Refractive Scattering and the Nuclear Rainbow
in the Interaction of $^{12,13}$C with $^{12}$C at 20 MeV/N

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The elastic and inelastic scattering and the neutron transfer have been measured for the systems $^{12}$C+$^{12}$C and $^{13}$C+$^{12}$C at 20 MeV/N up to $\theta_{cm}=60^\circ$ with the $Q3D$-spectrometer. The angular distributions of the elastic scattering show an enhanced cross section at angles larger than 40°. It can be identified as refractive scattering with the clear signature of a nuclear rainbow. L-cut-off calculations show that these contributions come from $L$-values which are significantly lower than the grazing $L$-value. The deflection function has a broad minimum in this $L$-range which is typical for rainbow scattering. The $S$-matrix is decomposed by a phenomenological parametrization into a refractive and a diffractive part. The interference of these amplitudes plays an important role in the rainbow enhancement. The spatial localization of the refractive scattering is deduced from the turning points of the corresponding trajectories; a localization between 2.5 fm and 4 fm is found. Semi-classical calculations with complex trajectories in the single-turning-point approximation show good agreement with the quantum-mechanical calculations. Refractive contributions are not observed in the inelastic scattering. This can be explained by reducing the strength of the conventional collective form factor in the internal region. In contrast to this the enhancement at large angles is seen in the one-neutron transfer channels where the refractive scattering is dominant. This is the first observation of such contributions to heavy-ion transfer reactions.

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1. Introduction

The elastic scattering of heavy ions is usually dominated by strong absorption and no information about the interaction inside the surface region can be obtained, because the scattering waves are absorbed in the interior. In this case the target nucleus can be replaced by a black disk with a diffuse surface, and the scattering can be described essentially by the diffraction on the edge of the disk. Within such a model the strong absorption radius can be deduced which is closely related to the imaginary part of the complex scattering potential. From the real part only the exponential tail outside the surface is seen in the presence of strong absorption. The strength and decay constant can be fixed at the surface, but nothing can be learned about the interior. The situation is more favorable for $\alpha$-scattering at energies larger than 15 MeV/N, because here the absorption is weak, and contributions to the scattering from the interior region are large enough to be observed. In analogy to optics these contributions are called refractive, since the scattered particles have partly penetrated the target nucleus. In $\alpha$-scattering the refractive contributions manifest themselves in the angular distribution as a broad bump at large angles. This phenomenon is interpreted as "nuclear rainbow scattering", because the intensity maximum is built up by many trajectories being essentially deflected to the same scattering angle, the
nuclear rainbow angle \( \theta_R \). The occurrence of a rainbow maximum is a special case of refractive scattering. The effect is described in more details in several papers about semi-classical methods for the calculation of elastic scattering [1-4] and will be discussed also in connection with the new data of the present paper. In a rainbow situation the trajectories are penetrating the interior of the nuclei with a probability of a few percent. The strong nuclear force attracts the projectiles on these trajectories towards the scattering center and deflects them to negative scattering angles which correspond to the region of the rainbow maximum. For \( \alpha \)-scattering a deep real potential \( (V_0 \approx 100-200 \text{ MeV}) \) is required to describe this behavior. The sensitivity to the internal region also allows the determination of the optical potential in a much larger radial region than in the case of strong absorption, e.g. the Igo-ambiguity can be resolved when using a Woods-Saxon potential.

The elastic scattering of light heavy-ion projectiles has been investigated by several groups with respect to refractive scattering and the nuclear rainbow effect. Clear indications have been reported for \( ^6\text{Li} \)-beams [5]. Several papers have been published also on the observation of nuclear rainbow scattering in the elastic scattering of \( ^{12}\text{C} \) on \( ^{12}\text{C} \) [6-9]. The effect is not as pronounced as in \( \alpha \)-scattering and some authors [2, 10] tend to describe the whole angular distribution as pure diffractive scattering. Up to now the rainbow effect is not reported for heavier systems. In this paper we have investigated the systems \( ^{12}\text{C} + ^{12}\text{C} \) and \( ^{13}\text{C} + ^{12}\text{C} \) at 20 MeV/N with respect to the rainbow scattering (which in our interpretation is due to refractive scattering from the nuclear interior). We show quantitatively its magnitude and its localization in \( L \)- and \( R \)-space for the elastic and inelastic scattering and the one-neutron transfer.

For light scattering systems like \( ^{12}\text{C} + ^{12}\text{C} \) at energies of 20 MeV/N or higher, semi-classical concepts should work rather well [1, 11-16], and notions like trajectories, impact parameters, deflection functions and turning points are useful in interpreting the results. In particular the method of complex trajectories can be used in order to identify the spatial localization of the refractive scattering by looking at the turning points in the complex plane. It turns out that a single-turning-point approximation for each (real) \( L \)-value is sufficient to describe the full angular distribution in good agreement with the quantal calculation. In this case a clear correlation exists between \( L \)- and \( R \)-space.

Earlier results on the elastic scattering of the \( ^{12}\text{C} + ^{12}\text{C} \)-system indicate an intermediate situation with respect to weak or strong absorption, because the angular distributions show an increased cross section at large angles, but not a pronounced bump as in \( \alpha \)-scattering. Optical model fits in the energy range from 25 to 86 MeV/N have shown [6-8] that the absorption is not very strong and that the ratio of the real to the imaginary potential is close to one or larger in the surface region. A deep real part of the optical potential is required in the calculations to obtain the magnitude of the cross section at large angles. The analysis of [6] has demonstrated with sensitivity tests [17] that a strength of about 100 MeV is necessary at 3 fm to describe the large angles data at 25 MeV/N, the corresponding depth of the potential at \( R=0 \text{ fm} \) was 235 MeV. A deep nuclear potential and a low Coulomb potential guarantees the deflection of internal trajectories to large negative scattering angles, if the incident energy is sufficiently high. The corresponding part of the scattering amplitude belongs to the "far-side" scattering [18]. As pointed out in [2], strong absorption reduces considerably these contributions and any remaining cross section from the internal region may become negligibly small. In this case no rainbow scattering is observed, but the shape of the angular distribution at large angles is still governed by the far-side scattering, because the near-side amplitude decreases more steeply with increasing angles. The cross section of this part of the angular distribution would originate from diffractive scattering only, but it is still dependent on the depth of the real nuclear potential [2]. The far-side scattering cross section is smoothly decreasing with angle. If, however, a nuclear rainbow is present, it is built up from trajectories further inside the surface, and any significant contribution changes the smooth slope of the diffractive scattering in the vicinity of the rainbow angle. If this effect is observed, the diffractive and refractive part can be separated in a quantitative analysis and the strength of the S-matrix and the cross section can be specified for both parts. This is done in the present paper. Since the rainbow scattering is rather sensitive to the absorptive strength, we have studied the scattering system \( ^{12}\text{C} + ^{12}\text{C} \) in addition to \( ^{12}\text{C} + ^{12}\text{C} \) at 20 MeV/N to see whether the extra neutron increases the absorption significantly.

A further interest of the present work concerns the investigation of refractive scattering in the inelastic scattering and in transfer reactions. The observation of this effect in these channels would allow to study the corresponding transition potentials in a larger radial region in a similar way as the central potential for the elastic channel. We think that scattering systems where rainbow scattering has been observed in the elastic channel are good candidates to show this effect also in other channels.