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Rainbow effects in the scattering of $^{12}C+^{12}C$

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Abstract

We propose to measure the excitation function around $\theta_{cm} = 90^o$ of the inelastic channel $^{12}C(0^+)+^{12}C(0_2^+)$ in the energy range E_{lab} = 80 to 120 MeV to find the first A_1 and the second A_2 Airy minima in this channel. Their observation would confirm the presence of nuclear rainbows in inelastic channels and elucidate the properties of the ion-ion potential.

1 Motivation

The scattering of two nuclei is described using an effective interaction (the optical potential), the real part of which describes the relative motion and the imaginary part the absorption to non-elastic channels. A knowledge of this optical potential is an essential prerequisite before we can describe any other reaction processes (inelastic scattering, transfer reactions, breakup, fusion etc...) since models for these processes use the effective potential to describe the relative motion of the interacting ions.

Unfortunately, the scattering of heavy ions is dominated by strong absorption effects and this makes it impossible to determine the real part of the potential : ambiguities arise between the relative strength of the real and imaginary parts of the potential and in the geometry (radial variation). This ambiguity in turn compromises our ability to extract reliable spectroscopic information on the structure of the interacting nuclei. However, weak absorption has been observed in a few special cases of collisions between Light Heavy Ions with A $\leq$ 20. The signatures of this transparency are in the low energy domain, the presence of resonances (narrow structures) in the excitation function corresponding to nuclear molecules, and in the high energy domain the presence of broad structures corresponding to refractive effects like the nuclear rainbows and the associated Airy structures.

These two phenomena have been observed in collisions involving the closed or semi closed shell nuclei, ^{12}C, ^{14}C, ^{15}N and ^{16}O for which the selective observation of resonances can be explained by the small number of open channels in these reactions [1]. The survival of these "classical" phenomena such as rainbow scattering and Airy structures in the quantum systems reflect the weakness of the imaginary component of the interaction potential. Moreover, they offer a unique opportunity to circumvent the usual ambiguities and determine the strength of the real part of the potential.

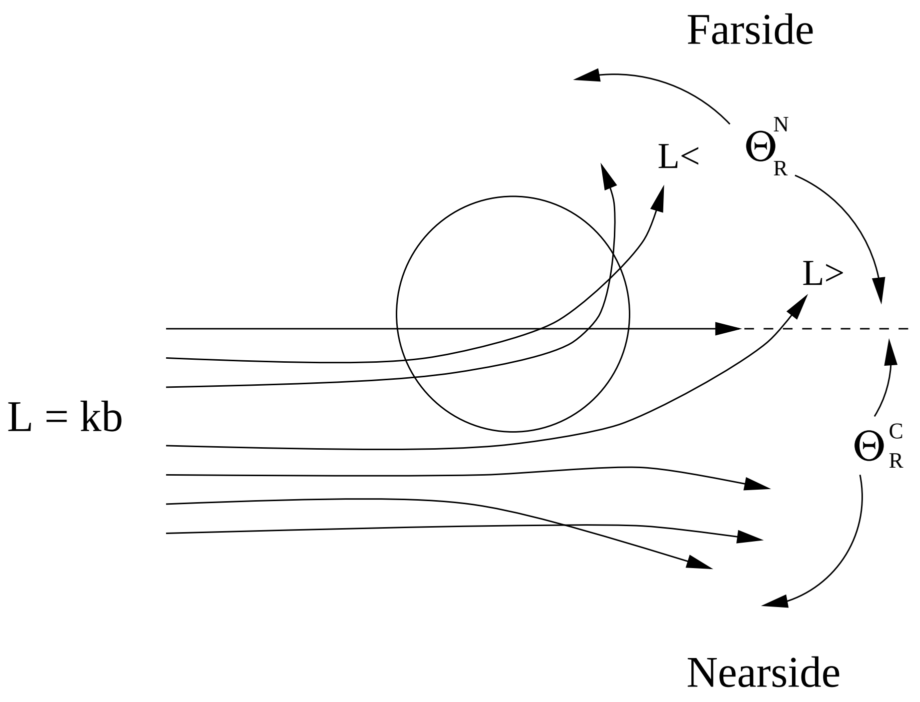

Figure 1: *Nearside and Farside trajectories as a function of impact parameter.*

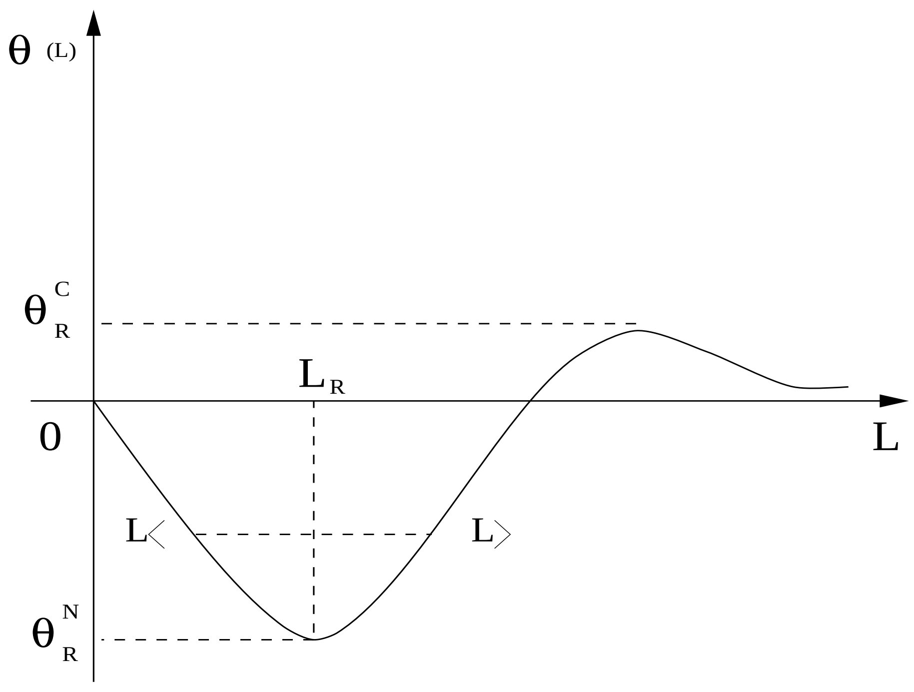

Figure 2: *Deflection function : scattering angle θ as a function of the angular momentum L=kb which depends on the wave number and impact parameter.*

The origin of the atmospheric rainbows has been described a long time ago by the reflection and refraction of light throught a transparent spherical drop of water. Nuclei can behave as spherical drops. Experiments using the elastic scattering of α particles on nuclei show nuclear rainbow phenomena and allow the ion-ion potential depth to be determined. Thus, the study of elastic scattering is very important to obtain information on the real part of the optical potential. To understand the observed phenomena in the elastic scattering in the presence of absorption, it is often useful to decompose the scattering amplitude of the optical model in terms of trajectories (figure 1):

- a Nearside component which corresponds to the positive angle deflection,
- a Farside component which corresponds to the negative angle deflection.

The decomposition in Nearside and Farside waves allow us to understand the origin of the oscillations which are observed in the elastic scattering angular distributions. In fact, three types of interference contribute :

- those between the Nearside waves which are associated with the Coulomb rainbow,
- those between the Nearside and Farside waves (from one side and the other side of the target nucleus) which correspond to Fraunhofer diffraction,
- and those between the two Farside waves $L_>$ and $L_<$ under the condition that $L_<$ is a weakly absorbed wave, which characterized the refractive effects (figure 2).

On the figure 1 are shown the Nearside and Farside trajectories as a function of impact paramater. For large impact parameters, the interference between the Nearside waves corresponds to oscillations observed at very forward angles and can be interpretated in terms of Coulomb rainbow. For the small impact parameters which correspond to the negative angle region (backward angles) there are two types of trajectories :

- those which by pass the nucleus,
- and those which penetrate.

The nuclear rainbow phenomenon is characterized by the most deviated trajectory, this is because it feels the attractive nuclear potential more than the others trajectories until a limiting angle, called the nuclear rainbow angle. The domain above this angle corresponds to a classicaly forbidden region where no trajectories can occur, in others terms "a dark side". In this figure 1, there are two trajectories associated with two different impact parameters which are scattered at the same angle. And the interference between these two Farside waves $L_>$ and $L_<$ (from one side and the other side of the rainbow wave) characterizes the refractive effects and the associated Airy structures. So the Airy minima observed in the elastic scattering angular distributions correspond to a destructive interference between the two Farside waves $L_>$ (grazing wave) and $L_<$ (internal wave) (figure 2).

In the last two years, analyses of how the pattern of Airy minima and refractive features change with energy have, for the first time, enabled unique potentials to be extracted for a number of scattering systems. Among these systems, the ^{12}C+^{12}C reaction is certainly the one which has been the most studied. In the 90^o excitation function for the ^{12}C+^{12}C elastic scattering at bombarding energies between the Coulomb barrier and 10 MeV per nucleon,

Figure 3: *Elastic scattering angular distributions for $^{12}C+^{12}C$ at E_{lab} = 240, 289, 360 and 1016 MeV. Curves are calculations with phenomenological potentials [14].*

complex structures of narrow and broad peaks and valleys have been observed. Between 60 and 130 MeV, detailed angular distributions and excitation functions have been reported for this channel [2][3]. At higher energies the data accumulated at $E_{lab} = 140$, 159 [4], 240 [5], 289 [6] , 300 [7], 360 [8], 1016 [9], 1030 [10], 1450 and 2400 [11] have permitted unique ion-ion potential to be determined [12][14]. The optical potentials used have a deep real part and a shallow imaginary part. The observation of the refractive effects are essential to obtain information on the ^{12}C+^{12}C interaction at smaller interaction radii than is usually the case in the strongly absorbing heavy ion collisions. A good example is the complete angular distribution (up to 90^o) measured for the ^{12}C+^{12}C elastic scattering at $E_{lab} = 360$ MeV [8] (figure 3). In this distribution, the exponential decrease of the differential cross section in the dark side region of the nuclear rainbow was clearly observed and allowed a determination of the potential without the usual discrete ambiguities [12][14]. These potentials were then successfully used to describe the detailed angular distributions and excitation functions at lower energies between 5 and 10 MeV per nucleon [2][3][12][14]. In particular the broad structures observed in the 90^o excitation function of the ^{12}C+^{12}C elastic scattering [2] have been interpretated in terms of refractive effects [12] and the remarkable deep minimum at $E_{lab} = 102.1$ MeV has been identified as the second Airy minimum A_2 (figure 4). No experimental results exist for A_1 which is predicted to occur at $\sim$ 130 MeV [12]. The presence of the precise energy of this minimum is essential to confirm the validity of the interaction potential.

It has been noted by Marty [13] a long time ago, that the deep minimum (A_2) at 90^o in the elastic scattering (0^+,0^+) at E_{lab} = 102.1 MeV was correlated with minima in the inelastic channels : at an incident energy of E_{lab} - 2×4.4 MeV for the (2^+,0^+) channel and at an energy of E_{lab} - 4×4.4 MeV for the (2^+,2^+) channel where 4.44 MeV is the excitation energy of the ^{12}C first excited 2^+ state. For E_{lab} = 102.1 MeV, this would to correspond to minima at energies of 93.3 and 84.5 MeV for the inelastic (2^+,0^+) and (2^+,2^+) channels respectively (figure 4). The observation was based on ^{12}C+^{12}C angular distributions from the Oak Ridge group [3] and seems now to be confirmed by the detailed 90^o excitation functions reported by the Strasbourg group for the elastic and inelastic (2^+,0^+) and (2^+,2^+) channels [2] (figure 4). This correlation is not understood, and its explanation remains an experimental and theoretical challenge.

In the case of collision between identical bosons, the angular distributions are symetric around 90^o and present, in general, a maximum at 90^o because only the even partial waves contribute to the cross section. The effects in the 90^o excitation function should be particularly strong for reactions with channel spin 0 in the entrance and exit channels. For other exit channels like the ^{12}C+^{12}C (2^+,0^+) and (2^+,2^+) channels, the effects at 90^o should be partially washed out due to the possible contributions of different intrinsic spin projections. This would not be the case for the ^{12}C+^{12}C (0^+_1,0^+_2) inelastic channel in which the 0^+_2 state at E_x = 7.65 MeV is excited. If for this channel the correlation noted by Marty [13] holds, its 90^o excitation function should present an Airy minimum A_2 at E_{lab} = 86.8 MeV corresponding to A_2 at 102.1 MeV in the (0^+,0^+) channel and an Airy minimum A_1 at E_{lab} = 114.7 MeV corresponding to the predicted A_1 at 130 MeV in the elastic channel [12]. Because of the zero channel spin the minima should not be affected by any interference from different partial waves which should make the theoretical interpretation of this phenomenon easier. Moreover, there is the possibility of observing, for the first time, the first Airy minimum, the precise energy of which will be a crucial test of the accuracy of the interaction potential.

2 Proposed Measurements

Previous measurements of ^{12}C+^{12}C scattering to multiple α-particle final states using position sensitive strip detectors (PSSD's) have proved successful [16]. We propose to measure the excitation function for the inelastic channel ^{12}C(0^+)+^{12}C(0^+_2) around θ_{cm} = 90^o up to E_{lab} = 120 MeV to highlight the first A_1 and the second A_2 Airy minima. The experimental setup would be similar to that explained in another proposal [15], using eight PSSD's in the Charissa MEGHA chamber to give angular coverage from 5^o to 60^o in the laboratory. From previous measurements for the exit channel ^{12}C(0^+)+^{12}C(0^+_2) shown in figure 5, we estimate that an average of 9 hours will be required to collect sufficient data at each energy using a 10 μg/cm^2 natural carbon target foil and an average beam of 20 enA with a data acquisition trigger of four coincident particles. Hence an excitation function in the range E_{lab} = 80 to 120 MeV in 2 MeV steps would take approximatively 9 days. One additionnal day is required for the necessary detector calibrations. In total

Figure 4: *Excitation function at θ_{cm} = 90° for the elastic (0^+,0^+) and inelastic (0^+,2^+) and (2^+,2^+) channels of the ^{12}C+^{12}C system for bombarding energies between E_{lab} = 60 to 120 MeV [2].*

10 days of beamtime are requested for this experiment. We note that this experiment uses an identical beam-target combination and experimental setup to that of proposal CH/PROP/ANU/99/01. The physics studied in that experiment is different, and does not require as much beamtime at each energy as the channels of interest have larger cross sections. In addition, the beam energy range to be covered is not as extensive. However, in the region of overlap sufficient data for proposal [15] be obtained in the present measurement. As a result should CH/PROP/ANU/99/01 be approved, this investigation would only require an additional 5 days.

We would further note that the same physics theme which we are addressing in the ^{12}C+^{12}C inelastic scattering channel should also be evident in ^{12}C+^{16}O inelastic scattering to the ^{12}C(0_2^+) state. This system is less extensively studied than ^{12}C+^{12}C, but could in principle display these features more clearly since there is not the problem of symmetrised scattering amplitudes caused by the identical particle nature of the entrance channel. The forward-backward angle symmetry which this produces can make it difficult to identify the Airy minima clearly in the angular distributions.

Elastic scattering angular distributions have been obtained by the Strasbourg group at 7 bombarding energies E_{lab} = 62, 75, 80, 94.8, 100, 115.9 and 124 MeV [17] and at higher energy E_{lab} = 132 MeV by Ogloblin [18] for the ^{12}C+^{16}O system. The figure 6 represents the angular distribution of the ^{12}C+^{16}O elastic channel at E_{lab} = 115.9 MeV.

Two deep minima are observed and could be associated to the third A_3 and the second A_2 Airy minima, and the first one A_1 is expected at larger angles where the contribution of the elastic transfer is very important. The study of the ^{12}C+^{16}O inelastic scattering to the ^{12}C(0_2^+) state could be a very successful way to decrease the contribution of the elastic transfer at the backward angles and hence it would be easier to observe the first A_1 Airy minimum.

It would be of interest to obtain some preliminary data on the ^{12}C+^{16}O system to investigate these ideas and this could be carried out with the same experimental setup. We would therefore like to ask for a further day to investigate this channel, which would enable us to come back with a detailed proposal at later date.

3 Summary

We propose to measure the excitation function around $\theta_{cm} = 90^o$ for the inelastic channel ^{12}C(0^+)+^{12}C(0_2^+) to the energy range E_{lab} = 80 to 120 MeV (same physics for ^{12}C+^{16}O). **11 days** of beamtime are requested for this experiment (both reactions). The aim of the present experiment is to trace the Airy minima in the different inelastic channels and especially in the (0^+,0_2^+) channel. We believe that if the refractive effects (interference between grazing and more internal partial waves) are observed in the elastic channel, they should also be seen in the inelastic channels. Their observation would give strong support not only to the presence of nuclear rainbows but also to the properties of the ion-ion potential.

Beam	Energy	Target	Proposal 1 approved	Proposal 1 not approved
^{12}C	80 to 120 MeV in 2 MeV steps	^{12}C	5 Days	10 Days
^{12}C	115.9 MeV	BeO	1 Day	1 Day

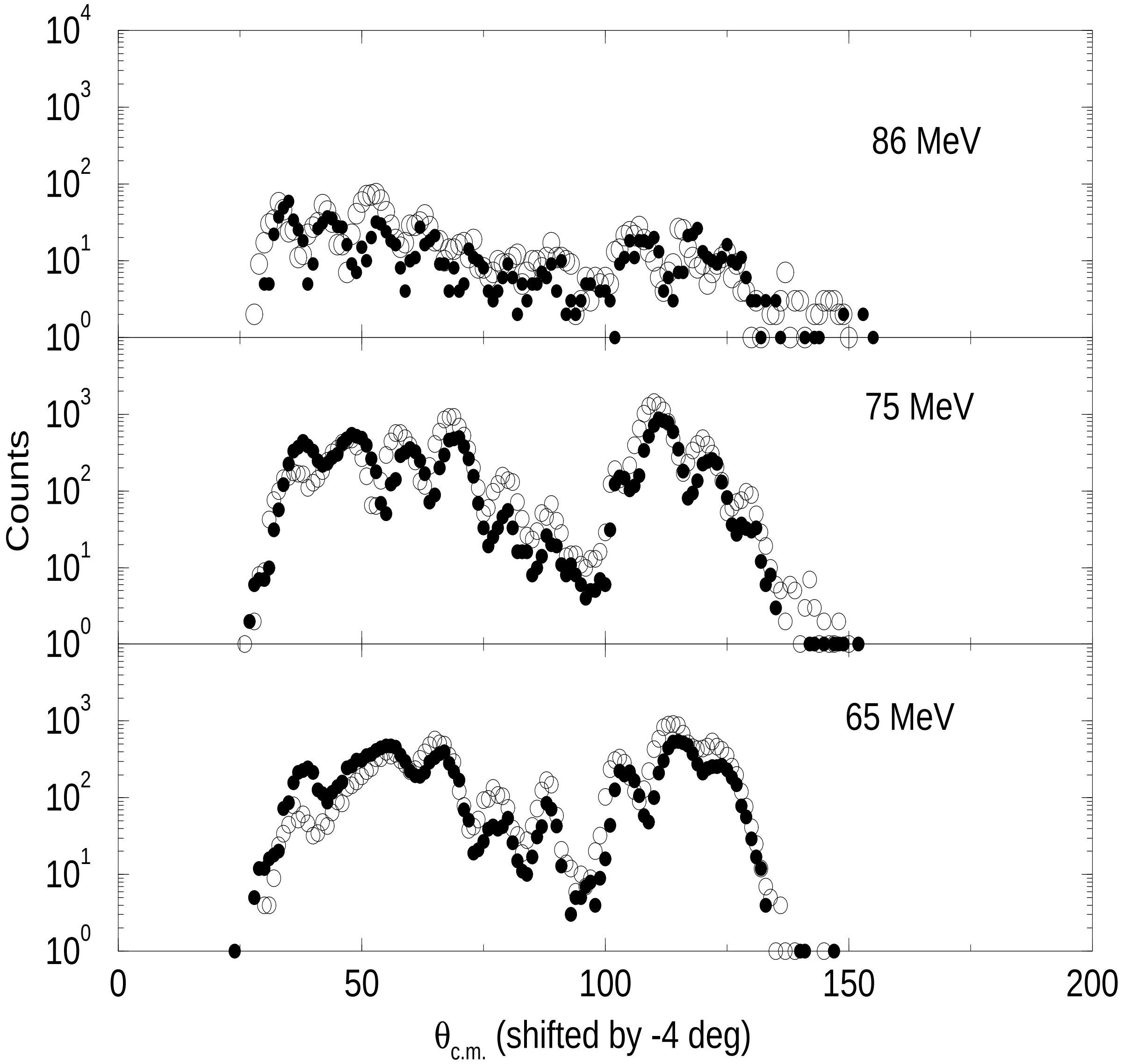

Figure 5: *Angular distributions of the inelastic channels* $^{12}C(0^+)+^{12}C(0_2^+)$ *at three bombarding energies* E_{lab} = *65, 75 and 86 MeV measured by the Charissa group at the ANU laboratory. These data correpond to 8 hours of recording. The two kinds of points refer to angles measured on each side of the beam direction.*

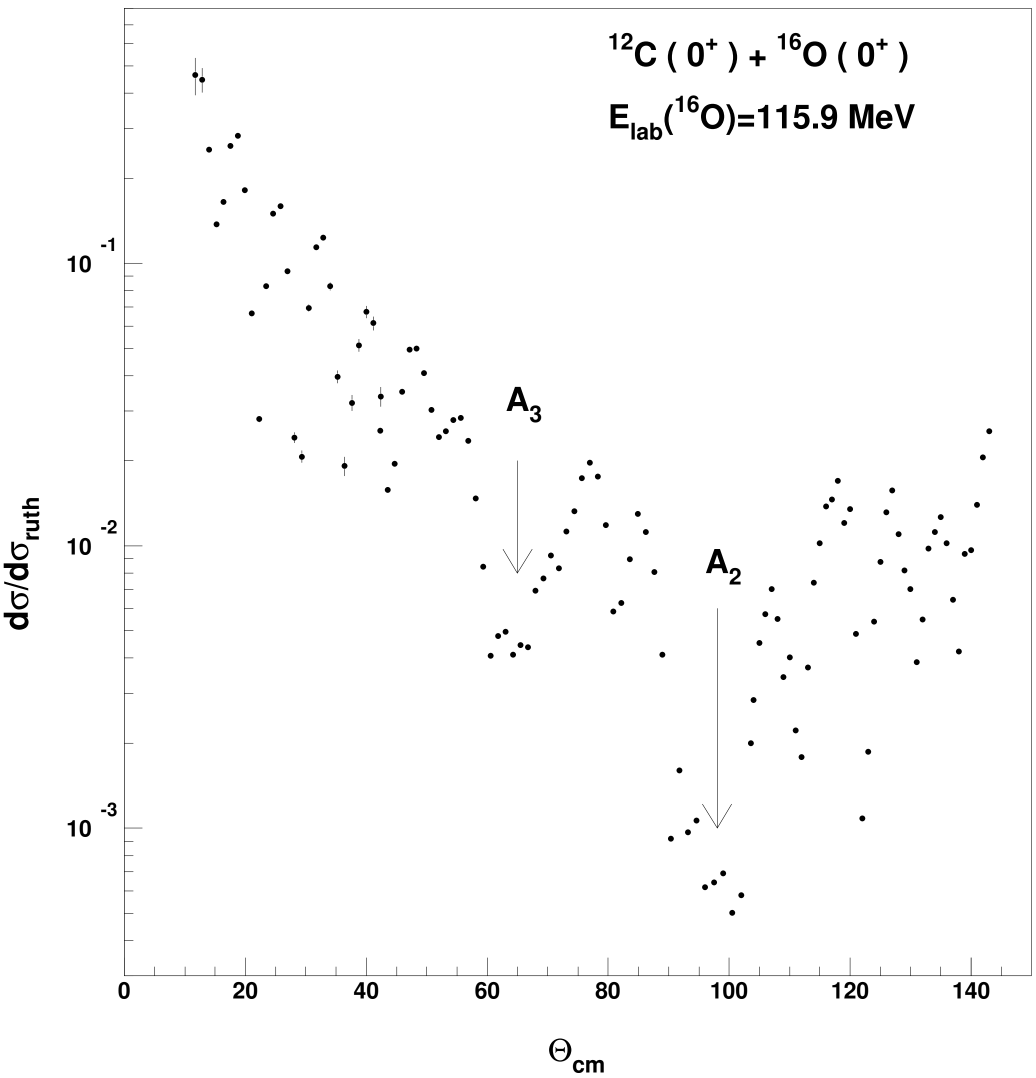

Figure 6: *Angular distributions of the elastic channel* ^{16}O+^{12}C *at* E_{lab} = *115.9 MeV measured by the Strasbourg group. We have indicated the position of the third* A_3 *and the second* A_2 *Airy minima.*

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