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EFFECTS OF THE DYNAMIC α-TRANSFER POLARIZATION POTENTIAL IN THE LARGE-ANGLE SCATTERING OF $^{16}O + ^{28}Si$

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ABSTRACT

We evaluate the trivially equivalent local α-transfer polarization potential for the process $^{16}O + ^{28}Si \rightarrow ^{12}C + ^{32}S \rightarrow ^{16}O + ^{28}Si$. The back-angle elastic scattering angular distributions of $^{16}O + ^{28}Si$ at several center of mass energies obtained with the polarization potential added to the E-18 interaction were found to be in good agreement with the data, if an α-transfer spectroscopic factor of 0.4 is used.

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Since its discovery in 1977, the anomalous back-angle elastic scattering of $^{16}O + ^{28}Si$ has attracted considerable attention[1-10]. The phenomenon presents a challenge to different models of the underlying reaction mechanism. In particular, several approaches based on the use of a one-body optical potential have been advanced. Invariably, these one-body OP's present very clear and significant deviations from normal -trong absorption potentials such as the E-18 interaction[11]. In a recent article, Kobos and Satchler[12], suggested a particular form for these deviations, which when summed with a slightly normalized double-folding optical potential, reproduce well the main trend of the experimental data. These authors, however, treated these deviations phenomenologically and no attempt was made to establish their dynamical origin.

The purpose of the present note is to investigate the deviations from normal optical potentials arising from the dynamic polarization of the two ions resulting from multiple α-transfer. We suggest that deviations of the type considered by Kobos and Satchler could in principle be related to the above polarization effects.

Dynamic transfer polarization potentials for heavy ion scattering have been discussed from different points of view by several authors[13,14,15]. Here we present a slightly different derivation for the purpose of completeness. As we have done in a previous publication, we take the following two-step α-transfer process $^{16}O + ^{28}Si \rightarrow ^{12}C + ^{32}S \rightarrow ^{16}O + ^{28}Si$ as a basis for our coupled channels discussion. Instead of treating the above process within a two coupled channels framework, we first construct the dynamic polarization potential

arising from the coupling between the $^{16}O + ^{28}Si$ and $^{12}C + ^{32}S$ channels and subsequently employ it, together with an adequate strong absorption potential (e.g. E-18 [11]), in a one-channel description of the elastic scattering of $^{16}O + ^{28}Si$.

We define the DPP, $V_{pol.}$, to be that which reproduces, to first order, the correction to the elastic scattering T-matrix arising from an explicit consideration of the two-step process above, namely

$$\Delta T^{(1)}_{oo}(\vec{k},\vec{k}') = \langle \phi_o; \tilde{\chi}^{(-)}_o(\vec{k}_o') | H_{01} \mathcal{G}^{(+)}_1 H_{10} | \phi_o, \chi^{(+)}_o(\vec{k}_o) \rangle$$
$$\equiv \langle \tilde{\chi}^{(-)}_o(\vec{k}_o') | V_{pol.} | \chi^{(+)}_o(\vec{k}_o) \rangle \qquad (1)$$

where $\tilde{\chi}^{(\pm)}$ are the waves distorted by the E18 interaction, ϕ_o is the intrinsic ground state of the combined system, H_{01} and H_{10} are appropriate-transfer coupling interactions and $\mathcal{G}^{(+)}_1$ is the E18-distorted Green function describing the propagation of $^{12}C + ^{32}S$. In all our discussion to follow we consider the participating nuclei to be always in their respective ground states.

Thus the non-local DPP is

$$V_{pol.}(\vec{r},\vec{r}') = \langle \vec{r}'; \phi_o | H_{01} \mathcal{G}^{(+)}_1 H_{10} | \phi_o, \vec{r} \rangle \qquad (2)$$

which when expanded in partial waves becomes

$$V_{pol.}(\vec{r},\vec{r}') = \frac{1}{r\,r'} \sum_{\ell,m} V^{\ell}_{pol.}(r,r')\, Y_{\ell m}(\Omega_{\hat{r}})\, Y^{*}_{\ell m}(\Omega_{\hat{r}'}) \qquad (3)$$

The ℓ-dependent potential $V^{\ell}_{pol.}(r,r')$ would then appear added to the E18 interaction in the radial Schrodinger equation that

generates the exact partial waves in the elastic channels, $\psi_\ell(r)$. It is convenient to define the trivially equivalent local potential

$$\bar{V}^{\ell}_{pol}(r)\, f^{o}_{\ell}(kr) \equiv \int_0^\infty dr'\, V^{\ell}_{pol.}(r,r')\, f^{o}_{\ell}(kr') \qquad (4)$$

in terms of the E18-distorted partial wave function $f_\ell(r)$.

Using the non recoil and zero-range approximation for the transfer matrix elements, we obtain the following relation

$$\bar{V}^{\ell}_{pol}(r) = \frac{1}{4\pi} \frac{\Delta T^{(1)}_{\ell}(k_o)}{I^{01}_{\ell}(k_o,k_1)} \left[\frac{f^{1}_{\ell}(k_1 r)}{f^{o}_{\ell}(k_o r)} \right] F(r) \qquad (5)$$

where $\Delta T^{(1)}_{\ell}$ is the partial wave components of $\Delta T^{(1)}_{00}$ (Eq.1), I^{01}_{ℓ} is the radial integral

$$I^{01}_{\ell}(k_o,k_1) = \int_0^\infty dr\, f^{o}_{\ell}(k_o r)\, F(r)\, f^{1}_{\ell}(k_1 r) \qquad (6)$$

where $f^{0}_{\ell}(k_0 r)$ ($f_\ell(k_1 r)$) is the distorted radial wave function in the elastic (transfer) channel, and finally $F(r)$ is an appropriate spherical form factor. It is easily checked that Eq.(5) is completely consistent with Eq. (1), within the NR-ZR approximation.

The quantity $\Delta T^{(1)}_{\ell}$ can be easily calculated using existing second-order DWBA codes. In the present paper, however,

we evaluate $\Delta T_\ell^{(1)}$ approximately using a procedure developed by Austern et al. based on the on-energy-shell approximation for $\mathcal{L}_1^{(+)}$. We obtain

$$\Delta T_\ell^{(1)} \simeq 2\left[\frac{-8\pi i \mu_1}{\hbar^2 k_1} \frac{\left[I_\ell^{01}(k_0,k_1)\right]^2}{S_{\ell,1}^N(k_1)}\right] \tag{7}$$

The expression inside the square brackets is the result obtained by using the on-shell approximation. The factor 2 multiplying it accounts approximately for the off shell effects under conditions of strong absorption and strong Coulomb repulsion[15]. In Eq. (7) $I_\ell^{01}(k_0,k_1)$ is the NR-ZR transfer radial integral, Eq. (6), and $S_{\ell,1}^N(k_1)$ is the nuclear elastic S-elements in the transfer channel.

We have evaluated the ratio $f_\ell^1(k_1 r)/f_\ell^0(k_0 r)$ for several center of mass energies for the process $^{16}O + {}^{28}Si \to {}^{12}C + {}^{32}S$ and have found it very close to unity in the surface and outside regions where the process is expected to occur. We thus set this ratio equal to I_ℓ^{01}/I_ℓ^{00} to guarantee that the final expression for $\bar{V}_{pol}$ satisfies Eq. (1).

We thus write

$$\bar{V}_{pol}^{\ell}(r) = C_\ell(E)\ \hat{F}(r) \tag{8}$$

with the renormalized form factor $\hat{F}(r)$ determined by the condition $\hat{F}(0) = 1$, and the energy-dependent complex strength C_ℓ given by

$$C_\ell(E) = A\left[\frac{-4i\mu_1}{\hbar^2 k_1} \frac{\left(I_\ell^{01}(k_0,k_1)\right)^2}{I_\ell^{00}(k_0)\ S_{\ell,1}^N(k_1)}\right] \tag{9}$$

The constant factor A contains the spectroscopic amplitude and accounts for the appropriate normalizations arising from the recoil and finite range effects. This last normalization factor was determined by adjusting the values of our calculated radial integral, to correspond to those obtained from the code PTOLEMY[17] (which is "exact" in so far as finite range and recoil effects are concerned).

Clearly, our polarization potential is ℓ-dependent. We exhibit this dependence in Fig. 1. We have used the E-18 potential both in the elastic and transfer channels. Pollarolo et al[15] have recently constructed an ℓ-independent potential for nucleon transfer, and it is useful to indicate how such an equivalent ℓ-independent potential is obtained. This is straightforwardly accomplished by converting the ℓ-dependence into a classical turning point dependence and using the turning point as the radial variable. Fig. 2 shows our ℓ-independent α-transfer polarization potential.

We should stress that in the inner region (both in ℓ- and r-spaces) the calculated potential is not to be taken too seriously owing to the nonvalidity of the on-shell approximation there. On the other hand, one knows that transfer coupling effects are peripheral in nature, and therefore are important in the surface region, precisely where we expect on-shell procedure to be reasonable. Accordingly, we have taken the liberty of removing in the final result for the S-matrix

deviation, the contributions of the low partial waves.

Our results for the elastic scattering angular distributions of $^{16}O + ^{28}Si$ at $E_{C.M.}$ = 26.2, 31.6 and 34.8 MeV, obtained by solving the Schrodinger equation with the interaction $V_{E18} + \bar{V}_{pol}$, are shown in Figure 3. Also shown are the data taken from Ref.[6]. The value of the spectroscopic amplitude used in all three cases is 0.4, in accord with results of α-clustering calculation in s d shell nuclei[18].

Owing to our approximate treatment of the transfer channel Green's function, Eq. (2), we have found it necessary to attach to our resulting polarization potential, $\bar{V}^{\ell}_{pol}(r)$, Eqs. (8) and (9), an over-all, energy-dependent phase $\phi(E)$. Our final results, Figs. (3), (4) and (5) were obtained with $\phi(E_{C.M.} = 26.2\ MeV) = 0.0$, $\phi(E_{C.M.} = 36.6\ MeV) = -0.065\,\pi$ and $\phi(E_{C.M.} = 34.8\ MeV) = -0.138\,\pi$.

We should mention that the 180°-excitation function calculated within the $V_{E18} + \bar{V}_{pol}$ model does not show the large-period oscillations seen in the data. In order to obtain this feature within our multistep α-transfer model, we would have to include in the effective optical potential, a parity-dependent component, which arises from the elastic transfer process $^{16}O + ^{28}Si \to X \to ^{28}Si + ^{16}O$, with X denoting either $^{20}Ne + ^{24}Mg \to ^{24}Mg + ^{20}Ne$ or a one-step ^{12}C transfer. One would expect from general grounds that this latter possibility is much less likely to occur than the former. The trivially equivalent local 3α-transfer polarization potential comes out to be

$$\bar{V}^{(3\alpha)}_{pol}(r) = (-)^{\ell}\left(\frac{-4i\mu_1}{\hbar^2 k_1}\right)^2 \frac{I^{11}_{\ell}(k_1,k_1)}{\left(S^{N}_{\ell,1}(k_1)\right)^2} \cdot \frac{\left(I^{01}_{\ell}(k_0,k_1)\right)^2}{I^{00}_{\ell}(k_0,k_0)} F(r) \qquad (10)$$

where the subscript 1 refers to $^{20}Ne + ^{24}Mg$ and F(r) is the form factor for the process $^{20}Ne + ^{24}Mg \to ^{28}Si + ^{16}O$. Clearly, had we considered the elastic transfer as arising from a ^{12}C-exchange, the resulting polarization potential would be just $(-)^{\ell} F_{^{12}C}(r)$, with $F_{^{12}C}(r)$ being real and independent of ℓ and E.

We have calculated $\bar{V}^{(3\alpha)}_{pol}(r)$, according to Eq.(10) and found that it becomes important (~ 10% $V^{1\alpha}_{pol}$ (Eq.(8))), in the surface region at $E_{C.M.} > 30.0$ MeV, in accord with the finding of Ref. 2.

So far in our discussion of the anomalous back-angle scattering of $^{16}O + ^{28}Si$ we have only considered the coupling to several α-transfer channels. There are, of course, other channels and effects to worry about. In particular single nucleon, pick-up and stripping reactions, in conjunction with multiple inelastic excitation of ^{28}Si even recently discussed in Ref. 4), where it was claimed that these processes are quite important, at least at energies close to the Coulomb barrier.

Here we present arguments to the effect that, though possibly important at low energies, both multiple Coulomb excitation and single nucleon transfer processes in $^{16}O + ^{28}Si$ are not that important at back angles, at least at center of mass energies, $E_{C.M.} > 25$ MeV.

First let us consider the polarization potential in the $^{16}O + ^{28}Si$ elastic channel arising from multiple Coulomb excitation of the deformed ^{28}Si nucleus (E_{2+} = 1.78 MeV,

E_{4+} = 4.62 MeV). Extensive theoretical studies of this polarization potential, recently reviewed in Ref. 14), have shown that its effects on $\frac{\sigma}{\sigma_{Ruth}}$ is basically an overall long range damping which, when only the 2^+ state is considered (in the sudden limit), goes as $\exp\left[-\frac{16\pi}{225}\frac{k^2}{a^2}\frac{B(E2)\uparrow}{z_T^2 e^2} g_2(\xi)\right]$ at $\theta = 180^o$, with $g_2(\xi)$ being a semiclassical energy loss factor, $\xi \equiv \frac{E_{2+}}{\hbar v} a = 50.1622\, E^{-3/2}$, the adiabaticity parameter of $O + Si$, and a is half the distance of closest approach for head-on collisions. Inserting, the experimental value of $B(E2)\uparrow$, namely 325 $fm^4 e^2$, we obtain for the damping factor at $E_{C.M.}$ = 25, 30 and 35 MeV the values 0.82, 0.62 and 0.43, respectively. Therefore multiple Coulomb excitation of ^{28}Si could result only in a rather small reduction of $\frac{\sigma}{\sigma_{Ruth}}$ at back angles. Clearly, nuclear inelastic excitation not discussed above become important at $E > 23$ MeV. However, they tend to influence the elastic scattering mostly in the quarter-point angle region.

We turn now to one-nucleon transfer polarization effects. To assess their importance we have calculated with PTOLEMY[17], both pick-up and stripping reactions of neutrons and protons, namely transitions to that following final channels $^{15}O(\frac{1}{2}^-) + {}^{29}Si(\frac{1}{2}^+)$, $^{15}N(\frac{1}{2}^+) + {}^{29}P(\frac{1}{2}^-)$, $^{17}O(\frac{5}{2}^+) + {}^{27}Si(\frac{5}{2}^+)$ and $^{17}F(\frac{5}{2}^+) + {}^{27}Al(\frac{5}{2}^+)$, at $E_{C.M.}$ = 25, 30 and 35 MeV.

The resulting radial integrals, a basic input in our polarization potential, attain maximum values of, 10^{-3} at $\ell \sim 22$, 10^{-4} at $\ell \sim 16$ and 10^{-5} at $\ell \sim 12$ for all cases considered at the three center of mass energies mentioned above. These values are, at least, an order of magnitude smaller than their respective α-transfer counterpart. More importantly, the widths of the single-nucleon radial integrals are at least

twice as large as the α's. This would imply clearly, according to the recent findings of Ref. 19), that the single-nucleon transfer process, when considered at the level of the corresponding deviation in the elastic element of the S-matrix, would result, in a more localized deviation (centered around the $\theta_{1/4}$-region) in the elastic angular distribution from the "E-18" one, indicating clearly their lesser importance at $\theta \sim 180^o$.

We should, of course, mention that there are many more single-nucleon transfer channels that those of the α-type, which would therefore enhance the effect of the former. On the other hand, non orthogonality effects which tend to oppose the effect of the transfer coupling[20], are expected to be much more important for single nucleon transfer than for heavier particle transfer again because of the larger number of effective channels in the former!

Therefore, our neglect of both multiple inelastic excitation of ^{28}Si and single-nucleon transfer coupling effects in the treatment of the back-angle scattering of $^{16}O + {}^{28}Si$ at $E_{C.M.} > 25$ MeV is fully justified.

In conclusion, we have, in the present paper, demonstrated semi-microscopically, that deviations of the Kobos-Satchler type, which have to be invoked in order to account for the back-angle anomalous elastic scattering of $^{16}O + {}^{28}Si$, can be traced to multistep α-transfer couplings. We have accomplished this through the construction and the eventual utilization of the corresponding α-transfer polarization potential. It is argued that single-nucleon transfer channels and multiple inelastic excitation have a minor effect at back angles at $E_{C.M.} > 25$ MeV.

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FIGURE CAPTIONS

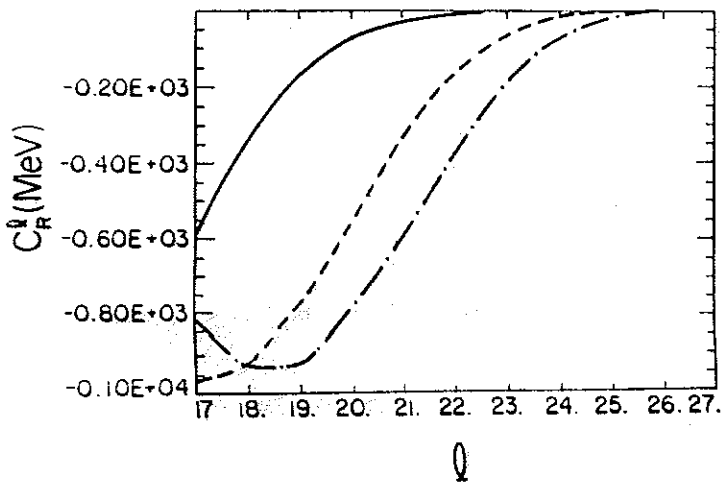
Figure 1 - The trivially equivalent local potential for α-transfer, at $E_{C.M.}$ = 26.2 (full curve), 31.6 (dashed) and 34.8 MeV (dashed-dotted). Shown is $C^{\ell} \equiv \bar{V}^{\ell}_{pol}(r)/F(r)$ vs. ℓ.

Figure 2 - Same as in figure 1 for the ℓ-independent version of $\bar{V}^{\ell}_{pol}(r)$ vs. r for $E_{C.M.}$ = 26.2 MeV (curve 1), 31.6 MeV (curve 2) and 34.8 MeV (curve 3). (See text for details).

Figure 3 - $E_{C.M.}$ = 26.2 MeV back-angle angular distribution of ^{16}O elastically scattered from ^{28}Si, obtained with the E18-interaction plus the polarization potential.

Figure 4 - Same as figure 3 at $E_{C.M.}$ = 31.6 MeV.

Figure 5 - Same as figure 3 at $E_{C.M.}$ = 34.8 MeV.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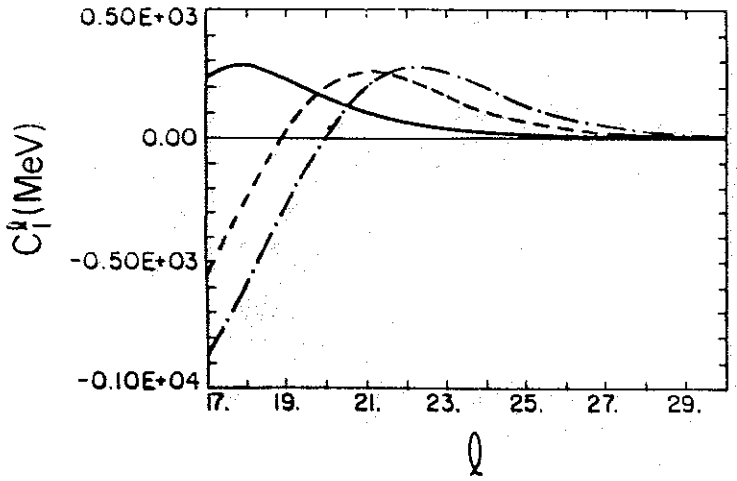
C_R^l(MeV)
l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C_I^l(MeV)
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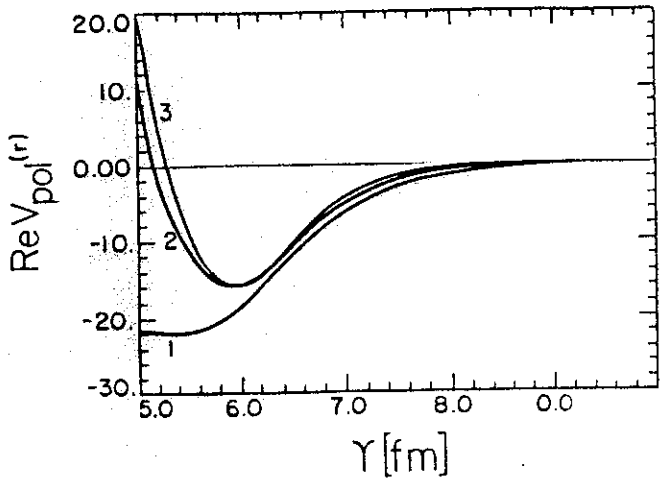
Fig. 1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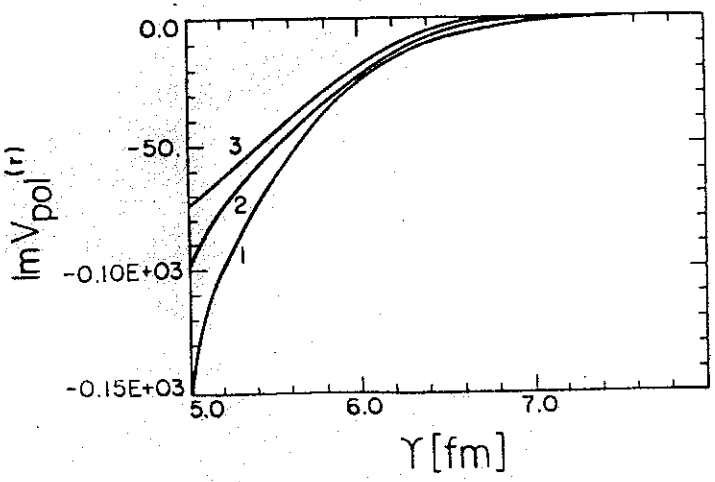
2
3
Υ[fm]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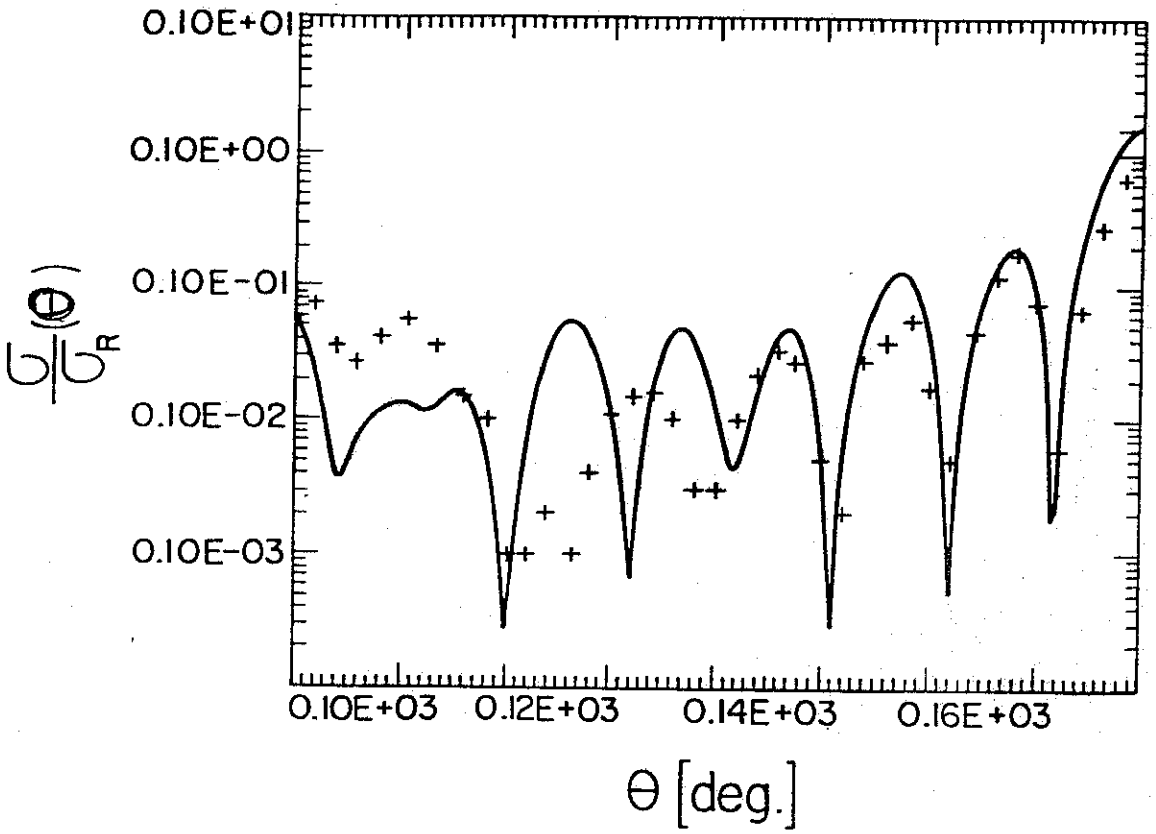
2
3
Υ[fm]

Fig. 2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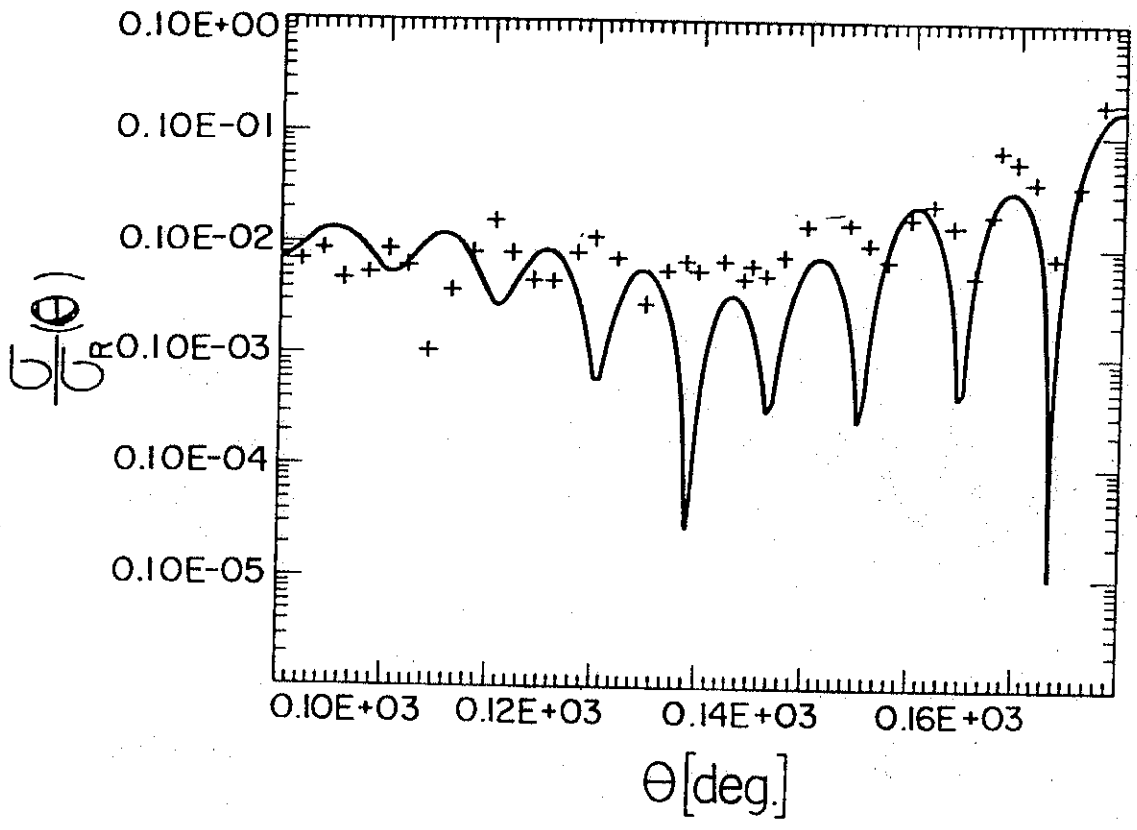
θ [deg.]

Fig. 3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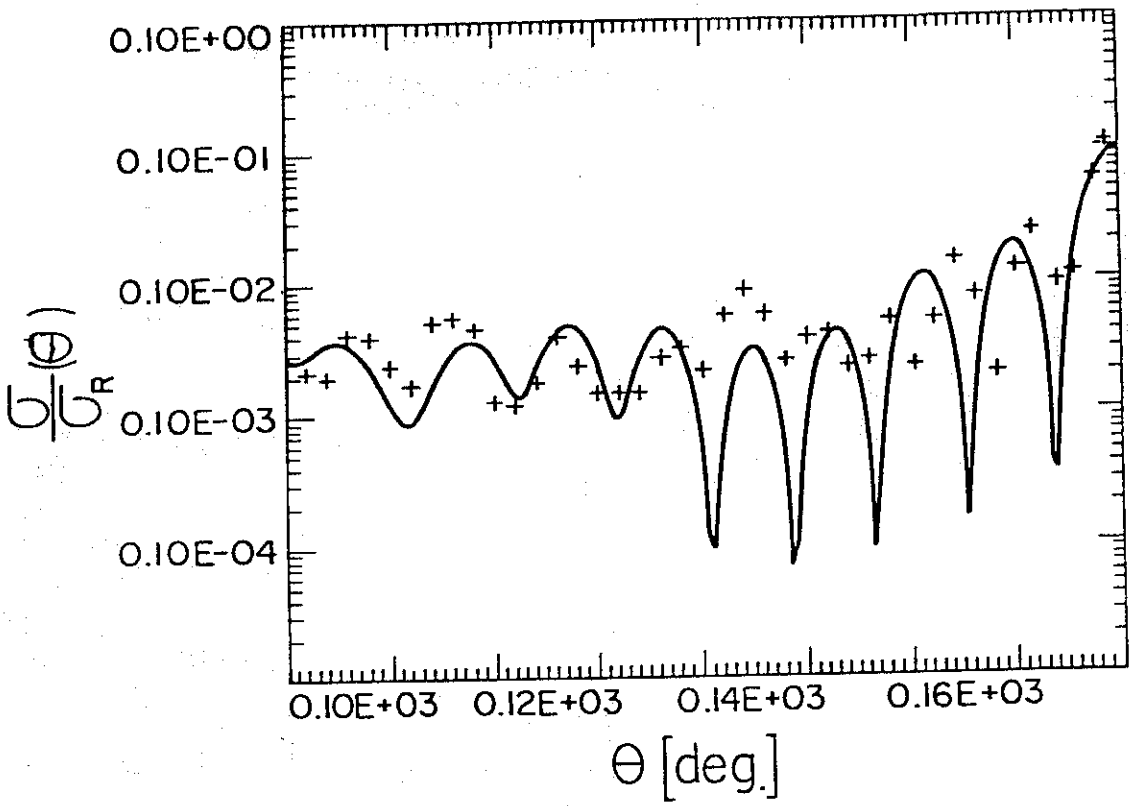
θ[deg.]

Fig. 4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0.10E-04
σ(Θ)/σR
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0.12E+03
0.14E+03
0.16E+03
Θ [deg.]

Fig. 5