Nuclear Rainbow Scattering in ^{12}C-^{12}C above 160 MeV

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(Received 30 March 1982)

Published ^{12}C-^{12}C elastic scattering data at 161.1, 288.6, and 1030 MeV have been analyzed. All three angular distributions show evidence for a nuclear rainbow whose energy evolution agrees with semiclassical predictions. Other features of "light-ion" scattering are confirmed by the optical-model analysis. It is concluded that the appearance of a nuclear rainbow is not determined by the mass of the projectile.

PACS numbers: 25.70.Hi, 25.70.Bc

Nuclear rainbows in heavy-ion elastic scattering have been the goal of many thorough searches over the last years.[1-3] First proposed[4] as a way to resolve optical-model ambiguities in α scattering, their existence for heavy-ion systems was later predicted by Knoll and Schaeffer's semiclassical theory of complex trajectories.[5] Up until now, nuclear rainbows have been found in α (Ref. 6) and ^{6}Li (Ref. 2) scattering from various targets, while searches with heavier projectiles, such as ^{9}Be (Ref. 3), ^{12}C (Ref. 2), and ^{16}O (Ref. 1) on ^{28}Si, have led so far to negative results. The conclusion has been drawn[2,3] that a fundamental difference exists between interactions induced by "light" ($A < 8$) and by "heavy" ($A > 8$) projectiles. Here I present a study of published data[7,8] for the system ^{12}C-^{12}C between 161 and 1030 MeV, whose elastic-scattering angular distributions show features similar to those expected for a nuclear rainbow. The analysis confirms the presence of a nuclear rainbow in the data, as well as other features commonly associated with "light" ions.

Nuclear rainbows are caused[4,5] by the attraction of the real nuclear potential which bends the trajectories to negative deflection angles. At energies above a critical value E_0, there is a maximum negative angle θ_R ($<-\pi$), beyond which no classical trajectory may reach. A distinctive feature of the presence of the rainbow in an angular distribution is, for intermediate energies, the damping out of the diffraction oscillations and the appearance of a structureless falloff of the cross section beyond θ_R. At high energies[5] (~100 MeV/nucleon), the diffraction oscillations, rather than being replaced by the rainbow, do pass over it. The position of the rainbow is mostly determined by the strength of the real potential, and the magnitude of the cross section at θ_R, mostly by the imaginary potential. It is this dependence on the two components of the potential that explains the value of the rainbow in resolving parameter ambiguities.

The data analyzed in this Letter are shown in Fig. 1. They are plotted as a function of the parameter $\epsilon = \theta_{c.m.} E_{c.m.}$, defined by Knoll and Schaeffer.[5] According to their theory, the trajectory pattern that determines the angular distribution should scale with energy as a function of ϵ. In particular, for a given potential, the nuclear-rainbow region appears at fixed values of ϵ. The rainbow in this system is expected to

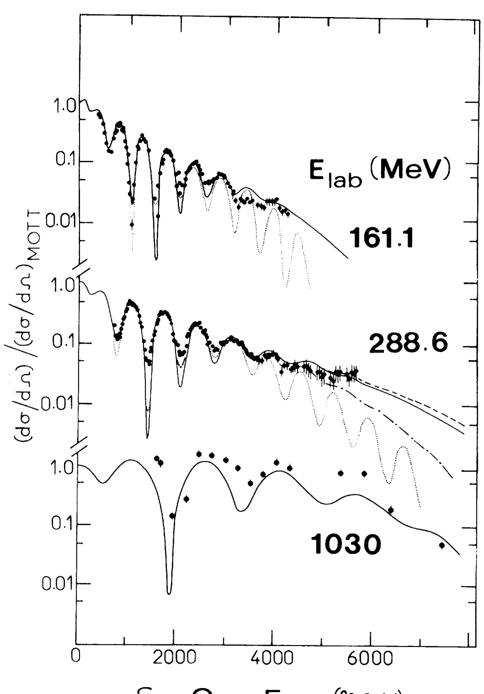

FIG. 1. Elastic-scattering angular distributions. Data at 161.1 and 288.6 MeV are from Ref. 7; Those at 1030 MeV, from Ref. 8. Solid curves are four-parameter optical-model fits with a double-folded real part (parameter set F in Table I); dotted, dot-dashed, and dashed curves correspond to the V = 10-, 90-, and 150-MeV WS potentials in Table I, respectively. At 161 MeV, the geometry of the V = 10-MeV WS set was slightly optimized.

exist only at energies above $E_0 \sim 70$ MeV (c.m.), according to optical-model (OM) analyses.[9] As shown by the data in Fig. 1, at 161 and especially at 289 MeV, the diffraction oscillations dominate the forward angular distribution, die away around $\epsilon = 4000$ deg MeV, and are replaced by a featureless structure, which I interpret as the refractive nuclear rainbow. At 1030 MeV, the relative contributions to the cross section from diffractive and refractive scattering are comparable over most of the measured range of ϵ and the Fraunhoffer oscillations appear superimposed on the rainbow. The evolution with energy of the main features shown by the data is what Knoll and Schaeffer predict (Fig. 24, Ref. 5) for strongly attractive heavy-ion systems. It is this overall qualitative agreement, besides the features shown by the data at each energy and by the OM analysis, that leads me to the positive conclusion of the existence of a nuclear rainbow in this system.

The solid curves in Fig. 1 (potentials F in Table I) represent the result of the OM analysis. I used a complex nuclear potential with a Woods-Saxon imaginary part and a double-folded real part,[10] about 380 MeV at the center, similar to that used in Ref. 9. This choice of form factors follows from the study by Stokstad *et al.*[9] The four-parameter OM analysis of these and other energies between 10 and 86 MeV/nucleon showed few of the ambiguities commonly encountered[11] and provided parameters which vary smoothly with incident energy.[12] Table I lists the potential parameters corresponding to the curves in Fig. 1. The calculations reproduce well the features observed in the data: for the lowest two energies, the transition from oscillatory diffraction to the exponentially decaying rainbow; and for the highest energy, the simultaneous presence of both processes.

As expected for nuclear rainbow scattering, the real potential renormalization N (Table I) was well determined by the data. However, since N was the only adjustable real parameter, this result may be fortuitous. In order to localize the region of the potential to whose strength the data were most sensitive, and therefore to have a realistic estimate of how much information about the potential is contained in the measured angular distributions, "notch perturbation" studies of the kind proposed by Cramer and DeVries[13] were performed. The "sensitive region" of the potential is defined as being that radial zone where a perturbation produces an appreciable modification (χ^2/N at least twice its unperturbed value) in the calculated cross section. The sensitive regions found in this way at 289 and 1030 MeV are shown in Fig. 2. In spite of the evidence for a nuclear rainbow in the angular distribution, the present data are not yet sensitive to values of the real potential near the center. Therefore, one should not expect an unambiguous determination of the potential $V(r)$ for all values of r. Indeed, I do succeed in fitting the 289-MeV angular distribution with a Woods-Saxon real potential, of depth 150 MeV at the center, which only agrees with the folded one in the sensitive region, as shown in Fig. 2. The calculated angular distribution (dashed curve in Fig. 1) is almost indistinguishable from the one obtained with the folded potential. The excellent fit to the data does not contradict the conclusions of Ref. 9 about the need for a real shape different from Woods-Saxon, since the data only reach up to $\theta_{c.m.} = 40°$.

Several depths of Woods-Saxon real parts were tried, searching on the other five parameters, and good fits could be found as long as $V \gtrsim 90$ MeV, as Fig. 1 illustrates. Shallow potentials, including the $E18$ type which has successfully

TABLE I. Optical-model potential parameters.

E_{lab} (MeV)	Set	V (MeV)	r^a (fm)	a (fm)	W (MeV)	r_i^a (fm)	a_i (fm)	N^b	θ_R (deg)
161.1	F				55.0	0.91	0.80	0.98	
288.6	F				65.0	0.91	0.80	0.98	
288.6	WS	10.0	1.41	0.58	35.0	1.18	0.51		−17
288.6	WS	90.0	0.91	0.75	68.0	0.92	0.76		−47
288.6	WS	150.0	0.85	0.68	66.0	0.91	0.80		−66
288.6	WS	200.0	0.70	0.87	68.0	0.96	0.69		−61
1030	F				56.6	0.93	0.64	0.53	

$^a R = r(12^{1/3} + 12^{1/3})$.

^{b}Renormalization factor for the folded potential.

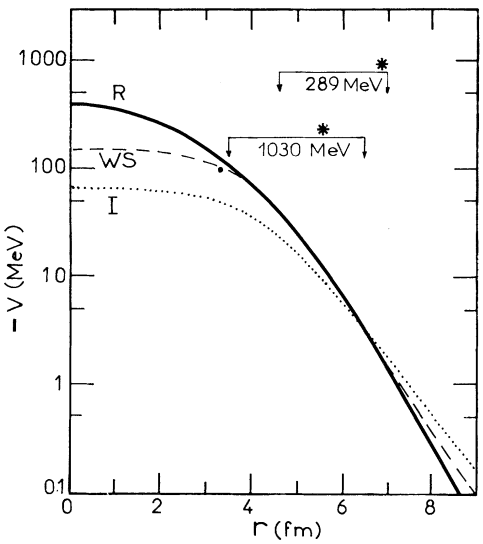

FIG. 2. Real (R) and imaginary (I) potentials for 289 MeV, corresponding to the solid curve in Fig. 1. The dashed curve (WS) is the 150-MeV-deep real potential mentioned in the text. To obtain the real potential at 1030 MeV multiply $R(r)$ by 0.53/0.98. Arrows indicate the limits of the potential "sensitive region" at the two energies. Asterisks show the strong absorption radii $D_{1/2}$ (Ref. 11) at each energy.

been used[1,2] to describe other heavy-ion systems, proved unable to reproduce the lack of oscillations exhibited by the data at the most backward angles. The dotted curves in Fig. 1 show the best fit obtained with a $V=10$-MeV potential. For the shallower potentials, increasing the absorption merely changes the slope of the calculated distribution, without smoothing out the oscillations. As V gets larger (~50 MeV), a smoother structure starts to develop but its falloff occurs much too forward compared with the data. It is only when $V \sim 90$ MeV that the agreement becomes satisfactory (dot-dashed curve in Fig. 1). Real depths between 90 and 200 MeV produce equally good fits, in terms of χ^2/N, and it is not possible to single out an optimum parameter set. Some examples are given as potentials WS in Table I. These conclusions also apply to the 161-MeV case.

The mentioned results indicate the refractive origin of the structureless pattern, with its angular location directly related to the strength of the real potential. Data extending to more backward angles, spanning the entire rainbow region, should permit one to determine a single value for the real strength, as expected.[4] This remaining ambiguity in the value of V results in an ambiguous evaluation of θ_R from the OM analysis, as is shown by the last column in Table I. The listed θ_R are the results from semiclassical calculations of the deflection function, similar to those proposed by Schaeffer.[14]

Model calculations show that interference effects near 90° due to the symmetrization requirement for identical particles become particularly important if $\theta_R \gtrsim 90°$. These data, however, do not extend sufficiently far into the most backward angles to be sensitive to these contributions.

In summary, I have found evidence for a nuclear rainbow in the system ^{12}C-^{12}C at energies above 160 MeV. Two other features which are said to define[3] "light-ion" behavior, namely, the need for energy-dependent OM parameters and deeper real than imaginary potentials at the center, also apply to this system. On the other hand, ^{12}C incident on ^{28}Si has been found[2] to behave as a "heavy ion." The apparent contradiction arises from associating with the projectile features which correspond to the system as a whole. Potentials describing a nuclear system may be weakly absorptive and refractive, as for ^{12}C-^{12}C, or strongly absorptive and diffractive, as for ^{12}C-^{28}Si, depending on characteristics of the system, not on the mass of the projectile. The OM analysis has shown that the relation $W(r) < V(r)$ always holds for most of the radial sensitive region, in particular for the smaller radii which correspond to the distances of closest approach for the rainbow partial waves. This supports the suggestion[3] that a necessary condition to observe refractive effects would be weak absorption for the partial waves leading to the rainbow.

The author thanks Professor David Brink and Professor Richard Schaeffer for enlightening discussions, and M. Bernard Bonin for performing the semiclassical calculations.

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Spin Correlation for pp Elastic Scattering at $\theta_{c.m.} = \pi/2$ in the Energy Region of Dibaryon Resonances

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Precise measurements are reported of the spin-correlation parameter A_{NN} for 500–800 MeV pp elastic scattering at $\theta_{c.m.} = \pi/2$. While not reproducing the large value of A_{NN} reported earlier at 697 MeV, the data show a pronounced maximum in the 90° triplet-to-singlet ratio near the location of the reported ${}^3F_3$ dibaryon resonance. In contradiction with an earlier report, structure is not found in the moduli of the singlet and triplet amplitudes.

PACS numbers: 24.70.+s, 21.30.+y, 25.10.+s, 25.40.Cm

In studies of the spin dependence of nucleon-nucleon scattering at the zero-gradient synchroton (ZGS), Yokosawa and co-workers[1] found a striking structure in the total-cross-section differences for longitudinal initial spin states, $\Delta\sigma_L$, in pp scattering. Hidaka *et al.*[2] have interpreted this as a manifestation of an $I=1$ ${}^3F_3$ dibaryon resonance. Hoshizaki's single-channel fits to his set of phase shifts[3] indicated the existence of the diproton resonances ${}^1D_2$ (2.17 GeV) and ${}^3F_3$ (2.22 GeV). Recent analyses by Arndt *et al.*[4] have also shown sharp energy variations for the $I=1$ ${}^1D_2$ and the ${}^3F_3$ phases in the 2.08–2.25 GeV region. A recent experiment[5] at the Clinton P. Anderson Meson Physics Facility (LAMPF) has corroborated the earlier ZGS $\Delta\sigma_L$ data. Whereas the correctness of the $\Delta\sigma_L$ data is no longer in doubt, convincing proof for the existence of these resonances is still lacking. For instance, several theoretical analyses have shown that, although it seems to be compatible with resonances of the type that have been suggested, the existing limited data base does not demand such resonances.[6,7] High-precision measurements of some carefully chosen set of observables may remove this ambiguity. Measurements of the energy dependence of the spin-correlation parameter, A_{NN}, for pp elastic scattering at $\theta_{c.m.}=\pi/2$ are especially important since together with measurements of $d\sigma/d\Omega(90°)$, they uniquely determine the modulus of the singlet amplitude. (See MacGregor, Moravcsik, and Stapp, or Beretvas, Ref. 7.)

