Unambiguous Imaginary Potential in the Optical-Model Description of Light Heavy-Ion Elastic Scattering

María-Ester Brandan
Instituto de Física, Universidad Nacional Autónoma de México, México 01000, Distrito Federal, Mexico
(Received 16 October 1987)

Shallow imaginary potentials ($W_0 \approx 18$–25 MeV) are found to be essential to describe various sets of elastic-scattering data for ^{12}C-^{12}C and ^{16}O-^{12}C at intermediate energies. This result does not show a continuous ambiguity. An energy-dependent Woods-Saxon-shaped optical-model potential is presented for 60 MeV $\lesssim E_{c.m.} \lesssim 650$ MeV.

PACS numbers: 25.70.Cd, 24.10.Ht

The study of heavy ions, over two decades old, still suffers from an incomplete knowledge of the optical potential, the simplest representation of the interaction. The elastic scattering between complex nuclei is generally dominated by strong absorption, with the implication that the data are only sensitive to the surface of the interaction region and, therefore, the optical-model potential required to describe the measurements is not uniquely determined. However, data from the lighter heavy-ion systems at intermediate energies show in their angular distributions refractive features whose appearance indicates a relatively high degree of "transparency." Nuclear rainbows, indicative of this condition, were first claimed to exist in ^{12}C-^{12}C data above 160 MeV,[1] and subsequently interpreted as the dominance of contributions from the far side of the scattering center.[2] A similar explanation has been given to recent measurements in ^{16}O-^{12}C above 600 MeV.[3,4] Either interpretation requires[2] the absorption to be weak enough to support those trajectories that produce the observed slower falloff in the angular distribution beyond the Fraunhofer oscillations.

Nuclear rainbows in α-nucleus scattering have permitted the removal of discrete ambiguities from the real part of the nuclear potential.[5] For the heavy ions mentioned above, the effect of the refractive features in the angular distributions has been, in general, a substantial reduction in the ambiguities associated with the real potential. In only one case, ^{12}C-^{12}C at 240 MeV,[6] has it been suggested that the imaginary potential is the key factor to describe the measurements.[7] In spite of these facts, no unified optical-model description of these systems over the wide range of intermediate energies where data are available has yet been presented.

This work is aimed at the study of the imaginary potential needed to describe the measured elastic scattering of ^{12}C-^{12}C and ^{16}O-^{12}C at particular energies whose angular distributions show features clearly attributable to refraction, and probably also to low absorption. The results obtained here suggest a global description of various sets of measurements of center-of-mass energies between 60 and 650 MeV.

Four sets of data were chosen for the main study, ^{12}C-^{12}C at 139.5 and 158.8 MeV,[8] and ^{16}O-^{12}C at 608 (Ref. 3) and 1503 MeV.[4] The first two are particularly complete since the measured angular distribution reaches 90°. They have not so far been successfully described, by either optical-model[8] (OM) or coupled-channels analyses.[9] The other two sets of data are the most complete measurements in this system up to now. In the present study the complex OM potential has the standard six-parameter Woods-Saxon shape. Grid searches on the central depths V_0 and W_0 showed a striking preference

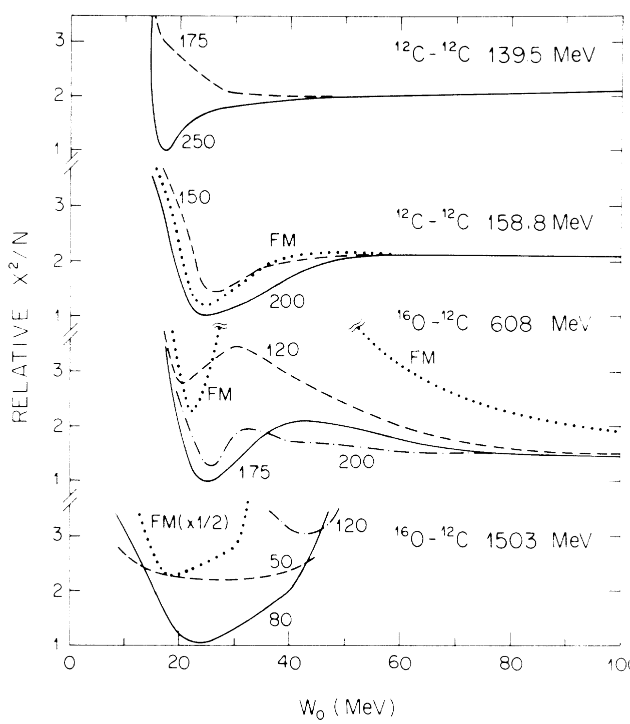

FIG. 1. Curves of χ^2/N vs the central imaginary depth. The labels indicate the value of V_0, the central real depth. Curves FM refer to real potentials calculated by double folding the DDM3Y effective interaction.

TABLE I. Optical-model parameters. Point-charge-plus-sphere Coulomb potential with reduced radius equal to 0.95 fm.

E_{lab} (MeV)	V_0 (MeV)	r [a] (fm)	a (fm)	W_0 (MeV)	r_i [a] (fm)	a_i (fm)	J_v (MeV fm^3)	J_w (MeV fm^3)
				^{12}C-^{12}C				
139.5	250	0.625	0.900	17.3	1.224	0.485	336.6	95.1
158.8	200	0.704	0.870	25.0	1.109	0.717	334.3	114.0
240.0	175	0.723	0.839	27.0	1.129	0.650	301.9	125.4
288.6	175	0.671	0.955	22.0	1.163	0.663	288.3	111.4
360.0	175	0.626	0.894	25.0	1.063	0.645	235.0	98.4
1016	120	0.657	0.879	25.0	0.964	0.862	175.0	86.0
				^{16}O-^{12}C				
139.2	275	0.717	0.747	15.0	1.295	0.436	360.3	82.8
215.8	175	0.786	0.849	25.0	1.155	0.601	308.5	104.2
311.4	175	0.795	0.846	25.0	1.183	0.643	316.7	113.0
608.0	175	0.654	0.975	24.7	1.084	0.662	231.5	88.5
1503	80	0.881	0.763	23.1	1.054	0.825	175.0	82.7

[a] $R = r(A_t^{1/3} + A_p^{1/3})$.

for shallow imaginary potentials, with W_0 about 18–25 MeV. *This search would not allow a continuous ambiguity:* Changes beyond some 15% in W_0 would result in a worsening of the fit which could not be compensated by any readjustment of the remaining five parameters. Figure 1 shows curves of χ^2/N as functions of W_0 for different values of the real central depth after optimizing the four geometrical parameters. The analysis assumed uniform uncertainties for all data points, otherwise the most interesting backward-angle measurements would not have sufficient weight in χ^2/N to assure an optimized description. This correction was not necessary at 1503 MeV and these data were treated with their original, mostly statistical, uncertainties. Table I lists the parameters corresponding to the minima in χ^2/N. The calculated differential cross sections, together with the data, are shown in Fig. 2.

The dependence of this result on the real part of the OM potential was studied further. Folding-model real potentials calculated from the density-dependent effective interaction[10] DDM3Y together with a Woods-Saxon imaginary term were fitted to the data. The curves labeled FM in Fig. 1 show that, even if the four-parameter folding-model fits are not as good as those with a Woods-Saxon real geometry, they all require—unambiguously—similar imaginary parts. A report on the folding-model analysis can be found elsewhere.[11] For ^{16}O-^{12}C at 608 MeV, a grid search using a squared Woods-Saxon real part together with a Woods-Saxon imaginary term[12] gives the same qualitative preference for $W_0 \approx 25$ MeV seen in Fig. 1.

It is possible to impose some restrictions on the Woods-Saxon real potential. For ^{12}C-^{12}C at 158.8 MeV good fits are obtained with V_0 between 175 and 225 MeV. For larger central depths the Fraunhofer oscillations leak out beyond 40°, superimposing on the smooth falloff a structure not shown by the data. At 139.5 MeV the best fits are those with $V_0 \approx 250$–275 MeV. Again, deeper potentials create stronger oscillations between 50° and 70°. For ^{16}O-^{12}C at 608 MeV the curves in Fig. 1 indicate two types of solutions depending on the value of the absorption. The shallow imaginary potential

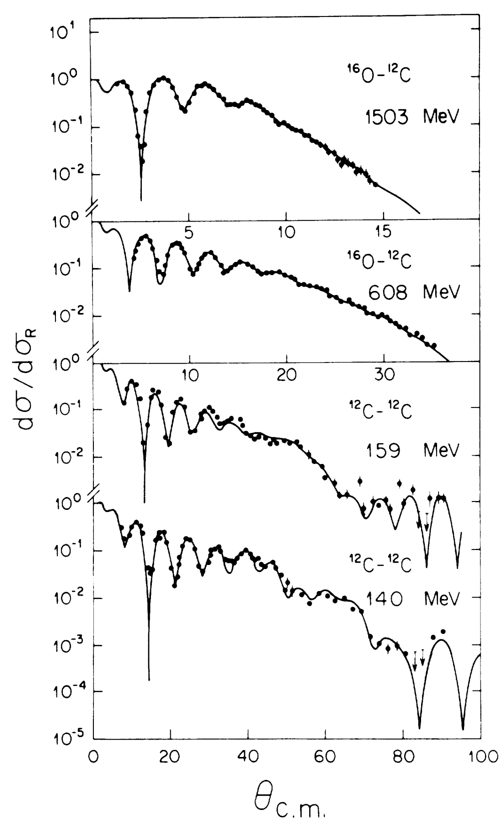

FIG. 2. Differential cross section relative to Rutherford (^{16}O-^{12}C) or Mott (^{12}C-^{12}C) calculated with the OM parameters in Table I. These are the four sets chosen for the main study.

near $W_0 = 25$ MeV selects real central depths about 175 MeV. The continuously ambiguous deep W_0 solution ($W_0 \gtrsim 100$ MeV) gives equally good fits to the data, but cannot discriminate among an infinite variety of real potentials, all of them related through their own continuous ambiguity. The original OM analysis of these data,[3] based on a grid search at W_0 values of 20, 40, 60,... MeV missed the narrow minimum around 25 MeV and only reported the high-absorption result. At 1503 MeV the optimum potential corresponds to the one originally reported.[4] In this case, both V_0 and W_0 seem to be well determined.[13]

The predictive power of these solutions was tested on other measurements that exist for these two systems: ^{12}C-^{12}C at 240,[6] 288.8,[14] 360,[15] and 1016 MeV,[16] and ^{16}O-^{12}C at 139, 216, and 311 MeV.[17] The central depths were fixed at values similar to those found in the main study, and the geometrical parameters were left free to optimize the fit. In some cases a further optimization of W_0 helped to improve the agreement with the data. This never took one far from the shallow imaginary potentials found in the main study. In all cases excellent fits were obtained; some of them are shown in Fig. 3, with parameters listed in Table I.

As a function of energy the most significant change occurs in the real potential, which decreases in strength as the energy increases. Similar results have been obtained previously in folding-model analyses of these systems[11,18] and in OM studies of some of the data sets included in this study.[15] The volume integral of the real potential per target-projectile pair, listed as J_v in Table I, is a decreasing function of energy, similar to the result for α-nucleus scattering.[19] The imaginary potential does not change significantly over the energy interval considered here, and its volume integral J_w attains values that resemble those known for light ions.[20]

The strongly refractive—and weakly absorptive—potentials found here support the presence of nuclear rainbows in some of the data. Near/far decomposition[21] indicates that in ^{12}C-^{12}C at 140 and 159 MeV, the minima observed around 75° and 65°, respectively, correspond to the last Airy minimum, and the broad "humps" forward of them are the corresponding maxima in the far-side contribution. The last Airy maximum occurs close to 90° and the interference caused by the identity of target and projectile prevents its observation. As the energy increases, the Airy interference pattern moves forward, and at 240 MeV the last maximum lies around 50°. Even if the imaginary potential at this energy is similar to those at lower energies, the expected hump of the rainbow has been reduced by absorption to the rather flat falloff shown by the data beyond 40°. This is also the case at 289 and 360 MeV. A detailed study of the features shown by these angular distributions is presently in progress.[22]

In summary, this report presents evidence for an imaginary potential free of ambiguities, necessary to describe the elastic scattering of two light heavy-ion systems over a wide range of energies. The imaginary part is crucial to the description, and because it represents a rather transparent potential, it also allows a relatively good determination of the real part. The OM parameters for a Woods-Saxon geometry are reasonably smooth functions of the center-of-mass energy, and the volume integrals for both parts are in agreement with what is known for lighter projectiles. This finding provides an analytical local potential badly needed as a reference in heavy-ion studies.

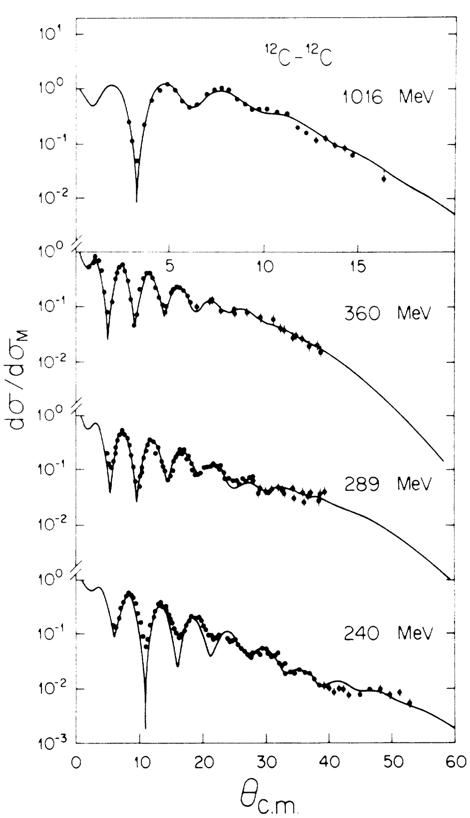

FIG. 3. Differential cross section relative to Mott predicted by optical potentials deduced from the results of the main study.

[1]M. E. Brandan, Phys. Rev. Lett. **49**, 1132 (1982).

[2]K. W. McVoy and G. R. Satchler, Nucl. Phys. **A417**, 157 (1984).

[3]M. E. Brandan *et al.*, Phys. Rev. C **34**, 1484 (1986).

[4]P. Roussel *et al.*, Phys. Rev. Lett. **54**, 1779 (1985).

[5]D. A. Goldberg and S. M. Smith, Phys. Rev. Lett. **29**, 500 (1972); D. A. Goldberg *et al.*, Phys. Rev. C **10**, 1367 (1974).

[6]H. G. Bohlen *et al.*, Z. Phys. **A322**, 241 (1985).

[7]S. H. Fricke and K. W. McVoy, Nucl. Phys. **A467**, 291 (1987).

[8]S. Kubono *et al.*, Phys. Lett. **127B**, 19 (1983).

[9]S. Kubono *et al.*, Phys. Rev. C **31**, 2082 (1985); Y. Sa-

kuragi, thesis, Kyushu University, 1985 (unpublished).
[10]M. El-Azab Farid and G. R. Satchler, Nucl. Phys. **A438**, 525 (1985).
[11]M. E. Brandan, Notas Fis. **10**, 1 (1987); M. E. Brandan and G. R. Satchler, to be published.
[12]G. R. Satchler, private communication.
[13]A. M. Kobos and G. R. Satchler, in Proceedings of the Supercomputing Symposium '87, Calgary, Canada, 1987 (unpublished); A. M. Kobos, M. E. Brandan, and G. R. Satchler, to be published.
[14]A. J. Cole *et al.*, Phys. Rev. Lett. **47**, 1705 (1981).
[15]M. Buenerd *et al.*, Nucl. Phys. **A424**, 313 (1984).
[16]M. Buenerd *et al.*, Phys. Rev. C **26**, 1299 (1982).
[17]M. E. Brandan and A. Menchaca-Rocha, Phys. Rev. C **23**, 1272 (1981).
[18]M. E. Brandan, J. Phys. G **9**, 197 (1983).
[19]S. K. Gupta and K. H. N. Murthy, Z. Phys. A **307**, 187 (1982).
[20]S. K. Gupta *et al.*, Phys. Rev. C **31**, 1965 (1985), and references therein.
[21]M. S. Hussein and K. W. McVoy, Prog. Part. Nucl. Phys. **12**, 103 (1984).
[22]M. E. Brandan, S. H. Fricke, and K. W. McVoy, to be published.