Resonant elastic scattering of $\alpha$ particles on $^9$Be and cluster states in $^{13}$C

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Abstract. We discuss the preliminary results obtained by studying the $\alpha + ^9$Be elastic scattering at bombarding energies from 3.5 to 10 MeV. Experimental spectra show the presence of elastic and inelastic scattering phenomena. Elastic scattering excitation functions have been obtained at various angles; their shape is in good agreement with data at backward angles reported in the literature.

1. Introduction

An important topic in Nuclear Physics concerns the investigation on the possible presence of $\alpha$ cluster structure in light nuclei [1]. This aspect plays a fundamental role in the description of the structure of light self-conjugated nuclei (such as $^8$Be, $^{12}$C, $^{16}$O, $^{20}$Ne), for which the study on the existence of $\alpha$ cluster states with large deformation has been the subject of many investigations since long time ago. Recently, accurate studies on $^{12}$C spectroscopy pointed out the possible existence of a rotational band built on the (very-intriguing) Hoyle state [2]. Furthermore, it has been suggested that $\alpha$ cluster effects can also arise in neutron rich isotopes of beryllium, carbon, oxygen and neon [3]. For example, a clear molecular structure of $^9$Be, that is characterized by very large deformation [4], has been evidenced by investigating rotational states characterizing the level scheme of this nucleus [5, 6].

Other interesting physics cases are constituted by $^{13}$C and other, more neutron rich, carbon isotopes. As observed in [7], the spectroscopy of the states in $^{13}$C around and above the $\alpha$ emission threshold shows some recurrences that could suggest the existence of rotational bands associated to large-deformation molecular-like configurations. Unfortunately, many ambiguities in $J^\pi$ assignments do exist for $^{13}$C high-lying states (especially in the excitation energy region between 12 and 18 MeV, containing some members of the suggested rotational bands). In order to clarify this interesting question, an improved spectroscopic evaluation of high-lying $^{13}$C states is needed. To populate excited states that are characterized by large $\alpha$ structure, the most suited nuclear reactions seem to be the $\alpha$-transfer (as the $^9$Be($^6$Li,d)$^{13}$C, [8, 9]) and the Resonant Elastic Scattering $^9$Be($\alpha,\alpha)^9$Be. In the last case, experimental excitation functions of $^9$Be($\alpha,\alpha)^9$Be scattering, obtained both in direct kinematics and with the Thick Target Inverse Kinematic (TTIK) method, have been reported [10, 11]. Data have been analyzed by means of Blatt-Biedenharn or $R$-matrix formalisms, thus contributing to improve the spectroscopy of $^{13}$C states. In order to enlarge the experimental investigation on this topic, we performed a new
resonant elastic scattering experiment $\alpha + ^9\text{Be}$ in direct kinematics, in the bombarding energy range from 3.5 to 10 MeV. Excitation functions have been obtained at various polar angles. The preliminary results of this experiment will be discussed in the following sections.

2. Experimental Setup

The experiment has been performed at the TTT-3 Tandem facility of the University of Naples Federico II [12]. After magnetic analysis, $^4\text{He}^{++}$ beams of energies ranging from 3.5 up to 10 MeV bombarded a self-supporting $^9\text{Be}$ target (0.66 $\mu\text{m}$ thick). The beam energy was varied at 60 keV steps in order to obtain suitable excitation functions. The beam energy spread was of the order of 1 per thousand. Beam current was of the order of 10 enA, and was measured by a Faraday cup followed by a current integrator. Ejectiles have been detected at various angles (principally in the backward hemisphere) by means of 10 collimated silicon detectors, their resolution being 0.7-1.0% for the 5.48 MeV peak of a standard $\alpha$ source. Data have been stored in memory for subsequent analysis, and dead-time corrections have been applied to calculate absolute differential cross sections.

3. Preliminary results

An example of experimental spectra obtained at 70° and 150° is reported in Figure 1. The strongest peak in both spectra is due to the elastic scattering of $\alpha$ particles by the $^9\text{Be}$ layer. The two peaks at higher energies are due to the elastic scattering of $\alpha$ particles by carbon and oxygen contaminants, that are present both in the back and front face of the target. Due to the combination of kinematics and energy loss effects, the scattering by the front and back contaminants becomes explicitly visible at backward scattering angles, as we can see in the 150° spectrum, presented in Figure 1. The nature of the carbon and oxygen contaminants is confirmed by studying the trends of excitation functions obtained from peaks corresponding to the scattering on the front contaminants; they are very similar to those reported in the literature for the $\alpha + ^{12}\text{C}$ and $\alpha + ^{16}\text{O}$ elastic scattering. The low energy products observed at 70° are due to inelastic scattering of $\alpha$ particles on $^9\text{Be}$ and $^{12}\text{C}$. In particular, the peak associated to the $^9\text{Be}(\alpha,\alpha_2)$ scattering is clearly recognized.
Starting from the experimental spectra, it is possible to obtain the excitation functions for the $\alpha + ^9$Be elastic scattering process at various scattering angles. As an example, in Figure 1 (right panel) we report the $160^\circ$ and $135^\circ$ excitation functions, together with the results of Goss et al ([10], 157.3°, direct kinematics). As we can observe, the shapes of the excitation functions at around $160^\circ$ are in good agreement. In particular, a strong peak is observed at 5.05 MeV and a large bump at around 5.88 MeV. The first state corresponds to a member of the $K = \frac{3}{2}^-$ proposed rotational band [7] at $^{13}$C excitation energy of 14.13 MeV. Assignment of spin-parity for this level is quite ambiguous [10, 11, 13]. In the systematics [13], it is reported as a $\frac{7}{2}^+$ state, while in Ref. [10], the existence of a doublet of states at 14.11 and 14.16 MeV in $^{13}$C is claimed, with $J^\pi = \frac{5}{2}^-$ and $\frac{7}{2}^+$ assignments respectively. In the more recent paper by [11], the trend of the $180^\circ$ elastic scattering excitation function in correspondence of the 5 MeV bump is nicely reproduced by $R$-matrix calculations performed by assuming a single state at 14.13 MeV excitation energy, having $J^\pi = \frac{5}{2}^-$. The large bump at around 5.88 MeV would correspond to a state with excitation energy around 14.72 MeV. This state has not been reported in the systematics [13] but has been observed in $^9$Be($\alpha,\alpha$)$^9$Be [11] and $^8$Be($^6$Li,$d$)$^{13}$C reactions [8]. We plan to perform $R$-matrix fit of our experimental excitation functions, obtained at various angles (from 70 to 160° in the lab. frame), in order to extract refined spectroscopic evaluations of high-lying excited states in $^{13}$C that could be of interest to unveil the (possible) cluster structure in such non self-conjugated nucleus.

4. Conclusions

In this paper we report preliminary results obtained by studying the scattering of $\alpha$ particles on $^9$Be. The experiment has been performed by using a $^4$He beam with energies from 3.5 to 10 MeV, and by varying the energy at 60 keV energy step. Experimental spectra, taken at various polar angles, show clearly the presence of elastic and inelastic scattering events. Excitation functions of the elastic scattering process $\alpha + ^9$Be have been obtained at various angles. Their shape is in good agreement with data at backward angles reported in the literature and obtained both by using the direct kinematics method and the TTIK method. Many anomalies are clearly visible in the excitation functions. An analysis performed in term of the $R$-matrix model would allow to improve the spectroscopy of the $^{13}$C compound nucleus in an excitation energy region where the possible existence of rotational bands, due to the molecular structure of this nucleus, has been suggested.

Acknowledgments

We acknowledge A. Brondi, E. Perillo and D. Pierrouatskou for their support. We are indebted to C. Marchetta and E. Costa for providing us $^9$Be targets.

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