

### Observation of rainbow scattering in the $^{12}\text{C} + ^{12}\text{C}$ system at $E_{\text{c.m.}} = 508 \text{ MeV}$

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The elastic scattering cross section for  $^{12}\text{C} + ^{12}\text{C}$  has been measured in the range  $\theta_{\text{lab}} = 1.5\text{--}9^\circ$ . Evidence for a nuclear rainbow effect is reported. A value of the reaction cross section is deduced from the optical model analysis.

[NUCLEAR REACTIONS  $^{12}\text{C} + ^{12}\text{C}$  elastic scattering,  $E_{\text{lab}} = 1016 \text{ MeV}$ , optical model analysis, deduced nuclear rainbow angle, reaction cross section.]

Studying elastic scattering is the simplest approach to the nucleus-nucleus ( $\mathcal{N}$ - $\mathcal{N}$ ) interaction. This interaction is governed both by the nucleon-nucleon ( $N$ - $N$ ) interaction and by the blocking effect due to the Pauli exclusion principle. The interplay between these two quantities has been the object of numerous recent theoretical studies.<sup>1</sup> From these works one can conjecture an appreciable energy dependence of the  $\mathcal{N}$ - $\mathcal{N}$  potential over the range 10–200 MeV/nucleon of incident energy,<sup>2</sup> thereby providing strong motivations for heavy ion (HI) elastic scattering measurements covering this energy range and a wide projectile (target) mass range. Whereas data below 20 MeV/nucleon are currently available, no intermediate energy measurement could be performed until recently.<sup>3</sup>

For light projectiles ( $A \geq 4$ ), the data are generally analyzed in the optical model using a potential with Saxon-Woods geometry, generalized from the single nucleon shell-model potential. Similar potential shapes have also been extensively used for HI scattering at low incident energy although this is much less justified. Alternative methods, such as using semimicroscopic folding-model potentials<sup>4</sup> or nuclear-matter calculated interactions,<sup>1,2</sup> do exist, but their use is still rather limited and cannot yet provide the same systematic view of the problem as is available from a standard analysis.

A few years ago an experimental study of elastic scattering measured with projectiles up to  $A = 16$  at low incident energy concluded to the existence of a rapid transition between light ( $A < 6$ ) and heavy ( $A > 12$ ) ions.<sup>5</sup> For projectiles up to  $^6\text{Li}$ , the absorp-

tion is weak enough to allow refracted projectiles to populate the elastic channel and typical nuclear rainbow effects could be observed in the angular distributions. For heavier projectiles ( $A \geq 12$ ), the scattering process is dominated by strong absorption effects which give rise to strongly diffractive angular distributions. This transition can be expressed quantitatively by the ratio of the imaginary well depth to the real well depth of the optical potential  $W/V$ , which is found to be about  $\frac{1}{3}$  for light projectiles and larger than 1 for  $^{12}\text{C}$  and  $^{16}\text{O}$ .

In this Brief Report new measurements are reported for the  $^{12}\text{C} + ^{12}\text{C}$  system at  $E_{\text{lab}} = 1016 \text{ MeV}$ . The results show the existence of a nuclear rainbow in the studied system. It is concluded that this system does not fit into the classification based on the ratio  $W/V$  as suggested in Ref. 5.

The motivation for the new measurements was provided by the evident lack of data from the first set of measurements.<sup>3</sup> The experiment was performed under the same experimental conditions as described in Ref. 3, except that the detector angle was set by remote control. This angle reading was calibrated geometrically before the experiment. However, although the measurement procedure was slightly different, the angular accuracy was not much better than in the first experiment: The coincidence between the geometrical axis used for the calibration and the true beam position is estimated to be within 1 cm, setting a total of  $0.15^\circ$  laboratory maximum uncertainty on the angle determination. This uncertainty could not be removed by left-right measurements because of the mechanical arrangement.

The measured angular distribution is shown in Fig. 1. The results are in agreement with those reported in Ref. 3 but for a small angular shift of  $0.1^\circ$  laboratory towards small angles. This angular difference is close to the upper limit of the uncertainties estimated for the two experiments. Therefore one can consider that the true zero angle lies within the two determinations. We shall see below that this implies an appreciable uncertainty in the reaction cross section. The elastic data on Ca and Y targets have also been remeasured (not discussed here), but no such shift was found for these targets.

First of all, let us consider qualitatively the angular distribution shown in Fig. 1. In the small angle region, say  $\theta_{c.m.} \leq 8-10^\circ$ , the cross section is dominated by diffraction and exhibits a typical Fraunhofer diffraction pattern. Beyond this region the cross section exhibits a structureless exponential falloff. Such a behavior was identified some years ago in  $^4\text{He}$  scattering experiments as being a typical refraction effect generated by the nuclear rainbow.<sup>6</sup> Since then, nuclear rainbow scattering has been observed for  $^6\text{Li}$  projectiles,<sup>5</sup> but despite several attempts it could not be found for heavier projectiles such as  $^9\text{Be}$  (Ref. 7) and  $^{12}\text{C}$  (Ref. 5). Instead, a rapid onset of a diffraction dominance due to strong absorption was observed at low incident energies, occurring between  $^6\text{Li}$  and  $^{12}\text{C}$  as already mentioned. No evidence of rainbow scattering could be seen in the  $^{12}\text{C} + ^{12}\text{C}$  system studied at low incident energy,<sup>8</sup> although some positive indications are reported from a folding model analysis of data above 10 MeV/nucleon.<sup>9</sup> Its appearance at intermediate energy is very likely related to the considerable surface transparency observed in HI scattering at this incident energy.<sup>3</sup> The decrease of the absorbing area un masks the inner potential which can be probed in the scattering process and refraction effects can then be observed in the angular distribution.

A standard optical model (OM) analysis of the data has been performed. Good fits to the experimental

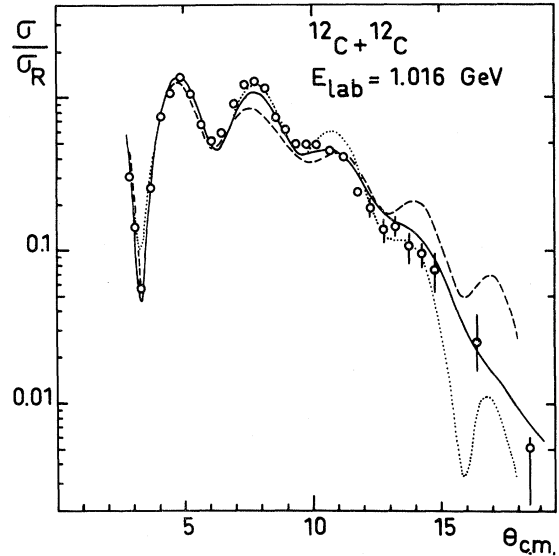


FIG. 1. Experimental angular distribution for  $^{12}\text{C} + ^{12}\text{C}$  elastic scattering at  $E_{c.m.} = 508$  MeV. Error bars are smaller than 10% when not shown. The curves are optical model fits discussed in the text. They correspond to parameter sets a (dashed curve), d (solid curve) and h (dotted curve).

angular distribution could be obtained. Some typical examples are displayed in Fig. 1. The three curves shown correspond to real potential depths of 15 MeV (dashed), 80 MeV (solid), and 200 MeV (dotted) corresponding to parameter sets a, d, and h in Table I, respectively. It is seen that the solid curve better reproduces the falloff in the large angle region. Such an effect was not unexpected since the experimental knowledge of the nuclear rainbow region has been shown to pin down the potential depth,<sup>6</sup> which can be related to  $\theta_R$  in a semiclassical theoretical approach.<sup>10</sup> This point has been more completely investigated and a grid search on the real potential depth has been performed covering the range 15–300 MeV. The

TABLE I. Optical model parameters obtained for fixed values of the real well depth  $V$ . The nuclear rainbow angle  $\theta_R$  ( $d^\circ$ ) and reaction cross section  $\sigma_R$  values are also given for each search.

Set	$V$	$r$	$a$	$W$	$r'$	$a'$	$\chi^2/N$	$\theta_R$	$\sigma_R$ (mb)
a	15	1.24	0.54	39.0	1.03	0.47	11		970
b	40	1.02	0.63	34.0	1.0	0.58	12	-7	1000
c	60	0.90	0.69	39.0	0.96	0.65	5.7	-11	1020
d	80	0.80	0.74	42.0	0.90	0.73	3.8	-11	1026
e	100	0.75	0.83	49.0	0.95	0.59	3.3	-17	1008
f	120	0.70	0.85	46.8	0.96	0.60	2.7	-16.5	1022
g	140	0.65	0.89	46.0	0.97	0.58	2.9	-17	1000
h	200	0.54	0.95	43.8	1.0	0.54	5.3	-19	1000
i	300	0.41	1.0	51.3	0.97	0.55	5.9	-21	1005

results are given in Table I. One can see that the  $\chi^2$  distribution exhibits a broad minimum in the region of real depth 80–140 MeV. We observe that the rise of  $\chi^2/N$  on the deep side ( $V \geq 140$  MeV) of the minimum is much less steep than on the shallow side ( $V \leq 80$  MeV). A few more data points in the rainbow region would probably make the effect sharper. However, we believe that these results already assess the evidence for a nuclear rainbow effect in this system. Note that the angular shift should mostly affect the imaginary (real) radius of the potential (see Ref. 3) and to a lesser extent the other parameters. Table I also gives the rainbow angles  $\theta_R$  obtained from the OM phase shifts according to the classical definition.<sup>6,11</sup> These values must be considered as approximate since the imaginary part of the potential is not small compared to the real part, at least for real depths  $V \leq 100$  MeV. In the region of the minimum  $\chi^2$ ,  $\theta_R$  is found in the range 10–17°, covering as expected the region of the falloff of the cross section. At this point, it must be noted that for the best fit parameter sets, say  $V = 80$ –140 MeV, the ratio  $W/V$  is found to be around 0.3–0.5, i.e., a value typical of “light” projectiles according to the criterion used in Ref. 5. Indeed, the geometry of the potential fitting the present  $^{12}\text{C} + ^{12}\text{C}$  data is rather close to the best fit sets of parameters ( $V 27$  and  $R 22$ ) fitting the  $^6\text{Li} + ^{28}\text{Si}$  scattering data (except for the imaginary diffuseness), and appreciably different from the best fit potential for the  $^{12}\text{C} + ^{28}\text{Si}$  data.<sup>5</sup> This suggests that the transition of the scattering properties with the projectile mass observed at low incident energies

does not hold at intermediate incident energies. We must point out however that we have not observed any indication of rainbow scattering in our  $^{12}\text{C} + \text{Ca}$  data at 1.016 GeV in the angular range investigated  $\theta_{\text{c.m.}} \leq 8^\circ$ . This might be due to the smaller angular range investigated.

Also given in Table I is the reaction cross section for each set of parameters. Two remarks can be made about these numbers. First the dependence on the parameter set is very small. This is at variance with the analysis of the first set of data previously reported<sup>3</sup> which were clearly insufficient to pin down the potential. Second, the average value is markedly larger than the values reported in Ref. 3. This difference is essentially due to the small angular shift mentioned above. Indeed, the position of the first minimum at a smaller angle in the present data corresponds to a larger area of the diffracting disc, and therefore to a larger reaction cross section. Taking into account the previous considerations on the angular uncertainty in the two experiments, we are able to assign the following value to the reaction cross section:  $\sigma_R = 1000^{+300}_{-250}$  mb. This value is in excellent agreement with the calculations of Peng *et al.*<sup>12</sup>

In conclusion we have reported the first evidence for a nuclear rainbow observed with  $^{12}\text{C}$  projectiles. The observation of such an effect is clearly associated with the large surface transparency of the projectile-target system occurring in this intermediate energy range. We have also obtained an optical model determination of the reaction cross section, in good agreement with Glauber calculations.

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<sup>10</sup>R. Schaeffer, in *Nuclear Physics with Heavy Ions and Mesons*, edited by R. Balian, M. Rho, and G. Ripka (North-Holland, Amsterdam, 1978), Vol. 1.

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