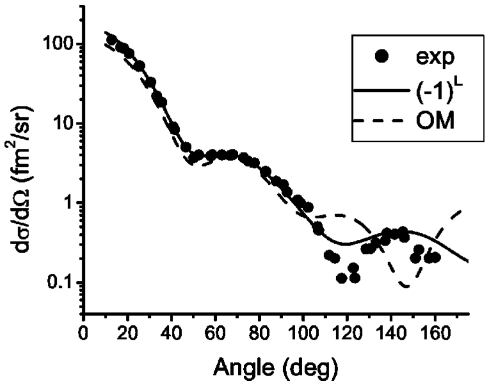

FIG. 6. Comparison of theoretical and experimental elastic differential cross sections for n-^{16}O scattering at $E_{\mathrm{LAB}}=20$ MeV. The solid curve is calculated using the L-dependent potential as described in the caption of Fig. 4, and the dotted line is the result of a conventional local optical potential of Ref. [32]. The same potentials gave rise to the S-matrix elements shown in Figs. 4 and 5, respectively.

carry out coupled channel calculations explicitly for such processes. This observation should also be relevant for describing the emission of nucleons by impact of high energy electrons on target nuclei [33].

In conclusion, it was shown that channel coupling (or virtual nuclear polarization during the scattering process) cannot be ruled out as a contributor to the form of Eq. (1) for the representation of the nonlocal optical potential of ^{16}O. Conversely, when the need for an optical potential of the form of Eq. (1) is established for a particular case, then the use of the distorted wave Born approximation to calculate inelastic or rearrangement scattering is suspect for this case. Although the arguments were confined to the scattering of nucleons on ^{16}O, they may also have implications for the optical potential describing atomic collisions. It would be interesting if the considerations presented here would also have implications for the representation of two- and three-body potentials between nucleons, used in the calculation of three-body systems, such as nucleon-deuteron scattering where discrepancies between *ab initio* theory and experiment still exist [34].

TABLE I. Fit parameters for the parity dependent potentials.

	A MeV	x_c fm	w fm	B MeV	x_0 fm	a fm
V_1	−60	0	2.078	0		
W_1	14.49	0	1.305	−5.56	4.685	0.571
V_2	6.98	0	0.841	−3.03	2.716	0.382
W_2	4.026	−0.10	0.937	0		
V_{so}	−2.941	1.052	1.259	0		
W_{so}	0.429	2.152	0.728	−2.726	1.340	0.257

APPENDIX: PARAMETRIZATION OF THE PARITY DEPENDENT POTENTIALS OF COOPER

The potentials defined in Eq. (1) are approximated by the sum of two analytic functions G and F, as $V(r)=G+F$. These functions are defined as

$$G(r;A,x_C,w)=A\ \exp[(r-x_c)^2/2w^2] \tag{A1}$$

and

$$F(r;B,x_0,a)=\frac{B}{1+\exp[(r-x_0)/a]}. \tag{A2}$$

Table I lists the values of the parameters for Eqs. (A1) and (A2), obtained by fitting the 22.7 MeV p-^{16}O potential curves shown in Fig. 4 of Ref. [6].

The parameters used for the calculation of the 20 MeV n-^{16}O scattering cross sections shown in Fig. 6, and for the S-matrix elements shown in Figs. 4 and 5, use the parameters listed in Table I, with only one modification: the value of w for V_1 was changed from 2.078 fm to 1.90 fm. The spin orbit potentials used in the solution of the Schrödinger equation are given by $(1/k)dV_{\mathrm{so}}/dr$.

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