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States of ^{14}C and ^{15}C via the (^{18}O,^{16}O) two-neutron transfer reaction at 84 MeV

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Abstract. A study of the ^{14}C and ^{15}C states was pursued at the Catania INFN-LNS laboratory by the ^{12}C(^{18}O,^{16}O)^{14}C and ^{13}C(^{18}O,^{16}O)^{15}C reactions at 84 MeV incident energy. The ^{16}O ejectiles were detected at forward angles by the MAGNEX magnetic spectrometer. Exploiting the large momentum acceptance (20%) and solid angle (50 msr) of the spectrometer, energy spectra were obtained with a relevant yield up to 20 MeV excitation energy. The application of the powerful trajectory reconstruction technique did allow to get energy spectra and angular distributions with resolution of about 160 keV and 0.3°. In the energy spectra several known low lying states of ^{14}C and ^{15}C have been observed and some unknown resonant structures at about 10.5 and 13.6 MeV in ^{15}C and 16 MeV in ^{14}C appear.

1. Introduction

Two-neutron transfer reactions are essential tools to investigate the structure of atomic nuclei thanks to their strong selectivity to specific modes of nuclear excitation and their role in emphasizing n-n correlations such as the pairing force [1-3].

This is valid if the direct transfer of a cluster of two neutrons is dominant with respect to other more complicated multi-step mechanisms. Normally this cluster transfer takes place when light projectiles such as tritons are used and the reaction products are detected at forward angles, this is true. When heavier projectiles are dealt with, the situation typically becomes more involved.

However in particular projectile-target systems and in specific energetic conditions the correlation between the transferred nucleons is strong and the one-step mechanism should prevail. The interplay of the two processes one-step and multi-step can represent a key point in the understanding of pairing correlations in nuclei.

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2. The experiment

The experiment was performed at INFN – Laboratori Nazionali del Sud (Italy). The ^{18}O beam, delivered by the Tandem Van der Graaff accelerator at 84 MeV, was focused on two self-supporting targets located in the MAGNEX scattering chamber: a 99% enriched ^{13}C target and a ^{12}C target (both 50 μg/cm^2 thick). The ^{16}O ejectiles were momentum analyzed by the MAGNEX spectrometer [4, 5] and detected by the Focal Plane Detector (FPD) [6, 7]. In the different experimental runs, the optical axis of the spectrometer was centred at the laboratory angles θ_{opt} = 6°, 12°, 18°, 24°. In all the runs the ejectiles trajectory were accepted between -5.2° and +6.3° in the horizontal direction and ± 7.0° in the vertical, with respect to the optical axis. In such a way an angular range between 3° and 30° was measured in the laboratory frame with overlaps of about 6° between two contiguous sets of measurements.

A system of diaphragms was used in order to limit the beam spot size and the angular divergence at the target to 1.2 mm × 0.8 mr in the horizontal direction and 2.3 mm × 3 mr in the vertical one. In such conditions, the contribution of the beam divergence to the overall energy spreading is maintained low. Particular care has been taken in aligning the diaphragm system to guarantee that the beam intercepts the target along the spectrometer optical axis, thus getting the best resolution.

The FPD was filled with 99.95% pure isobutane at 7 mbar pressure. A voltage of -1100 V was applied to the cathode while the multiplication wires were supplied with +650 V in order to maintain a proportional regime with a gain factor of about 200. In such working conditions the FPD allows to cleanly identify the detected ions in atomic (Z) and mass (A) number and electric charge (q), and to precisely measure the horizontal and vertical impact position (X_f, Y_f) and direction (θ_f, ϕ_f) of the ions trajectory in the focal plane [8].

3. Data reduction and spectra features

The first step of the MAGNEX data reduction procedure is to build a transport map that describes the evolution of the phase-space parameters from the target point to the focal plane. As discussed in recent publications [9, 10], in the MAGNEX case, the transport equations are solved by an algebraic technique based on the formalism of differential algebra [11, 12] implemented in the COSY INFINITY program [13]. Such a technique allows calculating the map up to high order without long ray-tracing procedures. In addition it makes possible to invert the transport equations in order to get the initial coordinates from the measured final ones. The initial parameters extracted from the solution of the inverse equation are directly related to the physical quantities of interest in a typical nuclear reaction analysis, as the modulus of the ion momentum and the scattering angle.

A precise reconstruction of the ions kinetic energy is one of the ingredients of the innovative technique to identify the reaction ejectiles crossing the spectrometer, described in detail in Ref. [14]. Such a technique is based on a standard $\Delta E - E$ method for the Z identification with a resolution $\Delta Z/Z$ = 1/48. The ΔE parameter is corrected for the actual length of the ion trajectory along the active region of the FPD. Mass identification is achieved thanks to the simultaneous measurement of the kinetic energy T and the reconstructed fractional momentum δ of the detected ions. In Ref. [14] it has been shown that this technique allows to obtain a clear identification of the detected ions with a mass resolution as high as $\Delta A/A$ = 1/160.

Once the ^{16}O^{8+} ejectiles are selected, the measured horizontal and vertical positions and angles at the focal plane are analyzed.

The ray-reconstruction algorithms have been used to build the transport map to 10th order. In the COSY INFINITY input, the geometry of the spectrometer (distances between the magnetic elements, length of the drift spaces, slits defining the solid angle) and the size and location of the FPD are set as the experimental ones. The dipole and quadrupole magnetic strengths have been measured by probes with an overall uncertainty of about ±0.1% (including the uncertainty in the probes position). The three-dimensional field shapes are described as Enge functions [15] obtained from interpolations of measured data, which account for the shape of the effective boundaries by 5th order polynomials [16 - 19].

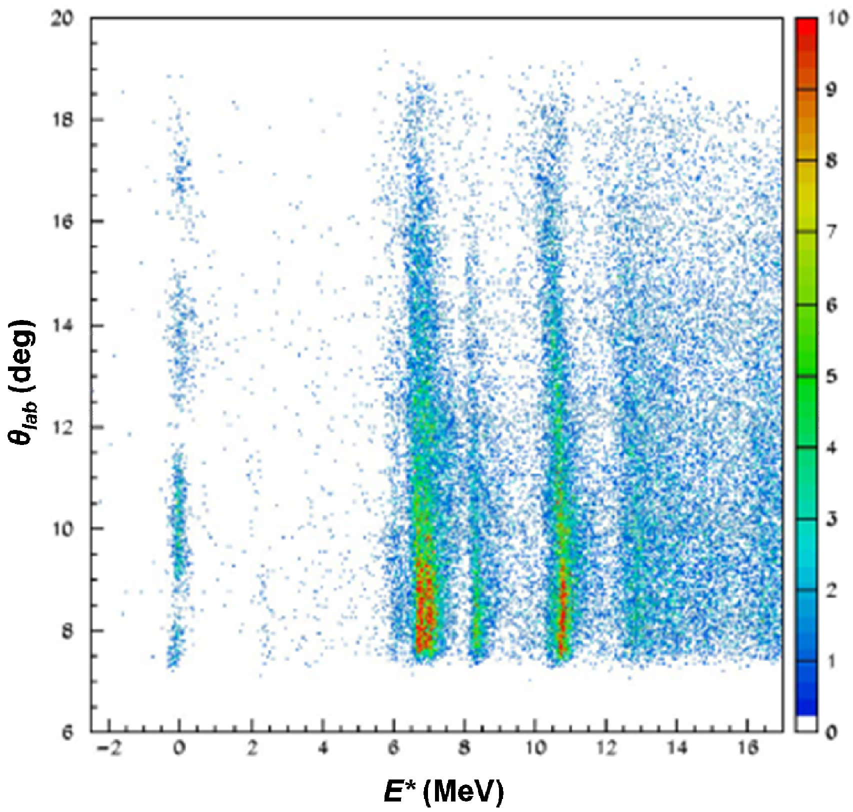

Figure 1. Two-dimensional plot of the reconstructed θ_{lab} against the ^{14}C apparent excitation energy E^* for the ^{12}C(^{18}O, ^{16}O)^{13}C reaction at 84 MeV.

Fig. 1 shows an example of reconstructed parameters for the $^{16}O^{8+}$ reaction ejectiles. In particular the scattering angle θ_{lab} is shown against the ^{14}C apparent excitation energy $E^* = Q_0 - Q$ (where Q_0 is the ground to ground state Q-value). The ^{14}C ground and several excited states are well visible as vertical and straight loci, as expected since the E^* parameter is not depending on the scattering angle for transitions to the ^{14}C states. It is interesting to notice that the oscillating pattern of the angular distribution for the transition to the $^{14}C_{g.s.}$ can be observed even in the two-dimensional plot.

A projection of the data on x axis provides more quantitative information on the excitation energy spectrum shape. An example is shown in Fig. 2 for the ^{12}C(^{18}O,^{16}O)^{14}C at 9.5° < θ_{lab} < 10.5°. Several excited states of ^{14}C are populated for which the spin and parity are well known from previous (t,p) reactions [20, 21]. The angular momentum transfer is also well identified for such transitions as listed in Ref. [20, 21]. For example it is well known that the ground state and the states at 7.01 and 10.74 MeV have a dominant configurations with a pair of two neutrons with L = 0, 2 and 4 respectively on a ^{12}C 0^+ core. These states are strongly populated through this reaction.

It is very interesting to note that this spectrum appears very similar to the ones excited with (t,p) reactions indicating a strong selectivity of the (^{18}O,^{16}O). Another interesting feature is the appearance of an unknown structure at about 16 MeV. Further studies regarding the nature of such a structure are foreseen including the analysis of the angular distribution.

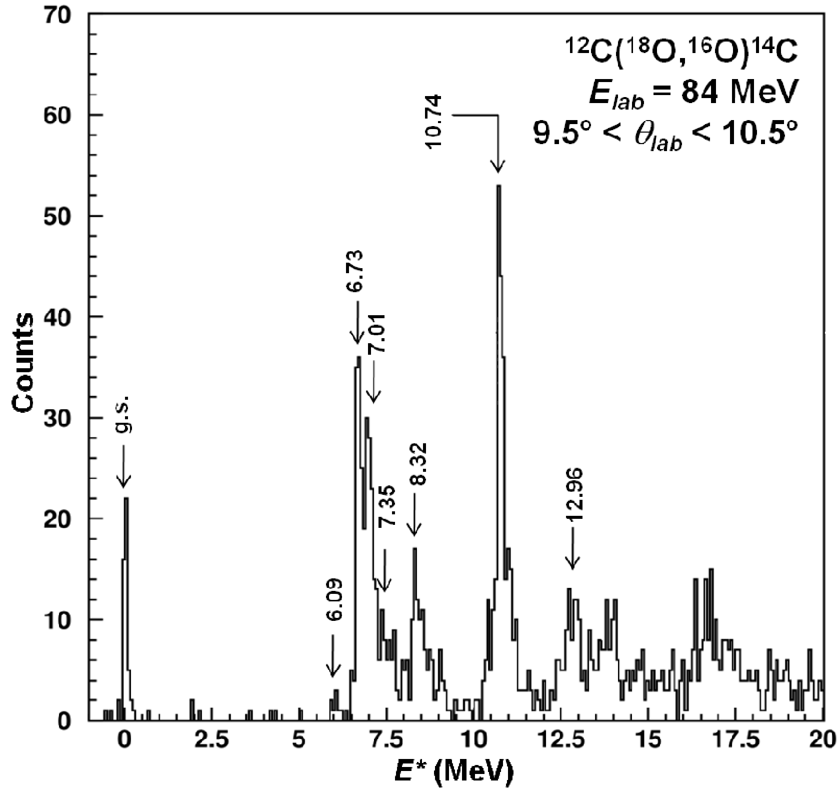

Figure 2. One-dimensional spectrum of the reconstructed ^{14}C excitation energy for the selected $^{16}O^{8+}$ ions of the reaction $^{12}C(^{18}O,^{16}O)^{14}C$ in the angular range 9.5° < θ_{lab} < 10.5°.

The energy spectrum for the $^{13}C(^{18}O,^{16}O)^{15}C$ reaction in the angular range 9° < θ_{lab} < 12° is shown in Fig. 3. Two narrow states of the ^{15}C are recognized below the one neutron separation energy (S_n = 1.218 MeV), namely the ground and the only bound excited state at 0.74 MeV. These have a well known single-particle configuration with the valence neutron in the $2s_{1/2}$ and $1d_{5/2}$ shell respectively over a ^{14}C 0^+ ground state core.

Above the one neutron separation threshold, narrow resonances at excitation energy of E_x = 3.10, 4.22 4.66, 6.84 7.35, MeV [22] are clearly identified. Such states are typically labeled as 2p-3h configurations and are strongly excited also by the (t,p) reaction reported by Truong and Fortune [22].

Above the two neutron threshold (S_{2n} = 9.394 MeV) two large unknown structures are strongly excited at energies E_x = 10.5 and 13.6 MeV over a continuously distributed shape due to the three-body and four-body phase-space. A more detailed analysis of the two-neutron transfer on the ^{15}C continuum is going to be published elsewhere.

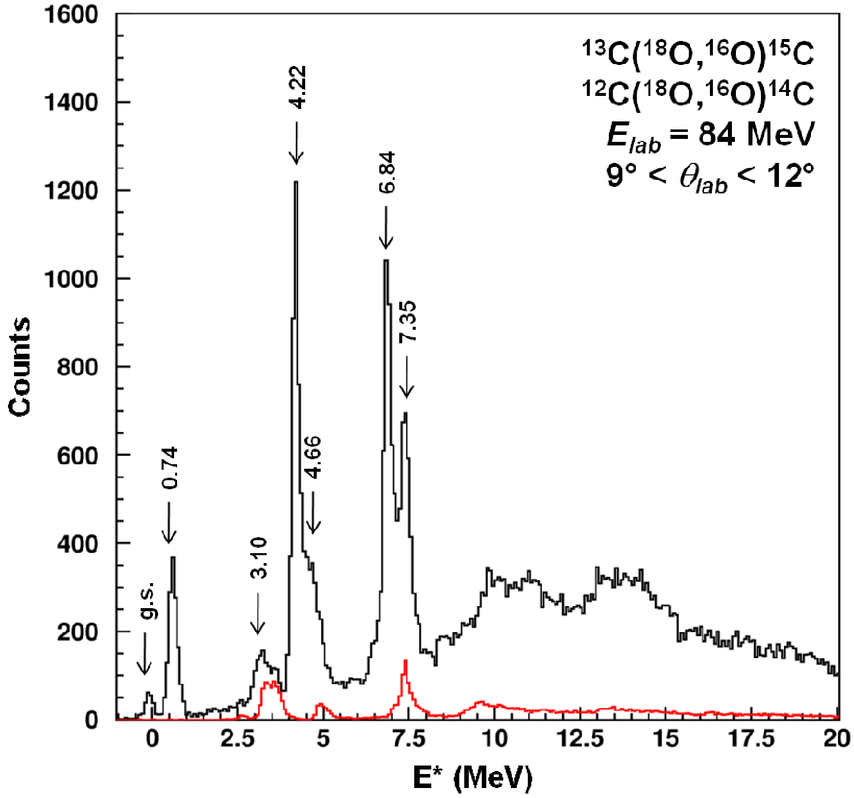

Figure 4. One-dimensional spectrum of the reconstructed ^{15}C excitation energy for the selected $^{16}O^{8+}$ ions of the reaction $^{13}C(^{18}O,^{16}O)^{15}C$ in the angular range 9° < θ_{lab} < 12°. The contribution due to the ^{12}C impurities in the ^{13}C target has been normalized and superimposed.

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