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Revisiting the ^{4}He(^{4}He,^{4}He)^{4}He* inelastic scattering at the MAGNEX facility

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Abstract. The ^{4}He(^{4}He,^{4}He)^{4}He* inelastic scattering was investigated at the MAGNEX facility of INFN - LNS, aiming at shedding light on the characteristics of the isoscalar monopole resonance of ^{4}He which lies at an energy slightly higher than the proton emission threshold and slightly lower than the neutron emission threshold. A complementary elastic scattering measurement was also performed to study the initial state interaction and set accurate coupled channel calculations. Here, the experimental setup, the data reduction and the theoretical interpretation strategy are briefly described.

1. Introduction

The ^{4}He nucleus is one of the simplest nuclear systems and one of the two stable helium isotopes (the other one is the ^{3}He). The most abundant helium isotope, ^{4}He, was produced in large quantities during Big Bang Nucleosynthesis while, its production continues on stars by nuclear fusion processes. The ^{4}He production in Earth is also fed by the α decay process of heavy radioactive elements. This nucleus is considered to be well bound, presenting a binding energy of 19.813 MeV for the ^{3}H + ^{1}H configuration, rising to 20.578 MeV for the ^{3}He + n, and even higher binding energies for other configurations. Regarding the ^{4}He level scheme, it should be mentioned that no bound states are present [1] however, a pronounced resonance with the same spin and parity (0^{+}) as the ground state exists with a centroid slightly above the proton emission energy threshold (S(p)= 19.813 MeV). Although several works have been devoted to the study of the 0^{+} first excited state of ^{4}He by using (e,e') [2, 3, 4, 5] or (^{4}He,^{4}He) probes [6, 7], many of its properties remain unclear. In more details, different values for the resonance centroid and width are met in the literature. Also, the resonance width measured from previous (^{4}He,^{4}He) studies is larger than that obtained from the (e,e') ones.

Recently, a puzzling inconsistency between ab-initio form factor calculations and the existing data from ^{4}He(e,e')^{4}He* was reported by S. Bacca et al.[8] calling for further investigation of the subject. In another recent theoretical work by Y. Kucuk et al. [9], the differential cross section angular distributions for the first excited state of ^{4}He (0^{+}) were calculated for the bombarding energy of 64 MeV by applying both macroscopic and microscopic models for the form factors. Additionally, L. C. Chamon et al. in [10] systematically analysed existing ^{4}He(^{4}He,^{4}He)^{4}He elastic scattering data at low energies where all reaction channels are closed. In this case, the real part of the optical potential has the leading role in the interpretation of the elastic scattering angular distribution. In a second step, this framework may be extended in an energy regime where only a few reaction channels are energetically available aiming to study coupling phenomena between elastic and non - elastic channels.

Taking into consideration all the above, an experimental exploration was performed for both the ^{4}He(^{4}He,^{4}He)^{4}He elastic and the ^{4}He(^{4}He,^{4}He)^{4}He* inelastic scattering channel to the first excited state (0^{+}) of ^{4}He, at the incident energy of 53 MeV ($E_{c.m.}$ = 26.5 MeV) aiming:

- to extract the characteristics of the 0^{+} resonance in a new exclusive measurement with very good energy and angular resolution in the MAGNEX facility,
- to resolve previous reported inconsistencies related to resonance energy and width between (e,e') and (^{4}He,^{4}He) data,
- to perform a global interpretation of inelastic together with the elastic scattering channel, measured simultaneously under the same experimental conditions, in a bombarding energy where only a few reaction channels are energetically allowed.

2. Experimental details

Two experiments were performed at the MAGNEX facility[11] of the Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. The experiment I was dedicated to the elastic scattering measurement in a wide angular range while, the experiment II was devoted to the inelastic scattering. An additional data set of elastic scattering was taken in the second experiment (II) with conditions similar to the first one (I) to cross check the data with those from the (I). The ^{4}He beam was accelerated by the K800 Superconducting Cyclotron at 53.0 MeV (13.2A MeV) incident energy and impinged on a target where the ^{4}He atoms were implanted in a thin metal foil (see Table 1). More details may be found in [12].

The elastic scattering measurement was performed by detecting the ^{4}He ejectiles in the MAGNEX Focal Plane Detector (FPD) [13] which consists of a gas tracker followed by a wall of 60 single silicon detectors. The gas tracker includes six sections allowing the measurement of the horizontal position (X_{foc}) and angle (θ_{foc}) as well as the vertical position (Y_{foc}) and angle (ϕ_{foc}). The energy loss (ΔE) of the ions inside the gas and the residual energy at the silicon detectors were also measured.

The inelastic scattering was investigated by performing a coincidence measurement between the inelastically scattered ^{4}He particles and one of the breakup fragments of the second ^{4}He particle (^{3}H or ^{3}He). Our study was designed such as to measure a large fraction of the continuum

Table 1. Thicknesses of the targets used.

experiment I		experiment II	
Target composition	Thickness (atoms/cm^2)	Target composition	Thickness (atoms/cm^2)
^{4}He	3.7 E+17	^{4}He	1.9 E+17
^{181}Ta	3.2 E+18	^{27}Al	4.6 E+18
^{16}O	5.5 E+17	^{16}O	1.0 E+17
		^{12}C	1.2 E+16

phase space for both the ^{3}H – ^{1}H (E$_{thresh.}$ = 19.813 MeV) and ^{3}He – n modes (E$_{thresh.}$ = 20.578 MeV). The ^{4}He ejectiles were momentum analyzed by the MAGNEX spectrometer [11] spanning an angular range between 2° and 12°. The energy acceptance of the spectrometer allowed the measurement of the ^{4}He ejectiles with a kinetic energy between 20.8 and 34.0 MeV corresponding to an excitation energy (E^*) up to 4.5 MeV above the ^{4}He breakup threshold. The ^{4}He ions were detected by the MAGNEX FPD while, the ^{3}H and ^{3}He fragments were detected by the OSCAR (hOdoscope of Silicons for Correlations and Analysis of Reactions) telescope detection assembly [14]. OSCAR is an array of a Single Sided Silicon Strip Detector (SSSSD), 20μm thick, measuring the energy loss ΔE, followed by 16 Silicon pads (arranged in a 4x4 mode), 300μm thick, which measure the ions residual energy. The OSCAR system was mounted at the scattering chamber of the MAGNEX facility, 15 cm far from the target, subtending an angular range between 19° and 38° with an angular resolution of about 1°.

3. Data reduction

After the successful identification (PID) of the detected ions in both MAGNEX and OSCAR obtained as described in [12], a 10th order reconstruction of the non-linear ejectiles trajectories impinging in the MAGNEX FPD was performed [15], based on measured magnetic fields maps [16, 17]. This technique allows to obtain the kinetic energy, the scattering angle, and the excitation energy spectra. The elastic scattering yields were determined with an angular step of 0.5° in MAGNEX over the angular range $6.5° \leq \theta_{lab} \leq 45°$ corresponding to $13° \leq \theta_{c.m.} \leq 90°$. The inelastic scattering exclusive yields were deduced for an angular step of 2° in MAGNEX over the angular range $2° \leq \theta_{lab} \leq 12°$, combined with the whole OSCAR telescope. The background due to target contaminants was negligible in the coincidence measurement however, it was subtracted using the data obtained in a measurement with a target composed of aluminum, oxygen and carbon in the appropriate proportions for the background estimation

An important aspect related to the extraction of inelastic scattering differential cross sections from the exclusive measurement was the estimation of the efficiency of the detection system. To this extent, the Monte Carlo simulation algorithm MULTIP [18] was used since it is a powerful tool for simulating the energy and angular profiles in two–, three– and four–body reactions kinematics and its validity has been tested in several previous works for many reactions (e.g. see [19, 20, 21]).

An observed asymmetry in the energy profile of the ^{4}He (0^+) resonance motivated an interpretation using the Fano function [22], a framework which was successfully applied in the case of ^{10}Li ($1/2^-$) resonance [23], lying also in an energy slightly above the breakup threshold. In this framework the cross section in the region of the resonance is given as $\sigma = \sigma_{cont} \left|q+\epsilon\right|^2 / (1+\epsilon^2)$, where σ_{cont} is the inelastic cross section of the non-resonant continuum, ϵ=$2(E-E_r)/\Gamma_r$ incorporates the resonance centre E_r and width Γ_r. The line shape is controlled by the Fano parameter q and reflects the interference of the resonant and non-resonant contributions. The deduced angular distribution cross section data for both the elastic and inelastic scattering channels will be considered in a global approach in a coupled - channels calculation framework. The theoretical interpretation of the data is in progress.

4. Summary

The ^{4}He(^{4}He,^{4}He)^{4}He* inelastic scattering was revisited in a new measurement performed in the MAGNEX facility of INFN - LNS, aiming at shedding light on the characteristics of the isoscalar monopole resonance of ^{4}He. The data interpretation, which is in progress, includes an analysis based on the Fano function motivated by the observed asymmetry in the energy profile of the resonance, as well as coupled - channels calculations considering both the elastic (experiment I & II) and inelastic scattering (experiment II) angular distribution data in a global study.

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