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Rainbow-like scattering in absorptive nuclear systems

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Nuclear rainbow phenomena is known to occur in nuclear scattering of weakly absorbing systems such as ^{12}C + ^{12}C, ^{12}C + ^{16}O, ^{16}O + ^{16}O, and α projectiles in various target nuclei. Following theoretical predictions based on the São Paulo Potential (SPP), the ^{16}O+^{27}Al elastic and inelastic scattering was measured at two beam energies (namely, 100 and 280 MeV) with the MAGNEX spectrometer at the LNS, Catania [2,3]. The results show rainbow-like characteristics at the largest scattering angles, even in this system for which absorption is stronger and surface reflection tends to dominate the elastic scattering angular distribution. The coupling to the inelastic channels appears to be fundamental for the possibility of some refractive scattering, according to the theoretical calculations, which is essential for nuclear rainbow formation. This can be best appreciated in a near-far decomposition of the angular distributions. Although the cross sections are very small, the large scattering angle region can provide important information from the inner parts of the nucleus-nucleus potential, which is practically inaccessible otherwise.

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1. Introduction

Nuclear rainbow is a very interesting phenomenon, related to the atmospheric one, which can have implications to the nuclear equation of state (EOS) of cold nuclear matter [1]. Classicaly, a rainbow appears at the extrema of the deflection funcion. Both nuclear (a minimum) and Coulomb (a maximum) rainbows are known in nuclear physics. Nuclear rainbow is normally observed in weakly absorptive systems, such as α + nucleus and relatively light (strongly bound) heavy-ion (^{12}C,^{16}O + ^{12}C,^{16}O) scattering. Since nuclear rainbow is a refractive scattering effect, it requires a deep overlap between the interacting nuclei. For heavier systems it is normally expected that such deep surface interactions will result in complete or incomplete fusion of the beam with the target nucleus, or deep-inelastic processes. It has been shown, however, that rainbow-like scattering is predicted to occur also in heavier systems such as ^{16}O + ^{27}Al or ^{60}Ni at sufficiently high energies, by coupled channel (CC) calculations based on the São Paulo Potential (SPP) [2]. These predictions have been experimentally corroborated with the measurement of elastic scattering of ^{16}O + ^{27}Al, at 100 [3, 4, 5] and 280 MeV. Here we present partial results of the experiment at 280 MeV [6].

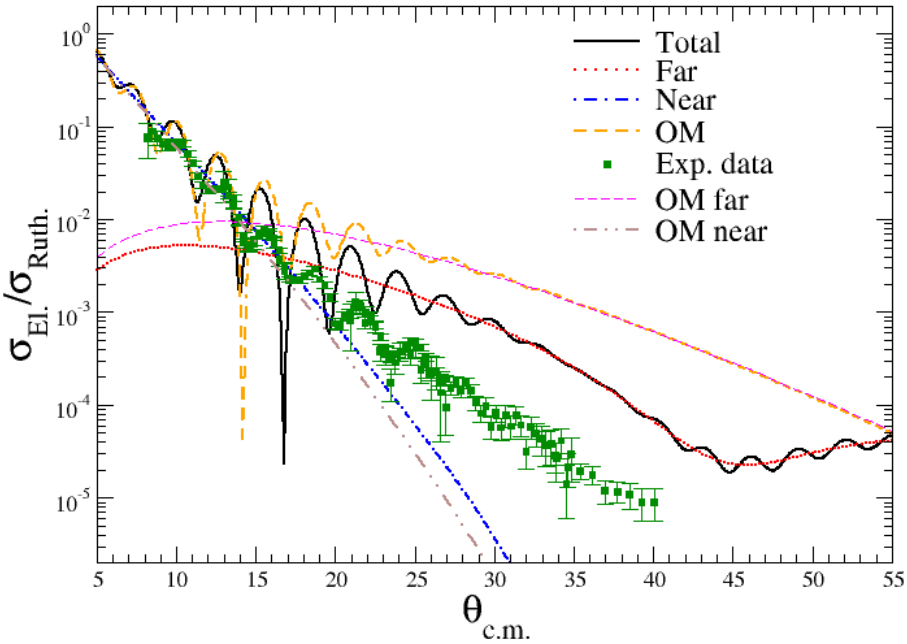
2. The experiment

The elastic and inelastic scattering angular distributions of ^{16}O on ^{27}Al (self supporting target, with 100μg/cm^2 thickness) at 280 MeV laboratory energy, were measured between 8° and 58° degree (in the center of mass frame) angles. The beam was provided by the CS (Superconducting Cyclotron) of the Laboratori Nazionali del Sud (LNS), Catania. The ^{16}O scattered ions were momentum analyzed and detected with the large angle acceptance magnetic spectrometer system MAGNEX [7]. At the largest angles, a 10pnA beam intensity was used to bombard the Al target. The final experimental energy resolution varied from 550 to 800 keV, at the most forward and backward angles, respectively. This energy resolution is sufficient to obtain separate measurements of the elastic and inelastic cross sections, since the first excited state of ^{27}Al is at 844 keV. In this challenging experiment, a large variation of cross sections, of more than eight orders of magnitude down to tens of nb/sr was consistently measured with the same equipment. Details of the experiment will be presented in a forthcoming article. Figure 1 presents the results of the elastic scattering up to about 40° in the center of mass. The green squares with error bars are the experimental data points. The data above 40° is not shown, since it is still under analysis with evaluation of upper bounds, but is consistent with a rainbow-like flattening of the angular distribution.

3. Theoretical calculations and results

The theoretical calculations were performed with the computer code FRESCO [8]. The optical potential was based on the model described in ref. [2]. The São Paulo Potential is employed both in the real and imaginary parts of the potential, with normalization factors of 1 and 0.6, respectively. Typically 500 partial waves are included in each run. In these CC calculations, only the coupling to the collective first excited state (the 2^+ at 1.779 MeV excitation) of the ^{28}Si core was considered. This is justified for ^{27}Al assuming the weak coupling model of the $d_{5/2}$ proton hole to the ^{28}Si core [9, 2]. The strength of the coupling between the ground and 2^+ states is obtained

Figure 1: Theoretical and experimental elastic scattering angular distributions relative to the Rutherford cross section of the ^{16}O on ^{27}Al at 280 MeV. See explanation in the text.



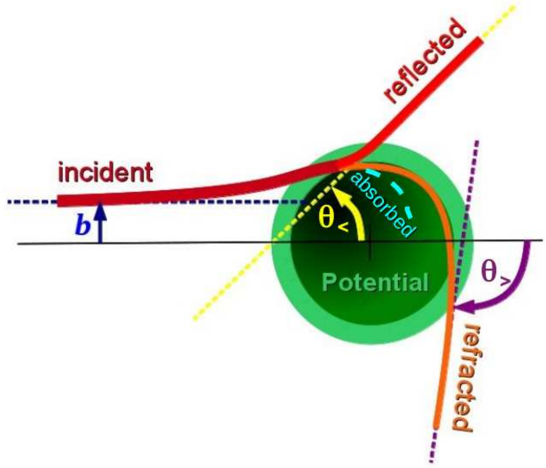
from the experimental electromagnetic transition probability, assuming the rotational model, and accordingly deforming the real potential.

Figure 1 presents the results of the CC calculation (black solid line) as well as the pure optical model (OM, with no coupling - the orange dash curve). The theoretical cross sections can be decomposed into Near and Far side components by the method of Fuller [10]. The Near components in Fig. 1 are represented by the blue dash-single-dot and brown dash-double-dot down-sloping curves for the CC and OM calculations, respectively, while the Far components are indicated by the red dot and magenta short-dash lines again for the CC and OM calculations, respectively. The crossing between the Near and Far side scattering components generates the Fraunhoffer oscillations.

4. Discussion and conclusions

From figure 1, it can be seen that channel couplings can have a large effect at large angles even at this high bombarding energy of 280 MeV. In contrast to the 100 MeV results [4, 5], the coupling to the core 2^+ state reduces, rather than increases, the cross section in comparison to the OM curve. Nevertheless, the rainbow pattern appears very clearly in the CC curve, with an Airy-like minimum at 46°. In this region, the OM result steadily decreases, roughly exponentially. Around this angle the Far-side (the refractive) component dominates completely the cross section in both CC and OM

Figure 2: Pictorial representation of the various competing scattering mechanisms for a given inpact parameter (or angular momentum component). The refraction trajectory towards large angles competes with the most intense reflection trajectory and with absorption.



cases, while, like at lower energy, the coupling appears to be essential for the rainbow formation. As discussed in [5], the standard procedure for the extraction of the deflection function from the angular momentum derivative of the quantum scattering function yelds only a reflective behavior, which is the dominant component of the scattering. Therefore, the refractive scattering component associated with the large angle rainbow pattern, which is much weaker, is not evidenced in the deflection function. This is pictorially represented in fig. 2.

The experimental results above 20° (Fig. 1) are strongly overestimated by both calculations. However, the CC results come much closer to the experimental ones in comparison to the pure OM curve. In addition, the experimental data appears to present an upward inflection (not shown in the figure as explained above) consistent with a rainbow pattern formation around the calculated Airy minimum region. It is important to note that other channels (inelastic states, transfers etc.) can influence the theoretical results. Preliminary attempts to include additional channels (inelastic transitions, 1n and alpha transfers) have not had success, so far, in approximating the theoretical curve to the experimental one. The inclusion of these other channels tends to increase, rather than decrease, the cross sections in the relevant region. However, it should be pointed out that not all the possible channels can be included at the same time, and it is not easy, *a priori*, to tell which ones are the most important to be included, so these calculations demand time. In addition, there is some model dependency of the coupling matrix elements in the extraction of the nuclear from the electromagnetic ones, when available. Another point is that, up to now, a reliable theory to include the expected effects form Pauli blocking at this energy, onto the imaginary part of the OM [4] has not been developed. The description of this large angle region is therefore a challenge to the present theoretical methods.

The lower angular region, however, say, below 15°, is much better described by the calculations, but the results are rather insensitive to the various (reasonable) models and parameters. The convolution of the experimental angular resolution with the theoretical curves presented in Fig. 1 have not been performed yet, and of course will reduce amplitude of the oscillations, which would improve the agreement with the experimental data. Also, the amplitude and phase of the oscillations are rather sensitive to details of the model, as discussed in [4, 5].

The description of the inelastic angular distributions present similar difficulties, being rather well controlled at the lower angle region, and discrepant at the large angle one. The simple ^{28}Si core 2^+ model, used for the CC elastic scattering calculations, over-predicts the inelastic cross sections above 15°. Both elastic and inelastic descriptions can be brought closer to agreement with the data at large angles when several additional couplings are included and the normalization of the imaginary potential is increased by about 70%. This cannot be considered a very successful result since there is no theoretical justification for such larger normalization factor.

In conclusion, one can say that the study of the large angle region of the elastic scattering of heavy ions, both theoretically and experimentally is a challenge to the development of low energy nuclear physics. This is the region where, contrary to general expectations, nuclear rainbow phenomena can appear and reveal important features of the nuclear matter.

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