Nuclear response to two-neutron transfer via the (^{18}O,^{16}O) reaction

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A systematic study of the response of nuclei to the (^{18}O,^{16}O) two-neutron transfer reaction at 84 MeV incident energy was pursued at the Catania INFN-LNS laboratory. The experiments were performed using several solid targets from light (^{9}Be, ^{11}B, ^{12,13}C, ^{16}O, ^{28}Si) to heavier ones (^{58,64}Ni, ^{120}Sn, ^{208}Pb). The ^{16}O ejectiles were detected at forward angles by the MAGNEX magnetic spectrometer. Thanks to an innovative technique the ejectiles were identified without the need of time of flight measurements. Exploiting the large momentum acceptance (≈ 25%) and solid angle (50 msr) of the spectrometer, energy spectra were obtained with a relevant yield up to about 20 MeV excitation energy. The application of the powerful trajectory reconstruction technique did allow to get energy spectra with energy resolution of about 150 keV and angular distributions with angular resolution better than 0.3°. A common feature observed with light nuclei is the appearance of unknown resonant structures at for example 10.5 and 13.6 MeV in ^{15}C and 16 MeV in ^{14}C. The strong population of these latter together with the measured width can reveal the excitation of a collective mode connected with the transfer of a pair. The measurement of the angular distributions can indicate if a transfer of a correlated neutron pair in L = 0 configuration, compatible with the Giant Pairing Vibration mode, is involved. Theoretical calculations were performed in order to estimate the contribution of the break-up of both two correlated neutrons and two independent ones.

1. Introduction

Two-neutron transfer reactions are useful tools to study 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].

Moreover the detailed description of these transfer reactions could provide useful information to the competition between one and two-step mechanisms in the two-neutron transfer channel. In the extreme case of very strong pairing correlation the one-step mechanism is expected to prevail, instead the two-step sequential process should be dominant in the case of pure uncorrelated nucleons. If the reaction mechanism is dominated by the direct transfer of the neutron pair it is expected a strong enhancement of the $L = 0$ channel. Therefore the interplay of these two processes is crucial to understand the role of pairing correlations in nuclei and consequently to build a microscopic description of nuclei beyond the mean field approximation.

Normally the transfer of a cluster takes place when light projectiles as for example tritons are used and the reaction products are detected at forward angles. 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 could prevail.

2. The experimental set-up

The experiment was performed at the INFN – Laboratori Nazionali del Sud (Italy). The ^{18}O beam, delivered by the Tandem Van der Graaff accelerator at 84 MeV, was focused on different solid targets located in the MAGNEX scattering chamber. The ^{16}O ejectiles were momentum analyzed by the MAGNEX spectrometer [4-6] and detected by the Focal Plane Detector (FPD) [7, 8]. 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.

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_{foc}, Y_{foc}) and direction (θ_{foc}, ϕ_{foc}) of the ions trajectory in the focal plane. Such results has been described in similar experimental conditions in Ref. [9].

3. Data reduction

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 [10, 11], the transport equations are solved by a sophisticated technique based on the formalism of differential algebra [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.

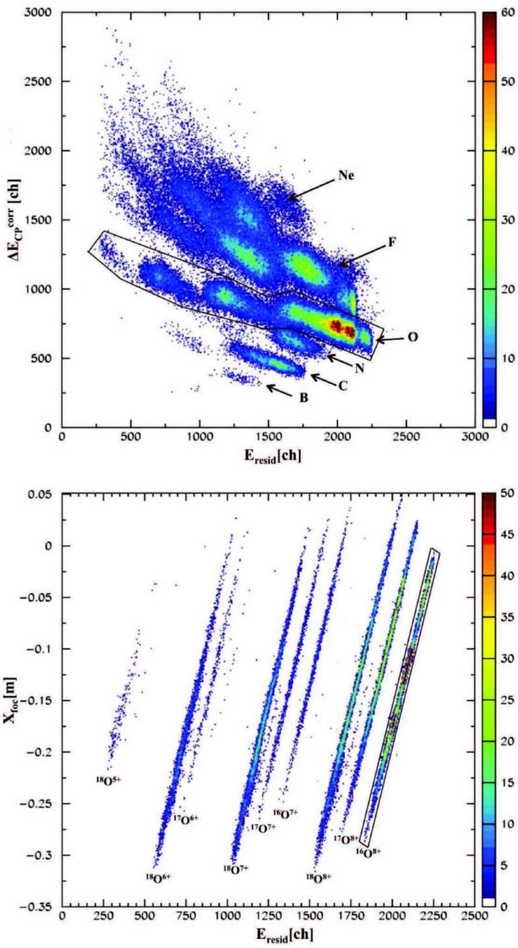

Fig. 1 Example of identification plots for the ^{18}O + ^{12}C reaction at 84 MeV. In the upper plot the energy-loss ΔE_{CP}^{corr} corrected for the measured incident angle at the focal plane is shown against the residual energy E_{resid} measured by the silicon detectors of the FPD. The graphical cut selects the oxygen ions. At the bottom the horizontal position at the focal plane X_{foc} is plotted against E_{resid} for the data selected by the graphical cut.

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]. Mass identification is achieved thanks to the simultaneous measurement of the kinetic energy T and the reconstructed fractional momentum δ of the detected ions. The standard $\Delta E - E$ method is used for the Z identification with a resolution $\Delta Z/Z = 1/48$. In Ref. [14] it has been shown that one can obtain in this way a clear identification of the detected ions with a mass resolution as high as $\Delta A/A = 1/160$. The relationship between δ and T can be maintained, even if with slightly lower resolution, using the non-reconstructed parameters X_{foc} (horizontal position at the focal plane) and E_{resid} (residual energy measured by the silicon detectors). An example of application of such an identification technique is shown in Fig. 1 for the ^{18}O + ^{12}C reaction at 84 MeV.

4. Spectra features

Once the reaction ejectiles are identified the reconstructed parameters are analysed. In particular the apparent excitation energy $E^* = Q_0 - Q$ (where Q_0 is the ground to ground state Q-value) is shown in Fig. 2 for different targets and angular settings. For example, in Fig. 2 a) the ^{14}C spectrum at $9.5° < \theta_{lab} < 10.5°$ is shown. Several excited states of ^{14}C are populated for which the spin and parity are well known from previous (t,p) reactions [15, 16]. 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. It is very interesting to note that this spectrum appears very similar to the ones excited with (t,p) reactions indicating the 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 including the analysis of the angular distribution are foreseen.

The energy spectrum for the ^{13}C(^{18}O,^{16}O)^{15}C reaction in the angular range $9° < \theta_{lab} < 12°$ is shown in Fig. 2b). 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^* = 3.10, 4.22 4.66, 6.84 7.35 MeV [17] 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 [17]. Above the two neutron threshold (S_{2n} = 9.394 MeV) two large unknown structures are strongly excited at energies E^* = 10.5 and 13.6 MeV over a continuously distributed shape due to the three-body and four-body phase-spaces. A more detailed analysis of the two-neutron transfer on the ^{15}C continuum is going to be published elsewhere [18].

In Fig. 2 c) and d) some preliminary results of the runs on ^{9}Be and ^{11}B targets are shown. In the ^{11}Be spectrum the ground and the known states at 0.32, 1.78, 2.69, 3.89, 3.96, 5.24 and 6.72 MeV are significantly populated together with a broad structure at about 8 MeV not observed in other experiments. In this sense a similarity with the cases of ^{14,15}C is observed, which is strengthen by the comparison with the ^{13}B spectrum. In fact also in this latter case one observes several peaks corresponding to transitions to known bound and resonant states and a broad structure between 8 and 12 MeV. Another interesting aspect of the ^{11}Be data is the missing of the high spin states observed in ref. [19] up to about 22 MeV and connected to a rotational band built on the 3.96 MeV state. This fact seems to confirm the low angular momentum transferred under these experimental conditions. Nevertheless only after an accurate treatment of the different sources of background in the spectra, including the break-up contribution to the measured ^{16}O yields, and after the extraction of the angular distributions one can draw conclusive arguments.

An example of ^{66}Ni energy spectrum is shown in Fig. 2 e). In this case the spectrum features are sensibly different from the light nuclei ones. A large bump is observed probably due to the convolution of the several peaks expected in this region. However one should notice that for such heavy nuclei the incident energy corresponds to 1.7 times the Coulomb barrier. Thus the dynamical conditions could be rather different compared for example to the ^{13}C target case, where the energy is 3.2 times the Coulomb barrier.

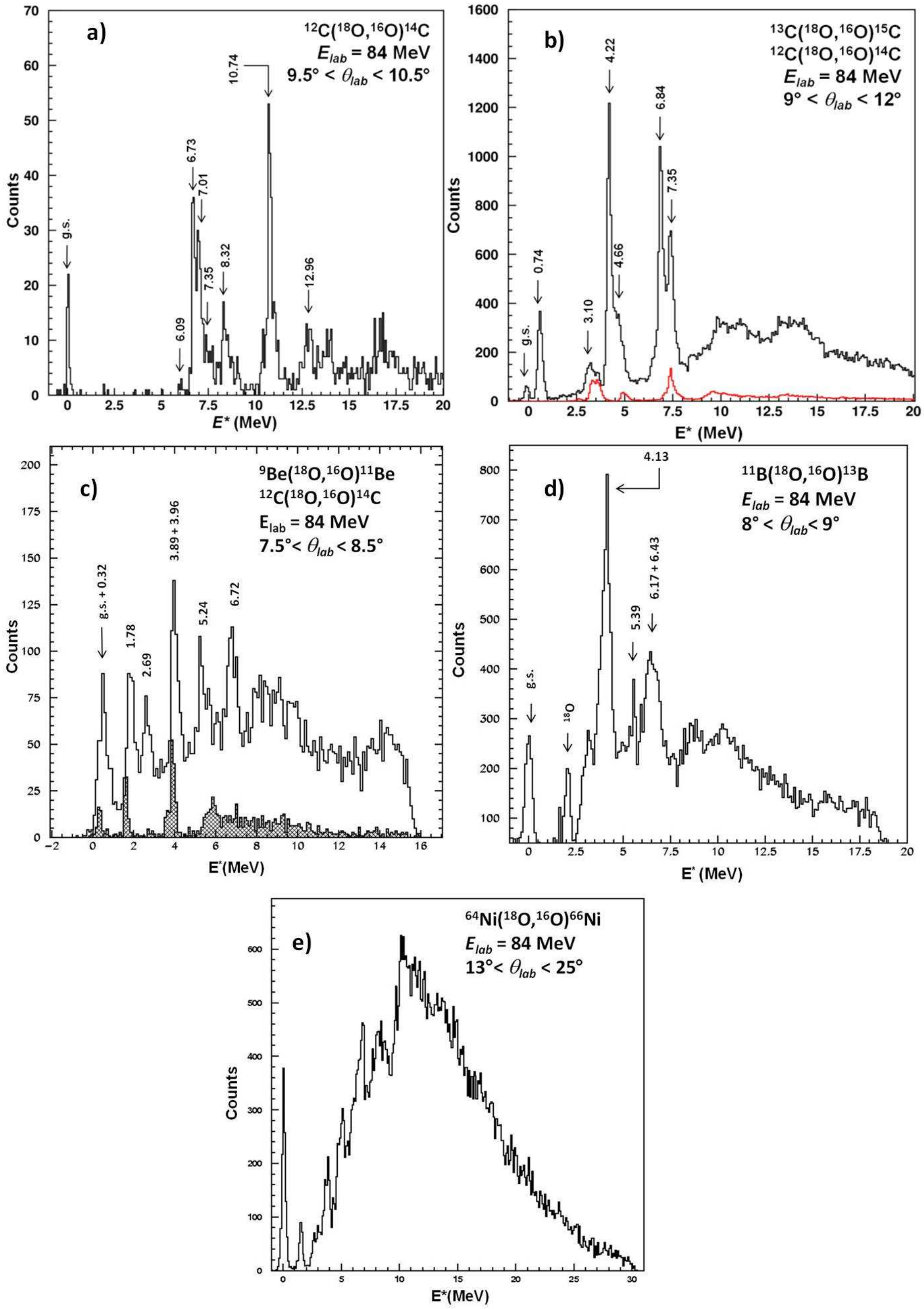

Fig. 2 One-dimensional spectra of the reconstructed ^{11}Be, ^{13}B, ^{14}C and ^{15}C excitation energy for the selected $^{16}O^{8+}$ ejectiles emitted in the (^{18}O,^{16}O) reaction at 84 MeV. The contribution due to the ^{12}C impurities in the targets is shown superimposed with red (in Fig.2 b) and dashed (in Fig.2 c) histograms and is subtracted in Fig.2 a), d) and e).

4. Conclusions

A study of the response of various nuclei to the (^{18}O,^{16}O) reaction at 84 MeV with the MAGNEX spectrometer at INFN-LNS is on the way. Several indications of the existence of a preformed pair in the ^{18}O that does not loose its identity during the transfer to the target appear. The good identification properties and energy resolution of the device allow to get interesting information from the analysis of the analysis of inclusive energy spectra and ejectiles angular distributions. In addition the development of modern microscopic theories describing heavy-ion collisions is a key tool to get a deeper understanding of the experimental data. The recent installation of the EDEN [20] array of 36 NE213 liquid scintillators at LNS opens new opportunities in this field. In fact it is now possible to disentangle neutron from gamma particles emitted in the decay of the populated resonances, to measured their kinetic energy and thus produce exclusive spectra where the decay modes can be ascertained.

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