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Publication Date
1975-03-01

Submitted to Physical Review Letters

LBL-3492 c.1
Preprint

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March 1975

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

LBL-3492 c.1

OPTICAL MODEL ANALYSIS OF N + C AND C + C ELASTIC SCATTERING*

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Abstract:

Two direct search methods have been applied to extract the optimum optical model parameters for the elastic scattering of ^{14}N by $^{12,13,14}C$, ^{12}C by $^{13,14}C$ and ^{13}C by ^{14}C for centre of mass energies in the range 7.8 to 12.6 MeV. The success of the analysis suggests that it is possible to interpret these data in terms of an optical model potential alone, indicating that such experiments do not provide unambiguous evidence for interference between the elastic scattering and elastic transfer modes.

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* Work performed under the auspices of the Atomic Energy Commission.

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Experiments [1-4) which have measured the elastic scattering of a heavy ion projectile A by a target nucleus a throughout most of the observable angular range have revealed the characteristic feature that, at energies above the Coulomb barrier, the ratio-to-Rutherford cross section, for systems where a and A differ by the order of a few nucleons, decreases relatively slowly with increasing centre of mass angle and displays regular oscillations which increase in amplitude on passing into the backward hemisphere, with an increase at the extreme backward angles in some cases. In a quantal description it is not possible to distinguish experimentally elastic scattering, a(A,A)a, observed at a centre of mass angle θ from the "elastic" (or Q=0) transfer reaction a(A,a)A observed at the centre of mass angle $\pi-\theta$. Therefore, it has been suggested 1,5) that since the differential cross section for elastic scattering usually decreases rapidly with increasing θ, and reaction cross sections are usually peaked at forward angles, a plausible model for such cases would be one which summed coherently an elastic scattering amplitude calculated at θ and an amplitude for the reaction calculated at $\pi-\theta$ (the analogy is Mott scattering of identical particles where both the amplitude at θ and $\pi-\theta$ is the one for elastic scattering). Such a model makes the implicit assumption that there is a large probability of the two nuclei reentering the elastic channel after the transfer reaction. Since experimentally the two processes are not distinguishable the testing of this model has rested on comparisons of similar systems, e.g. observed angular distributions of elastic scattering of ^{14}N by ^{12}C and by ^{13}C 1,2), or ^{12}C by ^{13}C and ^{13}C by ^{14}C 3,4,5) at similar centre of mass energies. On the basis of such comparisons the experimental results have been interpreted as unambiguous evidence for the interference between elastic scattering and elastic transfer processes. It was furthermore suggested that only by inclusion of the elastic transfer mode is it possible to obtain reasonable agreement with experiment, whence the hypothesis that the observed oscillatory structures in the angular distributions are due to the exchange of the mass difference of the two colliding nuclei$^{2)}$. The present study shows that this data finds a consistent interpretation in terms of the optical model alone and consequently such data does not provide unambiguous evidence for the need to include the elastic transfer mode explicitly.

The two search codes utilized in the present analysis differ in the method which they use to optimize the quality of fit parameter Δ $^{6)}$. The Hooke and Jeeves (HJ) algorithm in an n parameter search always makes trial moves along a fixed set of n orthogonal vectors (PAMINA code$^{6)}$), whereas the Davies, Swann and Campey (DSC) method relies upon generating a new set of n orthogonal vectors at the end of each iteration (SOPHIE code $^{7)}$). In the present application the HJ algorithm was found to be extremely efficient in its ability to follow an n-dimensional valley into a minimum, however in terms of the percentage decrease of Δ vs the number of times Δ is evaluated, the DSC algorithm is superior.

The data analysed in the present work was as follows:(all energies are quoted in centre of mass unless otherwise indicated) elastic scattering of ^{14}N by ^{12}C at 9.230, 9.922, 10.84, 11.54 and 12.60 MeV, ^{14}N by ^{13}C at 9.649 MeV, ^{14}N by ^{14}C at 10.00 and 12.50 MeV, ^{12}C by ^{13}C at 7.801 and 9.881 MeV, ^{13}C by ^{14}C at 7.778 and 9.852 MeV, and ^{12}C by ^{14}C at 8.078, 9.694 and

10.77 MeV. In table I the data is arranged in increasing order of η (the Sommerfeld parameter), and asymptotic wave number k; $R = A_a^{1/3} + A_A^{1/3}$, Δ , σ_A(total absorption or reaction cross section) are also tabulated. Table I shows a selection of some of the optical model parameter sets which were found; those cases where the data did not cover a sufficiently broad range in angle were not searched upon. The definition of the optical model potential was the same as that of Ref. 6) with a surface type absorbing potential. For the searches all six optical model parameters were varied simultaneously. In the 500-odd searches performed in the present work the absolute normalization was not varied and a relative error of 5% was set on each data point. The comparison between experimental and theoretical ratio -to-Rutherford cross sections is shown in Fig. 1 (a) and (b) for the parameters of table I. The potential found for the scattering of ^{12}C by ^{14}C at 9.694 MeV (18 MeV lab), which also gives a satisfactory description of the same system at 10.77 MeV (20 MeV lab) was used to show how the structures observed in the angular distributions evolve as a function of energy (cf. Fig. 1 (c)). The optical model predicts that such structures change relatively rapidly for the extreme backward angles ($>120^0$) for energies above the Coulomb barrier. Another feature is that the optical model predictions (especially in the backward hemisphere) are sensitive to the choice of the Coulomb radius r_c. The Coulomb radius used throughout the searches was 1.45 fm, and the effects of changing this radius to 1.225 fm and 1.0 fm are shown in Fig. 1 (b) by the solid and dotted curves, respectively, for $^{14}N + ^{12}C$ at 12.60 MeV, with the case corresponding to r_c=1.45 fm shown in Fig. 1 (a).

Fig. 1(a) and (b) together show fifteen experimental angular distributions; a careful comparison of this data reveals why it is important to classify heavy ion elastic scattering data (and optical model potentials derived therefrom) according to the Sommerfeld parameter η , the asymptotic wave number k, and possibly some interaction radius, e.g. $R = A_a^{1/3} + A_A^{1/3}$, defined by the system under consideration. In the following discussion the notation: label_I vs label_{II}; $\delta\eta$, δk, δR, is used where the labels are those of table I, and $\delta\eta$ is $\eta_I - \eta_{II}$ expressed as a percentage of η_I, etc. A variation of η alone produces a shift of the structures in the experimental angular distributions toward small angles (for a decrease in η) or toward large angles (for an increase in η) - compare C232 vs C243:-2.7,-0.8,-1.3, or C2N1 vs C3N1:-3.6, -0.7,-1.3, or C242 vs C341:-4.1,-0.3,1.3, or C3N1 vs C342:15.2,-1.0,0 or C243 vs C2N1:-15.3,-1.2,0, or C2N0 vs C232:18.6,-1.7,1.3. A variation of k alone produces a shift toward small angles (for an increase in k) or toward large angles (for a decrease in k) - compare C243 vs C342:-1.3,-2.9,-1.3, or C231 vs C242:0,-3.5,-1.3, or C3N1 vs C2N0:-0.1,4.3,1.3, or C341 vs C2N1:-1.1,-10.5,1.3, or C342 vs C2N4:-1.0,-10.7,1.3, or C242 vs C2N2:-0.7, -15.9,0. A variation in η alone produces either a compression or decompression of the structures in the experimental angular distribution, while a variation of k alone produces a difference in phase of the observed angular distributions, which changes as Θ approaches 180^0. The periodicity of this phase difference increases with increasing variation of k (cf. $\delta k \sim 10$) until (for $\delta k \sim 16$) the angular distributions are in phase throughout the measured angular range. An example where the variation of η and k act on the experimental angular distributions in an opposite sense to produce apparently little change in the positions of maxima and minima over the energy range 9.230 to 12.60 MeV is the data for ^{14}N scattered by ^{12}C where

$\delta\eta$ =14.4 and δk=16.8. That the optical model is successful in reproducing such effects, qualitatively, is demonstrated by the four cases of table I for which no searches were performed and another parameter set was used, as well as the dotted curve for ^{14}N + ^{13}C at 9.649 MeV in which the optical model parameters were the same as those used for ^{14}N + ^{12}C at 9.922 MeV (cf. Fig. 1 (a)).

The optical model has proved to be successful in its ability to reproduce the qualitative features of the fifteen experimental angular distributions shown in Fig. 1 (a) and (b). Therefore, such experimental angular distributions do not find a unique interpretation in terms of a model which requires the explicit inclusion of the elastic transfer channel. The potentials of table I should not be interpreted too literally, however, as the experimental angular distributions analyzed are not of uniform quality: e.g. excepting ^{14}N + ^{12}C at 11.54 and 12.60 MeV, the points measured at forward angles are too sparse, or ^{14}N + ^{12}C at 10.84 MeV where there seem to be problems of absolute normalization of the data. A more thorough analysis should await more detailed measurements. An important qualitative result would seem clear however: the heavy ion optical model potential for such systems has an imaginary part which produces sufficient reflected flux to allow for the possibility of interference with flux refracted by the real potential; this phenomenon provides a plausible interpretation for the structures observed in the experimental angular distributions in heavy ion elastic scattering for systems such as those discussed here.

The preliminary analysis (with PAMINA) was performed at Oxford and Darmstadt. The author is grateful to Dr. P. E. Hodgson for his hospitality during the visit to Oxford, to the SRC for making the visit possible, and to the GSI (Darmstadt) for time at their computer centre. The major part of the analysis, including the development and production work with SOPHIE, was performed at LBL. The author is grateful to Dr. N.K. Glendenning (LBL) for his criticism of this work.

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Table I

Optical model parameters for a(A,A)a

A	a	label	Energy[a] (MeV)	r_v (fm)	a_v (fm)	V (MeV)	r_w (fm)	a_w (fm)	W (MeV)	σ_A (mb)	Δ	η	k (fm^{-1})	R[b]
^{12}C	^{14}C	C244	10.77 (20.00)	no search (parameter set C243 used)								4.391	1.825	4.700
^{12}C	^{13}C	C232	9.881(19.00)	1.019	0.7010	67.79	1.077	0.1002	50.82	773.0	28.38	4.505	1.717	4.641
^{12}C	^{14}C	C243	9.694(18.00)	0.9777	0.5256	88.26	1.027	0.1230	39.41	523.1	5.624	4.628	1.731	4.700
^{13}C	^{14}C	C342	9.852(19.00)	no search (parameter set C3N1 used)								4.690	1.782	4.761
^{14}N	^{12}C	C2N4	12.60 (27.30)	0.9703	0.6636	85.47	0.9661	0.09149	92.87	653.7	12.50	4.737	1.973	4.700
^{14}N	^{12}C	C2N3	11.54 (25.00)	1.034	0.5909	79.10	0.9940	0.07685	97.59	527.8	14.96	4.950	1.888	4.700
^{14}N	^{14}C	C4N2	12.50 (25.00)	1.053	0.5473	84.23	1.016	0.1027	67.82	675.6	21.35	4.950	2.046	4.820
^{12}C	^{13}C	C231	7.801(15.00)	1.065	0.6220	69.91	1.109	0.1221	28.94	442.7	13.97	5.070	1.526	4.641
^{12}C	^{14}C	C242	8.078(15.00)	1.001	0.6771	80.23	1.063	0.1393	40.50	547.0	3.196	5.070	1.580	4.700
^{14}N	^{12}C	C2N2	10.84 (23.50)	no search (parameter set C2N3 used)								5.105	1.831	4.700
^{13}C	^{14}C	C341	7.778(15.00)	0.9752	0.7456	80.10	0.8646	0.1255	33.08	523.9	30.73	5.278	1.584	4.761
^{14}N	^{12}C	C2N1	9.922(21.50)	0.9847	0.6206	83.55	0.9487	0.2038	33.29	449.6	15.87	5.337	1.751	4.700
^{14}N	^{13}C	C3N1	9.649(20.04)	0.9751	0.6866	87.17	1.012	0.1389	43.15	510.1	13.73	5.528	1.764	4.761
^{14}N	^{12}C	C2N0	9.230(20.00)	0.9865	0.6251	82.18	0.9477	0.2101	28.88	367.0	5.032	5.534	1.689	4.700
^{14}N	^{14}C	C4N1	10.00 (20.00)	no search (parameter set C4N2 used)								5.534	1.830	4.820

[a] centre of mass with lab energy in parentheses

[b] $R = A_a^{1/3} + A_A^{1/3}$

CAPTION

Fig.1 Optical model predictions using the parameters of table I for (a) N + C, (b) C + C and $^{14}N + ^{12}C$ at 12.60 MeV with $r_c = 1.225$ fm (solid curve) and 1.0 fm (dotted curve) and (c) $^{12}C + ^{14}C$ in the lab energy range 13.5 to 25 MeV in steps of 0.5MeV, using C243 parameters, with some curves dotted for clarity. In (a) and (b) the c.m. energy (in MeV) is shown for each case - the data is from Refs. 1-4)(error bars are not shown).

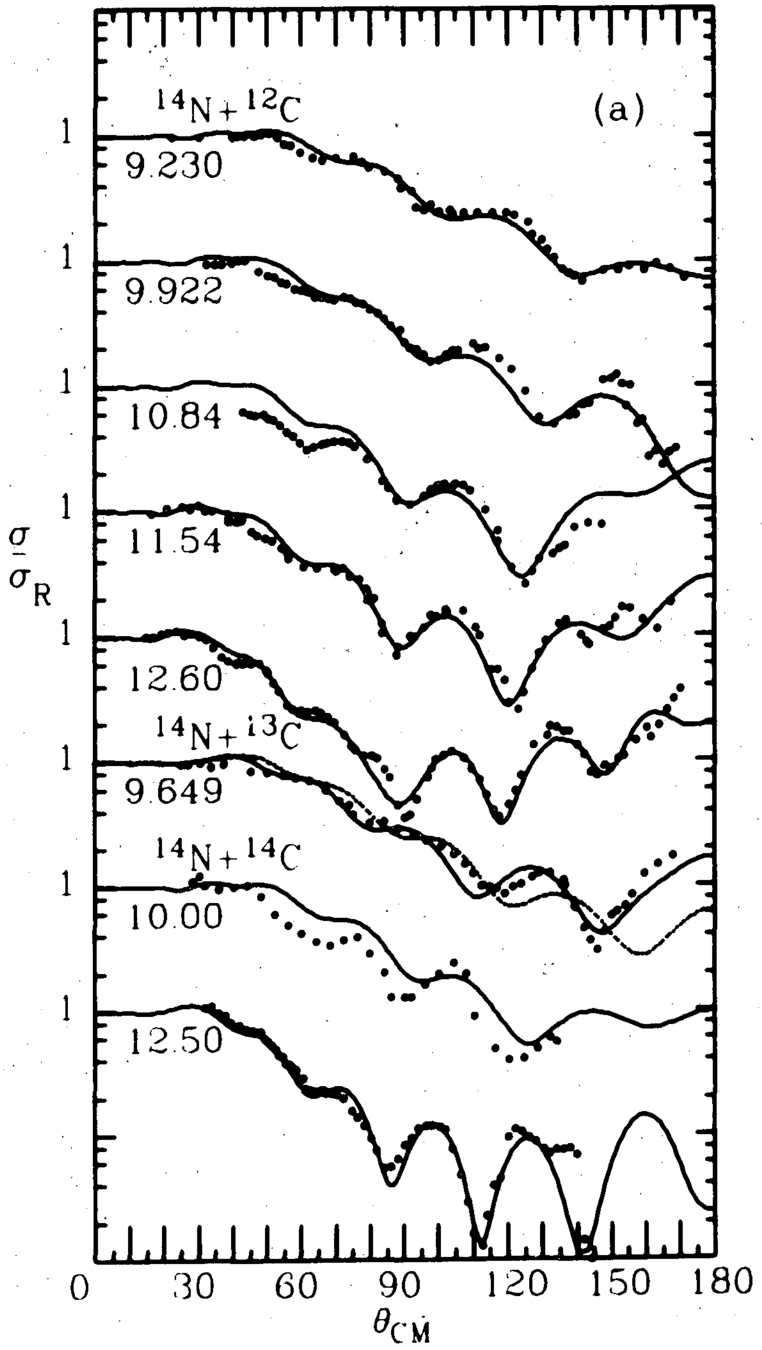
(a)
$^{14}N+^{12}C$
9.230
9.922
10.84
11.54
12.60
$^{14}N+^{13}C$
9.649
$^{14}N+^{14}C$
10.00
12.50
1
1
1
1
1
1
1
1
$\frac{\sigma}{\sigma_R}$
0
30
60
90
120
150
180
θ_{CM}

Fig. 1a

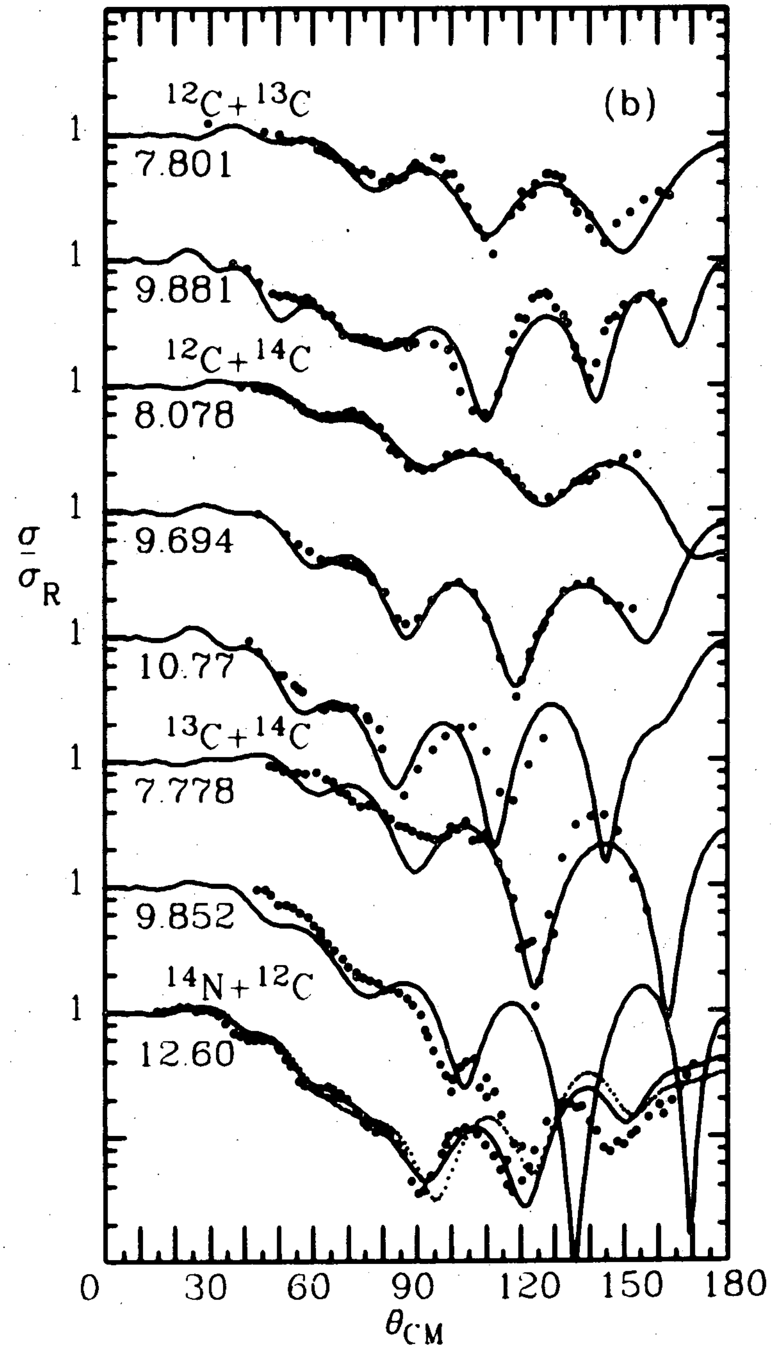
(b)
$^{12}C+^{13}C$
7.801
9.881
$^{12}C+^{14}C$
8.078
9.694
10.77
$^{13}C+^{14}C$
7.778
9.852
$^{14}N+^{12}C$
12.60
1
1
1
1
1
1
1
1
$\frac{\sigma}{\sigma_R}$
0
30
60
90
120
150
180
θ_{CM}

Fig. 1b

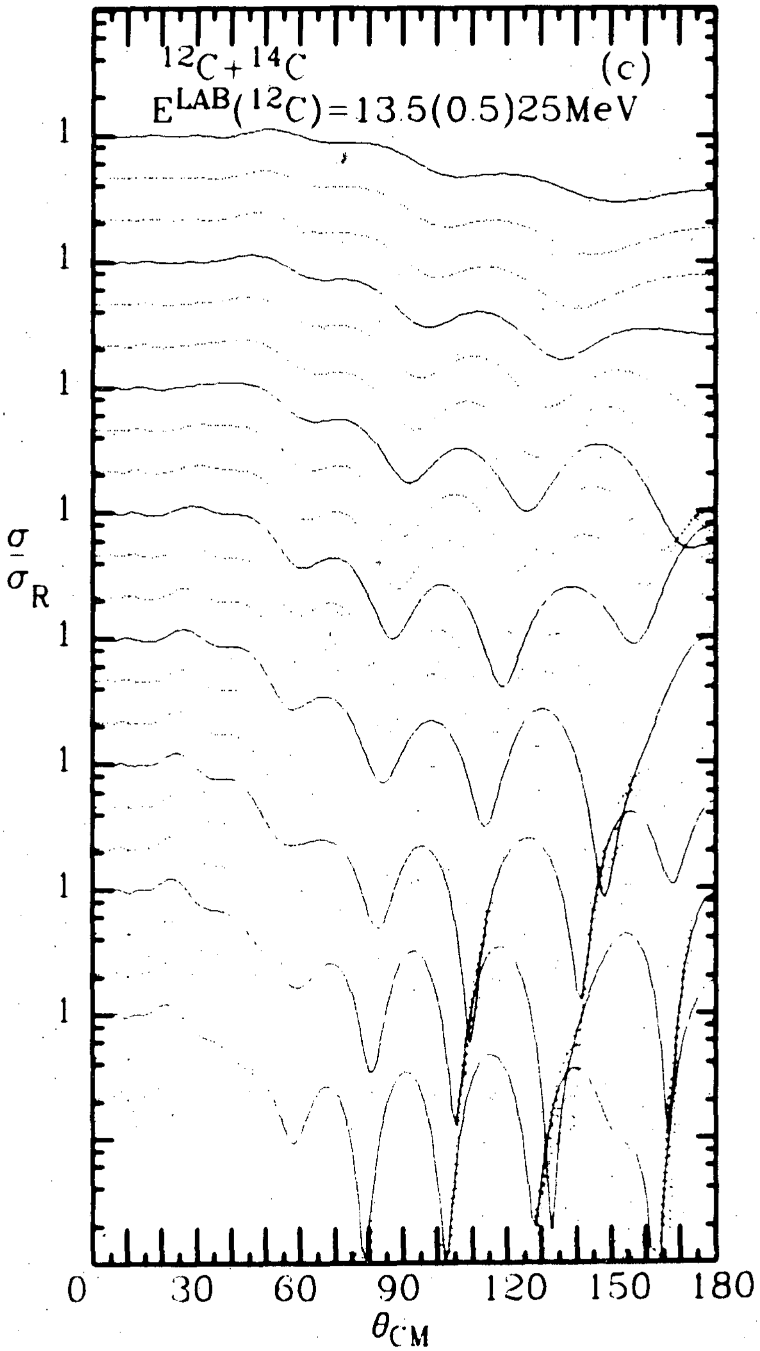
$^{12}C+^{14}C$
(c)
$E^{LAB}(^{12}C)=13.5(0.5)25$ MeV
1
1
1
1
1
1
1
1
$\frac{\sigma}{\sigma_R}$
0
30
60
90
120
150
180
θ_{CM}

Fig. 1c

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