POTENTIALS FOR HEAVY IONS SCATTERING FROM ^{208}Pb ☆

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Data for the elastic scattering of ^{12}C(96 MeV), ^{16}O(129.5 and 192 MeV) and ^{20}Ne (161.2 MeV) from ^{208}Pb have been used to deduce properties of the ion-ion potential. In particular, the strength of the absorptive potential in the surface region was found to be comparable to that of the real potential. The importance of small-angle data is emphasized.

Recent work e.g. [1] on transfer reactions between "light" heavy ions ($A \lesssim 18$) and intermediate mass targets ($A \lesssim 60$) has led to the interference that the corresponding optical potential U has only weak absorption in the surface region (typically $\mathrm{Im}\,U/\mathrm{Re}\,U \sim 1/5$). This was one of the features looked for in the present study of the elastic scattering of various projectiles from a heavier target, ^{208}Pb.

The data analyzed were obtained [2] at the Oak Ridge cyclotron and included 96 MeV ^{12}C, 129.5 and 192 MeV ^{16}O and 161.2 MeV ^{20}Ne. (The corresponding Coulomb barriers are 58, 77 and 96 MeV, respectively.) The analyses were made using both Woods-Saxon (WS) and folded forms [e.g. 3] for the real potential, and usually a WS form for the imaginary potential. However, the results are largely model-independent, being predicated only upon the assumption that the scattering can be described by a simple, complex potential $U(r)$ which depends only upon the separation r of the centers of mass of the two ions. Since the scattering is dominated by the potential at large separations r [3], the success of this assumption is almost assured.

The data have the usual characteristics; the angular distributions show Coulomb-nuclear interference oscillations about the Rutherford cross sections at small angles, followed by an exponential fall below Rutherford. The position and slope of this fall-off places constraints on the potential but the interference region at smaller angles is a particularly sensitive feature. (For this reason we present the cross sections plotted on a linear scale instead of the more usual semi-logarithmic plot. The latter may obscure this more interesting feature.) The analyses were made using the optical model search code GENOA [4], as modified [5] for use for heavy ions and with folded potentials.

What do we learn from the data? As previously emphasized [3], a characteristic given by data of this kind is the value of $\mathrm{Re}\,U(r)$ at the strong-absorption radius, r_{SA}, defined as the distance of closest approach for the classical Rutherford orbit for the angular momentum L for which the transmission coefficient $T_L = 1/2$. The values deduced from the present analyses are included in the table. (The value for 42 MeV α particles is included for comparison.) It was also found possible to place some limits on the slope of $\mathrm{Re}\,U$ at $r = r_{SA}$ and just beyond. If $\mathrm{Re}\,U$ is taken to have the form $\exp(-r/a)$ in this region, the favoured a is between 0.6 and 0.7 fm. Values significantly outside this range were found to be unacceptable; in

Table 1
Parameters [a] for scattering from ^{208}Pb.

	E_L (MeV)	r_{SA} (fm)	$\mathrm{Re}\,U(r_{SA})$ (MeV)	$\mathrm{Im}\,U/\mathrm{Re}\,U$ ($r \approx r_{SA}$)	N [b]
^{12}C	96	12.2	1.4	0.64	0.61
^{16}O	129.5	12.7	1.2	0.79	0.66
^{16}O	192	12.5	1.3	0.98	0.56
^{20}Ne	161.2	13.2	0.9	1.03	0.54
^{4}He	42	10.5	2.3	0.49	0.72

a) Obtained from analyses using a folded potential with a Gaussian interaction [3,6].
b) Renormalization factor for the interaction to give best fit.

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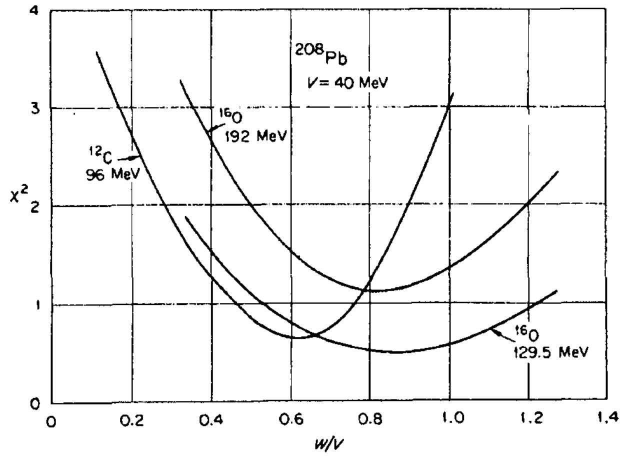

Fig. 1. Values of χ^2 as W is varied, for ^{12}C and ^{16}O scattering from ^{208}Pb. V is fixed at 40 MeV, r_0 and a are varied for best fits.

particular the small-angle oscillations about the Rutherford cross section will not agree with the data.

We were particularly interested to know what could be learnt about the imaginary potential strength. We concluded that the present data demand the ratio $\mathrm{Im}\,U/\mathrm{Re}\,U$ to be close to unity in the vicinity of the strong absorption radius. Some typical results are included in the table. (All the analyses used a WS form for $\mathrm{Im}\,U$, with either WS or folded forms for $\mathrm{Re}\,U$. Attempts to find fits with a deep, sharp-edged volume absorption plus a weak surface absorption [1] were unsuccessful.) As an example we describe fits obtained with a 4-parameter WS potential (i.e. using the same radius r_0 and diffuseness a for real and imaginary parts. The χ^2 values obtained with such a potential are as small as those obtained using more free parameters or using the folded form.) Experience has shown that any real depth V can be used so this was arbitrarily fixed at $V = 40$ MeV. Then a grid of W values was taken, each time adjusting r_0 and a for minimum χ^2. These values of χ^2 are shown in fig. 1 and indicate an optimum W/V ratio of about 0.6 for ^{12}C and about 0.85 for ^{16}O. (Other studies gave $W/V \approx 1.0$ for ^{20}Ne.)

Examples of the quality of fit are shown in fig. 2 for three values of W; $W = 25$ is close to the optimum in this case. Changing W mostly changes the amplitude of the oscillations about the Rutherford cross section at small angles. In the fall-off region the cross sections are the same for all three W values until $d\sigma/d\sigma_R < 10^{-3}$ and even then the differences are small. Precise data

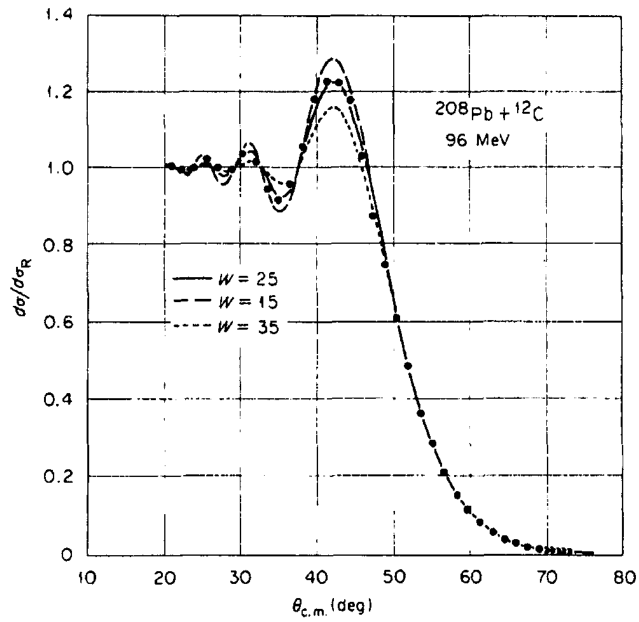

Fig. 2. Comparison between theory and data for three values of the imaginary strength W = 15, 25 and 35 MeV. The corresponding radius and diffuseness parameters are (r_0, a) = (1.298, 0.474), (1.256, 0.560) and (1.201, 0.664) fm, respectively. The real strength V = 40 MeV in each case.

in the small angle region can therefore help to determine W. The same behaviour is seen for the other projectiles.

Other features of the imaginary potential are more difficult to determine. There are indications that, when the WS form is used, the slope of the imaginary potential in the surface ($r \approx r_{SA}$) is preferred to be comparable to, but somewhat steeper than, the slope of the real potential. For example, when the folded form was used for the real potential, preliminary studies suggested that the most useful parameter of the imaginary potential to vary was the diffuseness a; it was sufficient to fix W and r_0 (the values W = 15 MeV, r_0 = 1.31 fm were chosen). The optimum values of a were then found to be about 0.5, 0.6 and 0.65 fm for ^{12}C, ^{16}O and ^{20}Ne, respectively. (This also indicates a increasing with the mass of the projectile.)

Studies were also made using a folded model for the real potential in which a nucleon-nucleon interaction v is folded into the mass distributions for the target and projectile [3].

The mass distributions were determined from an independent particle model, using a Wood–Saxon well, which gives charge distributions in agreement with electron scattering data and which gives the expected spectroscopic factors for pick-up reactions from these nuclei. Within reason, the folded potential is not sensitive to the details of these distributions provided some overall constraint, like the value of the mean square radius, is satisfied. A renormalization factor N is included, and allowed to vay, in order to account qualitatively for higher-order corrections. The model is successful if $N \approx 1$. Since we only need the real potential at (and beyond) the strong absorption radius, at which the half-central-density points of the two ions are still separated by about 3 fm, there is hope that the folded model has some physical significance.

The restriction, already mentioned, placed by the data upon the slope of the real potential in the outer surface rules out the use of a nucleon-nucleon interaction v with a range like the OPEP. This is encouraging because only the spin and isospin-independent part of v contributes and the OPEP does not have such a part. The longest range we would expect for v would be about one-half that of the OPEP and this gives folded potentials which satisfy the data.

A reasonable successful choice for v is the Gaussian even-state potential which fits low-energy nucleon-nucleon scattering [6]. A good fit for all projectiles is obtained with $N = 0.6$. (A similar value has also been obtained for targets of ^{28}Si, ^{60}Ni and ^{90}Zr, whereas 42 MeV ^{4}He on ^{208}Pb requires $N \approx 0.75$.) Other interactions v were also tried (including the zero-range form [7]) with comparable success provided the range was less than that of the OPEP. For example, the sums of Gaussians which fit nucleon-nucleon scattering up to 330 MeV [8] also require $N \approx 0.6$. However, using the long-range part of the even-state Hamada–Johnston potential [e.g. 9], which does contain a spurious OPEP component, gives a poor fit to the data and requires $N \approx 0.4$. Simply subtracting the OPEP component makes good the fit to the data, but requires N to be increased to 1.6.

It has been emphasized earlier [3] that the value of the real potential in the nuclear interior has no effect on the scattering in situations like those studied here. This can be re-emphasized here. For example, the folded model leads to potentials many hundred MeV deep but the scattering is indistinguishable from that with a WS potential only 40 MeV deep. Again, a 500 MeV deep folded real potential may be cut off at r = 11 fm, where it is about 10 MeV deep, and replaced by a constant -10 MeV potential for $r < 11$ fm, and still yield the same scattering down to where $d\sigma/d\sigma_R \lesssim 10^{-3}$. When a similar procedure is applied at r = 10 fm, where Re $U \approx -25$ MeV, no effect is seen until $d\sigma/d\sigma_R \lesssim 10^{-4}$. In other words, these experiments tell us very little about Re U for $r < 11$ fm.

A similar truncation procedure can be used to study the sensitivity to the imaginary potential in the interior. The main effect is to break the exponential fall of $d\sigma/d\sigma_R$ at some angle and to have it then tend to a constant value. For example, we took the Woods–Saxon well for ^{16}O + ^{208}Pb at 192 MeV corresponding to W = 35 MeV in fig. 1. The strong-absorption radius here is $r_{SA} \approx 12.5$ fm. Truncating Im U at 10.5 fm (so Im $U = -15.5$ MeV for $r < 10.5$ fm) produces no effect until $d\sigma/d\sigma_R < 10^{-5}$. Truncating at 11 fm (so Im $U = -10$ MeV for $f < 10$ fm) makes $d\sigma/d\sigma_R$ level off at about 2×10^{-5}. Neither case is detectable with the data available (which extend down to $d\sigma/d\sigma_R \sim 5 \times 10^{-4}$). Even moving the truncation point out to 11.5 fm (so Im $U = -5$ MeV for $r < 11.5$ fm, a factor of 7 decrease in the interior) does not produce significant changes until $d\sigma/d\sigma_R < 10^{-2}$; even then, the χ^2 of the fit to the present data is only increased by a factor of two because these small cross sections have relatively large errors associated with them. The cross sections in the small angle "interference" region are unaffected.

These results confirm that these data only determine the character of the imaginary potential near the strong absorption radius and do no more than place a lower limit on its value further in.

A more detailed account of these analyses will be included in a forthcoming publication [2].

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References

[1] E.H. Auerbach et al., Phys. Rev. Lett. 30 (1973) 1078;
C. Chasman et al., Phys. Rev. Lett. 31 (1973) 1074;
J. Ball et al., Phys. Lett. 49B (1974) 348.
[2] J.B. Ball et al., to be published.
[3] J.S. Blair, in Proc. Conf. on Nuclear reactions induced by

heavy ions, ed. W. Hering and R. Bock (North-Holland, Amsterdam, 1970);
G.R. Satchler, in Reactions between complex nuclei, ed. R.L. Robinson, F.K. McGowan, J.B. Ball and J.H. Hamilton (North-Holland, Amsterdam, 1974).
[4] F.G. Perey, unpublished.
[5] L.W. Owen, S.D. Blazier and C.Y. Wong, unpublished.
[6] I. Reichstein and Y.C. Tang, Nucl. Phys. A139 (1969) 144.
[7] J.P. Vary and C.B. Dover, Phys. Rev. Lett. 25 (1973) 1510.
[8] D. Gogny et al., Phys. Lett. 32B (1970) 591.
[9] G.R. Satchler, Zeit. fur Physik 260 (1973) 209.