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Measurement of Inelastic-Scattering Cross Sections in the $^{16}O +^{28} Si$ System to Discriminate Regular and Chaotic Regimes

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A new experiment to measure differential cross sections as a function of the bombarding energy and scattering angle for the $^{16}O +^{28} Si$ system in order to discriminate regular and chaotic regimes, was performed using the particle spectrometer CHICO combined with the multidetector array Gammasphere. In this contribution we summarize the characteristics of the method developed to analyze the experimental data and present the preliminary results.

1 Introduction

The elastic and inelastic differential cross sections of medium heavy nuclei have been thoroughly investigated in the last two decades. More recently, the interest on this subject has re-emerged in connection with observed irregular fluctuations in the cross sections considered as manifestations of the chaotic behavior that under certain circumstances is predicted by classical approaches.

The transition between ordered and disordered motion in the vicinity of the Coulomb barrier predicted by classical analysis has been explored for the ^{40}Ca+^{40}Ca system at 60 MeV as an example [1]. However, the results are essentially unmodified if other appropriate systems are considered. In fact, quantum mechanical manifestations of chaotic behavior have been studied employing detailed coupled-channel calculations in different nuclear systems such as ^{16}O+^{28}Si and ^{24}Mg+^{28}Si [2], [3].

The most noticeable result of these investigations has been the existence of well differentiated patterns of the scattering cross sections that are in clear correspondence with classical chaotic or non-chaotic (regular) regimes. The distinction becomes apparent only when the cross sections are displayed as a function of two variables: the bombarding energy and the scattering angle. An additional requirement is that, in the measurements, the energy and angle steps be fine enough and that the two-dimensional range be large enough in comparison with the typical size of the characteristic structures.

As an example, Fig. 1 shows the results of coupled channel calculations, taken from [2], for the scattering to the 2^+ excited state at 1.78 MeV of ^{28}Si in the ^{16}O+^{28}Si system. At the top (regular regime) and bottom (chaotic regime) panels of Fig. 1, one can observe two different cross-section patterns which are interpreted in terms of regular and chaotic behavior in the corresponding classical picture. The corresponding panels of Fig. 2 (top: regular regime, bottom: chaotic regime) show a representation of the previously measured experimental data, obtained from [4], and displayed in a suitable way to be compared with the results of the coupled channel calculations shown in Fig. 1. Ranges of angles and bombarding energies that provide evidence for the two regimes are considered. The qualitative aspect of the resulting patterns, as well as their evaluation via a mathematical procedure which is particularly sensitive to the relevant differences [4], [5], lead to the tentative conclusion that both types of behavior do appear, although an unambiguous confirmation is still lacking.

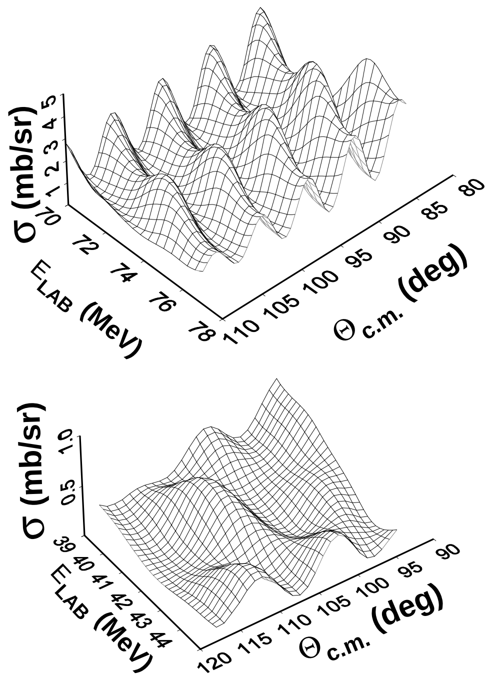

Figure 1. Results of coupled channel calculations of differential cross sections taken from Ref. [2] for the inelastic scattering to the 2^+ excited state at 1.78 MeV of ^{28}Si in the $^{16}O +^{28} Si$ system.

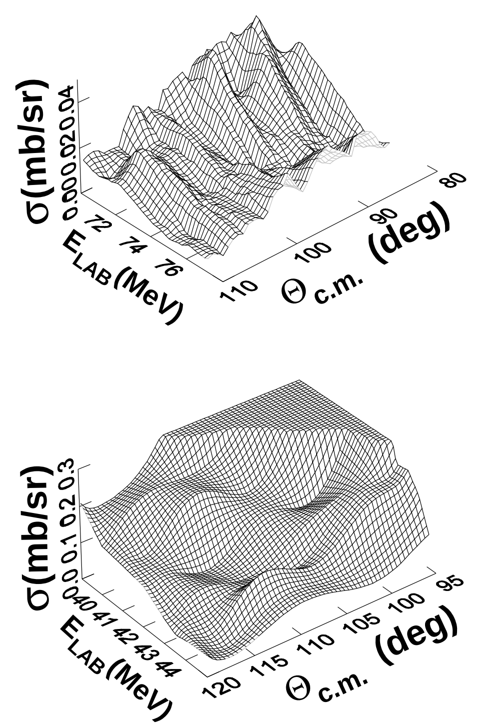

Figure 2. Representation of the differential cross sections for the inelastic scattering to the 2^+ excited state at 1.78 MeV of ^{28}Si in the $^{16}O +^{28} Si$ system based on the experimental data reported in Ref. [4].

2 Motivation

According to these remarks, several experimental aspects deserve substantial improvement. One of them is the possibility of carrying out measurements of wider angular distributions (i.e., simultaneous measurements over a large range of scattering angles) with improved geometric efficiency (i.e. large fraction of the whole range of azimuthal angles). The simultaneous measurement of all angles of interest is extremely important if one takes into account that the search for a definite pattern and structures can be seriously affected by matching problems that can arise when different runs are involved. In addition, large efficiencies are essential to be able to cover extended angular and energy ranges (as required for an adequate visualization of the characteristic patterns) using thin targets (suitable for the identification of individual states). An additional experimental improvement is required for the identification of the individual channels and the achievement of a better separation from the background. Kinematical coincidences of binary events are usually enough for these purposes, although the quality of the separation may vary significantly depending on the angular region under consideration. The coincident gamma rays measured with Gammasphere, will provide the suitable selection for the inelastic channels in their final states. The extension of the investigation to the case of scattering to excited states other than the first one is expected to provide additional useful information.

The aim of this work is to measure inelastic scattering angular distributions leading to the 2^+ (1.78MeV) excited states of ^{28}Si for the $^{16}O +^{28} Si$ system in two energy regions; one close to the Coulomb barrier (40-46 MeV) and the other well above (71-73-75 MeV) with precise angular information in the whole range of the scattering angles.

3 Experiments

The experiments were carried out at the Lawrence Berkeley National Laboratory. Beams of ^{16}O were provided by the 88” Cyclotron at energies from 40 to 46 Mev (“chaotic” region) in one MeV steps, and at 71 MeV, 73 MeV, and 75 MeV (“regular” region). The experiment consisted of a series of approximately 4-hour shifts per energy. The detection arrangement consisted of the Compact Heavy-Ion Counter (CHICO) [6] combined with the multidetector array Gammasphere [7]. This experimental setup meets most of the above-mentioned requirements. The particles emited in the angular range 20°-168° were detected by CHICO; from the data obtained using this detector one can obtain the following information: the scattering angle with respect to the beam direction Θ, the azimuthal angle Φ, and the difference between the time-of-flight of the two emerging nuclei following the binary reaction. In addition to kinematical considerations, the desired events are also selected via the detection of coincident gamma rays using

Gammasphere. The trigger requirement was either scaled-down particle-particle singles for normalization purposes, or three-fold particle-particle-gamma-ray coincidences for the forward hemisphere, or two-fold particle-gamma-ray coincidences for the backward hemisphere.

4 Data analysis and experimental results

The procedure to obtain the angular distributions is summarized in Fig. 3 through Fig. 5. Panels a) and b) of Fig. 3 show a region of a gamma-ray spectrum before and after Doppler shift correction, respectively. In addition, the Doppler shift corrected spectrum of panel 3b) displays the gating condition to obtain the events in coincidence with the 1.78 MeV γ-ray transition deexciting the 2^+ excited level in ^{28}Si, and Fig. 4 is the corresponding two dimensional angular plot obtained for binary reaction products. The indicated gating condition in this spectrum selects the reaction products of interest (oxygen and silicon) as shown in the mass distribution spectrum shown in Fig. 5. After gating on mass 16, the oxygen-branch of the two dimensional plot shown in Fig. 4 projected on either axis yield the desired laboratory angular distributions.

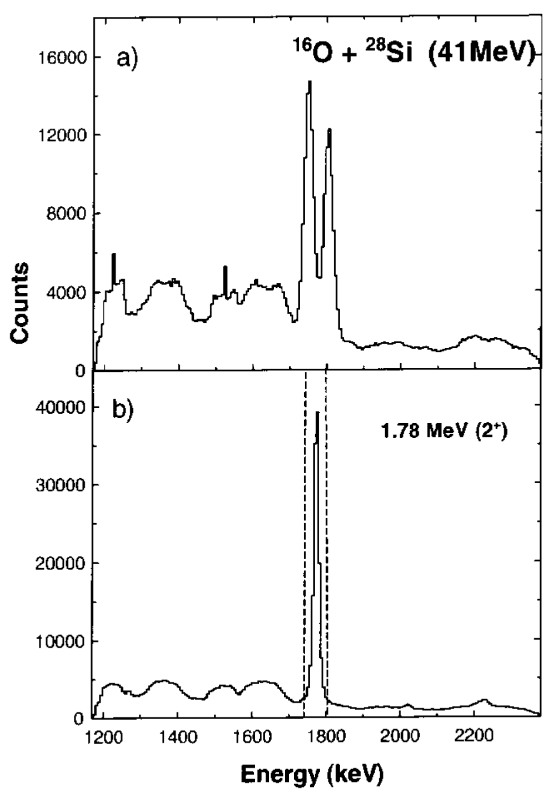

Figure 3. A region of a γ-ray spectrum; a) before Doppler shift correction and b) after Doppler Shift correction. Panel b) includes the gating condition to obtain the events in coincidence with the 1.78 MeV γ-ray transition deexciting the 2^+ excited level in ^{28}Si.

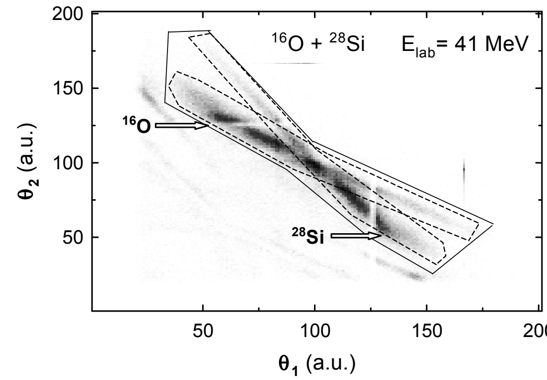

Figure 4. Coincident two-dimensional angular plot obtained for binary-reaction products. The gating condition in this spectrum selects the reaction products of interest (oxygen and silicon).

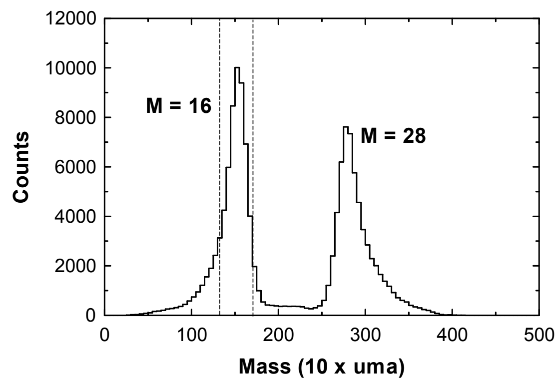

Figure 5. Mass distribution obtained through the gating condition displayed in the spectrum shown in Fig. 4.

When analyzing the preliminary results (angular distributions) reported in this section, it is worth keeping in mind that the ultimate purpose of this experiment is to describe the qualitative behavior of the two-dimensional maps of the cross sections as a function of both energy and scattering angle (as those shown in Fig. 1 and Fig. 2). Hence it is very important to obtain reliable descriptions of the positions and shapes of the relevant structures that appear in these maps, rather than extremely accurate absolute values for individual data points. The results obtained up to the present stage of the analysis are summarized in Fig. 6 which shows in a condensed format the angular distributions as a function of the centre of mass scattering angle for the energy range 40-46 MeV (chaotic regime). The analysis of the data corresponding to a) scattering to the backward hemisphere of CHICO and b) projectile energies around 70 MeV (above barrier) are still in progress.

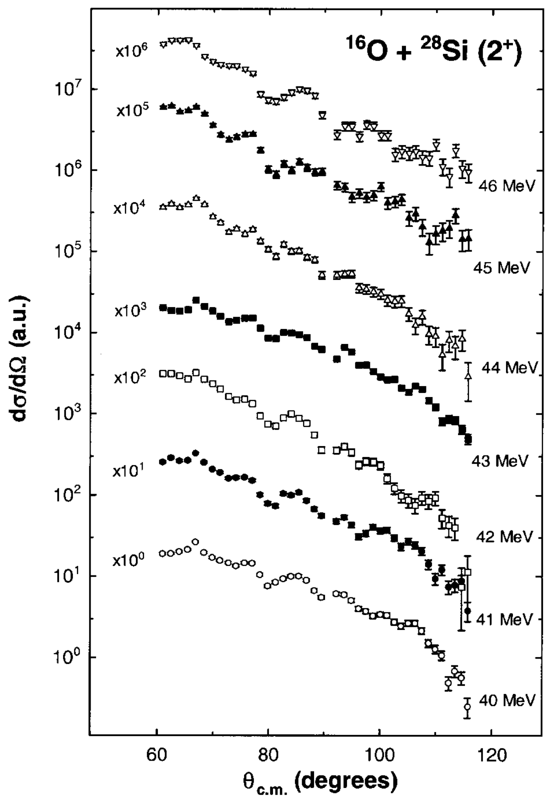

Figure 6. Angular distributions obtained in this work at all the bombarding energies analyzed so far which correspond to the low energy regime.

The angular distributions displayed in Fig. 6 correspond to the inelastic scattering that populates the 2^+ (1.78 MeV) state of ^{28}Si, and they have been obtained from projections of two-dimensional maps of the type shown in Fig. 4 for the Oxigen branch onto the Θ_1 axis. In all cases the error bars of the data points of the present work correspond to statistical uncertainties. The data were normalized at the cross-section value corresponding to 84° and 41 MeV angular distribution of Ref [8], and multiplied by a constant factor(see Fig. 6, left-hand side) at each energy in order to improve the visualization.

In connection with the discussion above, Fig. 6 summarizes the angular distributions obtained at all the bombarding energies that have been analyzed so far. These angular distributions, together with the ones still lacking for the backward hemisphere and for the high-energy region, will furnish the basic experimental ingredients for the subsequent evaluation of evidence for regular or chaotic behavior.

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