Chaos and nuclear scattering: experimental study of the $^{16}O+^{28}Si$ system


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In this contribution, we present the results of measured cross sections for the elastic and inelastic scattering of $^{16}O$ by $^{28}Si$ in two energy regions, one close to the Coulomb barrier and the other well above. Fine enough steps in both bombarding energy and scattering angle make it possible to compare the data with the theoretical calculations that predict, for each of these regions, distinctive cross-section patterns in correspondence with the classical occurrence of either regular or chaotic regimes. The qualitative aspect of the resulting experimental patterns, as well as their evaluation via a mathematical procedure which is particularly sensitive to the relevant differences, lead to the tentative conclusion that both types of behavior do appear, although an unambiguous confirmation is still lacking.

Keywords: Chaos; heavy-ion scattering

En esta contribución presentamos los resultados de mediciones de secciones eficaces para la dispersión elástica e inelástica de núcleos de $^{16}O$ por núcleos de $^{28}Si$ en dos regiones de energía, una cercana a la barrera coulombiana y la otra bien por encima. Pasos suficientemente finos tanto en la energía como en el ángulo de dispersión permiten comparar los datos con cálculos teóricos que predicen, para cada una de estas regiones, diferentes patrones de la sección eficaz en correspondencia con la aparición de los regímenes regular y caótico predichos clásicamente. El aspecto cualitativo de los patrones experimentales, así como la evaluación a través de un procedimiento matemático que es particularmente sensible a las diferencias más relevantes, permite concluir que ambos tipos de comportamiento están presentes, aunque aún resta obtener una confirmación libre de ambigüedades.

Descriptores: Caos; dispersión de iones pesados

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1. Introduction

1.1. Background and experimental overview

The cross sections obtained for elastic and inelastic processes in several reaction systems revealed a systematic of unusual features that they are still waiting for a complete theoretical explanation. For instance, the angular distributions for the elastic scattering of the $^{16}O+^{28}Si$ system show beside of the expected exponential fall-off for angles larger than the grazing angle, a surprisingly large cross sections at backward angles $\theta_{cm} \geq 90^\circ - 100^\circ$ and a strong backward rise near $\theta_{cm} = 180^\circ$ [1]. Moreover, the observation of oscillating structures, over a narrow interval of energies, whose width range from 50 keV to 2 MeV in the excitation functions of systems like $^{16}O+^{28}Si$ and $^{12}C+^{28}Si$, posed an intriguing problem, which up to date is not clearly understood.

Several interpretations were put forward to understand the origin of the large angle enhancement and the gross structure observed in the energy dependence of elastic and inelastic scattering. Different models have been proposed to reproduce the observed structures and several mechanisms were invoked to explain those unexpected results and to provide an insight into the underlying physics [1]. None of them has been able to give an exhaustive comprehension of the phenomenon and the only model-independent consideration which comes out from these analysis is the unexpected presence of a surface transparent ion-ion potential which appears to be a necessary condition for these structures to show up. Such a systematic of unexplained experimental data was the original motivation for searching a possible chaotic mechanism at the basis of such an irregular behavior [2].

1.2. Regular and chaotic behavior in nuclear scattering

During the last few years, using classical models, it was established that under certain assumptions the nuclear scattering problem present very peculiar characteristics, called as a whole chaotic behavior. They were recently the subject of interest of several investigations [3, 4]. Considering the point of view of the mentioned schematic model, the manifestation of chaotic phenomena becomes evident in nuclear scattering at energies close to the potential barrier built-up by the sum of the nuclear, centrifugal and Coulomb contributions. They merge as a consequence of the coupling of the relative motion variables of the reacting nuclei and their intrinsic degrees of freedom. Furthermore, the effects produced by permanent dynamic deformations (i.e. rotations or vibrations) of the nuclei taking part of the reaction, were already subject of investigation [5, 6].

These simplified classical models are not suitable to perform detailed predictions that allow by simple comparison with the experimental results, to determine the presence of the so called "regular" or "chaotic" regimes. In a recent publication [7] the relation between these regimes as they merge classically and its possible manifestation in the results of detailed fully quantal coupled channel calculations were exhaustively investigated. The study was focused on reaction systems characterized by a weak surface absorption. In this
way, the influence of the trajectories exploring the inner region of the potential barrier is expected to increase, because the calculations indeed predict that these inner trajectories are responsible of the “chaotic” regime. In this sense, the $^{16}$O+$^{28}$Si system is particularly suitable. The low absorption becomes evident because the cross-sections scattering at backward angles are abnormally high, and an adequate degree of freedom is related to the rotational character of the $^{28}$Si nucleus. For this system detailed coupled channel calculations using the state of the art calculation code [7,8], were performed covering wide angular and bombarding energy ranges. The corresponding differential cross-sections, analyzed as a function of the two variables $\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega(\Theta_{cm}, E_{lab})}$, show oscillating structures whose behavior is clearly different according to the chaotic or regular region predicted by the simplified calculation. The regular regime would be continuous and the positions of maxima and minima of the angular distribution would evolve smoothly as a function of the bombarding energy. The chaotic regime is characterized by a much more irregular trend, and the positions of maxima and minima of the angular distribution describe in the energy vs scattering angle plot a blurred image scarce of regularity.

One of the remarkable conclusions of the study performed in reference [7], is that the evidence of one or another kind of behavior, would be difficult to obtain as much as from the analysis of the angular distribution as from the excitation functions taken individually. The signature of either regular or erratic behavior is found in a bombarding energy-scattering angle plot of the cross sections. This is illustrated in the two dimensional plots shown in Fig. 1, (taken from Ref. 7), which shows a partial set of the results of the coupled-channel calculation of the cross section for the elastic and inelastic scattering of $^{16}$O leading to the first $2^+$ excited state of $^{28}$Si in the regular and chaotic regions pointed out by the classical analysis. The main point of Ref. 7 is associated with the observation of two different cross-section patterns, as shown in Fig. 1, and its interpretation in terms of either chaos or regularity in the corresponding classical picture. The purpose of the calculation was not to describe specific angular distributions in detail, but rather to distinguish globally between these different types of behavior. The experimental verification of whether these predicted differences in the cross-section patterns are indeed present requires more detailed measurements in the relevant bombarding energy-scattering angle regions and is the motivation of the present investigation.

We present the results of an experimental search for the predicted signature of the regular and chaotic behaviors in the $^{16}$O+$^{28}$Si system. Previous versions of this work were already published [9, 10]. A brief summary of the experimental details, is described in Sec. 2, the results of our measurements are given in Sec. 3 and discussed in Sec. 4, where in addition a quantitative interpretation of the experimental data is proposed. The conclusions are given in Sec. 5.

2. Experimental

The $^{16}$O+$^{28}$Si system was measured using the $^{16}$O($q = 5^+$) beam delivered by the 20 UD Tandem accelerator at Buenos Aires, at bombarding energies in the ranges $39 \leq E_{lab} \leq 45$ MeV and $70 \leq E_{lab} \leq 77$ MeV. The reaction products were detected in kinematical coincidence using two solid-state position-sensitive detectors (PSD’s) mounted in the scattering chamber. A significant improvement in the energy and the position resolution was obtained operating both detectors at temperatures $T$ in the range $-30^\circ C \leq T \leq -20^\circ C$. Both detectors were placed at distances from the center of the scattering chamber, covering an angular range of approximately $10^\circ$ in the horizontal plane. The distances were selected to have absolute efficiency equal to 1 for the reaction of interest, at the measured angular range and under the assumption of the detector position resolution of FWHM$_{(position)} = 0.5$ mm, the angular resolution was required to be less than $0.8^\circ$.

The data were recorded in the event-by-event mode. Each event was defined by the energy $E$, and the position $x$ x energy parameter, $(p \times E)$ being $p \times E = (x/l) \times E$, where $x$ is the particle incidence position over the sensitive area and $l$ is the total length of the detector. The Time coincidence was defined by the overlapping within 5 $\mu$s of the corresponding signals delivered for the detectors. The particle incidence position $p$ on each detector were obtained using specific software during the off-line data analysis. Further details about the experimental set-up and the data analysis can be found in Ref. 10.

3. Experimental results

The complete set of experimental data presented and discussed in this contribution, comprises two series of measurements. The first one, was obtained from the measurements performed in the center of mass angular range $90^\circ$ to $120^\circ$ and in the energy range $39$ MeV to $45$ MeV; in the second serie, the center of mass angular range was $80^\circ$ to $120^\circ$ and the energy range was $70$ MeV to $77$ MeV. In all cases the energy was varied in $0.5$ MeV or $1$ MeV energy steps and the angular binning was $0.8^\circ$.
FIGURE 2. Differential cross sections for elastic and inelastic scattering in the $^{16}$O+$^{28}$Si system, in the two regions of the bombarding energy-scattering angle plane that are predicted to present regular or chaotic behavior (high-energy and low-energy regimes, respectively) according to Ref. 7. The black curves represent the experimental angular distributions. The white curves are linear interpolations just intended to guide the eye.

The experimental cross sections as a function of both scattering angle and bombarding energy for the elastic and the $2^+$ (1.78 MeV) inelastic channel are displayed in Fig. 2. The dark curves correspond to the experimental angular distributions. For the sake of clarity, these are representative curves obtained by fitting the experimental points, rather than the actual data points (see Ref. 9 for details). The white curves are linear interpolations between adjacent experimental angular distributions. For both elastic and inelastic scattering the results exhibit a pronounced difference in the qualitative behavior when comparing the low-energy regime with the high-energy regime. In the high-energy region the valleys and ridges follow a markedly regular pattern which is very well defined by all the measured angular distributions. In turn, such regularities are not apparent in the low-energy region which shows rather non-regular shifts of the positions of the maxima and the minima when going from one energy to the next, and also a much less regular trend in the evolution of the absolute values of the cross section. The qualitative difference in the behavior of the experimental cross-section pattern between the predicted regular and chaotic energy regimes appears to be in correspondence with that illustrated in Fig. 3, which contains the same information as Fig. 1, but displayed in a somewhat more adequate format. The corresponding theoretical data were obtained from Ref. 11.

4. Discussion

The comparison between the theoretical calculations and the experimental results can also be performed in a somewhat more quantitative manner. The different cross-section patterns have been analyzed using a procedure that was intended to be particularly sensitive to the relevant qualitative features discussed above. The following is an outline of the procedure: for a given region in the $E_{lab} - \theta_{cm}$ plane (see Fig. 4) an arbitrarily oriented straight segment (defined by an orientation angle $\psi$ and limited by the boundaries of the region) is taken. Next, the one dimensional function that arises from its corresponding cut of the cross-section surface along that segment is considered, and the total number of relative maxima and minima is counted. These steps are then repeated for a representative set of parallel segments that cover the region under consideration. For this angle $\psi$ the total number of maxima and minima per unit length over all the parallel segments, $n(\psi)$, is computed. By plotting $n(\psi)$ vs. $\psi$, one should obtain two possible extreme results as it is shown in Fig. 5. For a very regular pattern of the cross-sections, the density of extremes function $n(\psi)$ is expected to show a pronounced structure. Irregular patterns (such as those obtained
as a consequence of the theoretical calculations for the chaotic region) should produce more or less flat $n(\psi)$ functions. The degree of regularity may be finally characterized by a single number $\epsilon$ obtained as follows

$$\epsilon = \sqrt{\frac{\sum [n(\psi) - \langle n \rangle]^2}{\langle n \rangle}},$$

being $\langle n \rangle$ the average value of $n(\psi)$.

5. Conclusions

The present experimental results for both elastic and inelastic scattering were found to be in reasonable agreement with the theoretical predictions. The values of $\epsilon$ obtained from the application of the procedure described in the text for the different cases are summarized in Table I. The procedure was first applied to paradigmatic patterns, and it was shown that the theoretical patterns for the high-energy and low-energy regimes can be characterized as regular and irregular, respectively, in accordance with the regular and chaotic character discussed in Ref. 7. Finally, the experimental values for the same regions are also in very reasonable agreement with both the theory and the paradigmatic cases.
theoretical predictions, both from a qualitative comparison between the cross-section patterns and from a quantitative estimate of their regular or irregular character. Therefore, the present data lend support to the interpretation that under certain circumstances chaotic behavior in nuclear scattering may manifest itself in the bombarding energy-scattering angle cross-section patterns. It is clear that in order to have a much more conclusive evidence, more experimental data in this and another nuclear reaction systems are necessary.