The $(^{18}\text{O},^{16}\text{O})$ two-neutron transfer reaction at 84 MeV

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Abstract. The $(^{18}\text{O},^{16}\text{O})$ two-neutron transfer reaction has been studied at 84 MeV incident energy on different targets. The charged ejectiles produced in the reactions have been momentum analyzed and identified by the MAGNEX spectrometer. Q-value spectra have been extracted with a remarkable energy resolution (FWHM = 160 keV) and several known bound and resonant states have been identified. $^{15}\text{C}$ excitation energy spectra populated by the $(^{18}\text{O},^{16}\text{O})^{15}\text{C}$ reaction show excited states with well known dominant 2p-4h configuration, similarly to the spectra populated by (p,t) reactions. This demonstrates the clear selectivity of $(^{18}\text{O},^{16}\text{O})$ reactions. Two unknown structures at 10.5 MeV and 13.6 MeV have been observed. Calculations based on the removal of two uncorrelated neutrons from the $^{18}\text{O}$ projectile describe the structure at 10.5 MeV as a resonance of $^{13}\text{C}$ near the $^{13}\text{C}+n+n$ threshold, while the second bump at 13.6 MeV is not described with such calculations. This model does not account neither for the strong population of the narrow resonances with known 2p-3h configuration observed between $S_{\text{n}}$ and $S_{\text{2n}}$, because of the lack of n–n correlations. This indicates that also the second bump can have a structure dominated by n-n correlations.

1. Introduction

Two neutron-transfer reactions are an important tool to test the neutron-neutron correlations inside the nuclei [1]. They reveal the features of the residual interaction, such as the pairing force, that are beyond the standard mean field description of nuclear structure. The direct one-step and the sequential two-step mechanisms contribute both to
the cross section, but from a spectroscopic point of view, the former only allows the excitation of pair modes in the residual nucleus, where the two neutrons cluster together with an intrinsic angular momentum $S$ orbiting around the core with an angular momentum $L$ ($L$-$S$ coupling). Sequential routes are more effective in exciting configurations where each neutron independently couples with the core with an angular momentum $j$ ($j$-$j$ coupling).

It has been established that at bombarding energies not much above the Coulomb barrier, heavy-ion direct transfer reactions are important probes for this type of study [2,3]. In this energy region a semi-classical approach can explain integral properties such as the selectivity of the reaction [5]. In addition the transfer to bound and unbound states can be treated in a coherent way and the different contributions to the reaction, such as elastic break-up and absorption from target bound states and resonances can be distinguished [6].

An experimental program, aiming at the systematic investigation of two-particle excitations via the ($^{18}$O,$^{16}$O) reaction, has been recently started at the INFN-LNS laboratories in Catania (Italy) using the MAGNEX spectrometer [7]. Such reactions are characterised by a high degree of selectivity for the excitation of two-particle configurations built over the target ground states [8-10]. The high resolution and large acceptance in the detection of the ejectiles allow to get high quality inclusive spectra, even in the largely unexplored region above the two-neutron emission threshold in the residual nucleus.

Nevertheless, the various components of projectile break-up in the energy spectra must be identified in order to isolate the spectral characteristics of the resonant-like excitations in the residue. An accurate and complete model of the two-neutron simultaneous removal mechanism populating final continuum states is at present not available, mainly because of the difficulties of introducing a simple, but coherent, treatment of neutron-neutron correlations in the reaction dynamics.

A recent study of the $^{15}$C continuum has shown two unknown structures that have been populated for the first time [6]. The point of view of an independent removal of two neutrons successfully describes part of the $^{15}$C($^{18}$O,$^{16}$O)$^{13}$C reaction spectrum.

2. The experiment and the data reduction

The experiment has been performed at INFN-LNS laboratory. A beam of $^{18}$O ions at 84 MeV incident energy, accelerated by the Tandem Van de Graaff, bombarded a self-supporting target of 99% enriched $^{13}$C 50 µg/cm² thick. The $^{18}$O isotopes produced in the collisions were momentum analysed by the MAGNEX spectrometer (see Figure 1) [7], working in full acceptance mode ($\Omega \sim$50 msr and $\Delta p/p \sim \pm$10%) and detected by the Focal Plane Detector [11]. During the measurement, the optical axis of spectrometer was centered at $\theta_{opt} = 12^\circ$. Thanks to the large acceptance of the spectrometer, an overall angular interval between 7.5° and 17.5° in the laboratory reference frame was spanned. In order to estimate the background in the $^{16}$O spectra produced by possible $^{12}$C impurities in the $^{13}$C target, supplementary runs were performed using a 49 µg/cm² $^{12}$C target. The magnetic fields were set to accept oxygen ions with electric charge from 6+ to 8+ at the maximum kinetic energy. Details about the identification technique are published in Ref. [12]. Once the $^{16}$O$^{8+}$ ejectiles are selected, the horizontal and vertical positions and angles at the focal plane are used as an input for a 10th order reconstruction of the scattering angle and momentum modulus, based on the fully algebraic method implemented in MAGNEX [13-14]. This allows a compensation of the high order aberrations connected with the large acceptance of the spectrometer. With this technique, an energy resolution of 160 KeV and angular resolution of 0.5° were obtained, mainly determined by straggling in the target. The
excitation energies $E_x = Q_0 - Q$ (where $Q_0$ is the ground state Q-value) are obtained by the application of relativistic kinematic transformations.

Figure 1. General view of the MAGNEX spectrometer at INFN-LNS in Catania.

3. Interpretation of the $^{15}$C spectrum and data analysis

An example of inclusive $^{15}$C spectrum is shown in Figure 2. Several peaks are identified as related to transitions to known states of $^{15}$C. Two large unknown structures centered at 10.5 ± 0.1 and 13.6 ± 0.1 MeV are also observed.

Figure 2. Excitation energy spectrum of the $^{13}$C$(^{16}$O,$^{16}$O)$^{15}$C reaction at 84 MeV and 8.7°< $\theta$ < 10.0°. The red histogram represent the background arising from the same reaction on $^{12}$C target.

The $^{15}$C spectrum can be divided into three parts bounded by the one- ($S_n = 1.22$ MeV) and two- ($S_{2n} = 9.39$ MeV) neutron emission thresholds in $^{15}$C:
Between 0 and 1.22 MeV the ground state and the first excited state at $E_x = 0.74$ MeV are populated. These states are characterized by single particle configurations.

Between 1.22 and 9.39 MeV some narrow resonances is present. These states are strongly excited also by the (t,p) reaction of Ref. [15] where their complex nature of a p-shell neutron hole coupled with a two-neutron pair in the sd-shell was ascertained.

For $E_x > 9.39$ MeV, that is above the threshold for the two-neutron emission in the continuum, the $^{15}$C + 2n system is also unbound, and a supplementary continuous contribution is expected from this channel. Exploratory calculations on $^{15}$C using a generalization of the one-nucleon transfer to unbound states model [16] have been performed. The method, in turn, extends the formalism of the transfer to bound states [17, 18] to the case of unbound ones [19, 20], assuming an uncorrelated removal of the two neutrons. What is left out is the specific treatment of nucleon-nucleon correlations beyond the $^{15}$C mean field, as, for example, those due to the neutron-neutron pairing in the sd shells.

The reaction studied is described as a two-step mechanism: $^{18}$O + $^{13}$C $\rightarrow ^{17}$O + $^{14}$C$_{p1}$ $\rightarrow ^{16}$O + $^{14}$C$_{p2}$ + n starting from $S_n$: $^{18}$O + $^{13}$C $\rightarrow ^{17}$O + $^{13}$C$_{p2}$ + n $\rightarrow ^{16}$O + $^{13}$C$_{p1}$ + n + n starting from $S_{2n}$. The reason of this interpretation depends on the fact that there is a perfect matching condition between the single neutron separation energy of $^{15}$O ($S_0$($^{15}$O) = 8.04 MeV), and the energy needed by the $^{15}$C to get one neutron, i.e the single neutron separation energy of $^{14}$C ($S_0$($^{14}$C) = 8.18 MeV). Thus, in the first step of the reaction, the ground state to ground state Q-value is very small $Q_0 = 0.13$ MeV, which indicates an almost sudden process for the first neutron transfer, while the other neutron is transferred to the continuum of $^{14}$C. Depending on the energy carried by the neutron, the ground and first bound excited state of $^{15}$C are populated. For higher neutron energies, the continuum resonances of $^{15}$C are populated up to the 2n threshold energy. Crossing this threshold, the transfer to the continuum of $^{14}$C and the transfer to the continuum of $^{13}$C, originated on the first step, merge together.

A detailed description of the used formalism has been recently published in Ref. [6]. There, the differential transfer probability is:

$$\frac{dP}{d\sigma} = \sum_J S_J^2 \left( 1 - |S_J|^2 \right)^2 + 1 - |S_J|^2 \frac{e^{-\alpha_b \eta b}}{\pi b} F(J_1, J_2)$$

(1)

where $e^{-\alpha_b \eta b}$ is the form factor. The function $F(J_1, J_2)$ is given in the Ref.[20] which includes the kinematics and the angular momentum couplings. $S_J$ is the energy averaged and spin dependent optical model S-matrix which describes the neutron-target interaction.

The first term in (1), proportional to $\left( 1 - |S_J|^2 \right)^2$, corresponds to the probability that the nucleon undergoes an elastic breakup in which the target is left in its ground state, while the second term, proportional to $1 - |S_J|^2$, represents the probability of its absorption by the target. This absorption can be due to compound nucleus formation or to inelastic breakup in which the target is left in an excited state.

The one nucleon transfer is obtained using a semi-classical approximation for the relative motion between the incident core and the target nucleus.

The energy spectrum of $^{15}$C in the angular range $7.5^\circ < \theta_{lab} < 17.5^\circ$ is given in Figure 3. The experimental data are plotted together with results obtained using the approach described
above. Between $S_n$ and $S_{2n}$ the calculation contains the three-body physical background due to the elastic break-up only, as given by the first term of Eq. (1). In this region the absorption observed in the data is dominated by the narrow 2p-3h resonances stabilized by n-n pairing, which is not accounted for in our approach. Above the $S_{2n}$ threshold, the resonances are quite smooth and both the elastic and the absorption terms are calculated. The main contribution to the structure at 10.5 MeV in the experimental spectrum comes from the absorption of the two neutrons. This means that a $^{13}$C+n+n resonant configuration can account for the observed structure, without the need of introducing specific n-n correlations. On the other hand, the second bump at 13.6 meV is not reproduced by the calculations. This indicates that such a structure could be related to the presence of the pairing force in the nucleus. Thus a more complete description of the $^{13}$C+n+n system, including the n-n correlations, is required.

Since Eq. (1) contains an incoherent sum over final angular momenta, it allows an estimation of the contribution of each single $\ell$ value to the total sum. In this way it is possible to understand the origin of the strength distribution in the spectrum. Partial waves decomposition in the region above $S_{2n}$ have been estimated and the main contribution in this region comes from the $d_5/2$ and the $d_3/2$ states [6].

Figure 3. Inclusive energy spectrum of the reaction for $7.5^\circ<\theta_{lab}<17.5^\circ$ and theoretical calculations of various break-up components. The green dashed (el_n1) and the blue dotted curve (el_n2) represent the one- and two neutron elastic break-up, respectively. The violet dashed-dotted curve (abs_n2) is the two neutron absorption term. The red full curve (el_n1+(el+abs)_n2) is the sum of all contributions.
4. The $^{11}$Be and $^{14}$C spectra

A remarkably similar behaviour to the $^{15}$C case is observed in the $^{11}$Be and $^{14}$C spectra populated via the same ($^{18}$O,$^{16}$O) reaction shown in Figure 4. In both cases narrow peaks are present up to the corresponding $S_{2n}$ energy threshold and a sudden enhancement of the yield, fragmented in larger structures, is observed just above. The narrow peaks correspond to transitions to well-known excited states of $^{11}$Be and $^{14}$C efficiently populated also by $(t,p)$ reactions [21-23].

For the $^{14}$C case the states at 7.02 and 10.74 MeV, whose main configuration requires the coupling of two neutrons in the sd shell with the $^{12}$C gs$(0^+)$ ground state core [22, 24], are strongly populated. Near the $S_{2n}$ threshold, the narrow states at 12.58, 12.89 and 12.96 MeV are superimposed to a large structure, steeply emerging at the threshold and slowing down up to about 16 MeV energy. A second unreported structure is also observed in the region between about 16 and 17.5 MeV.

Also in the $^{11}$Be spectrum, the states at 3.96, 5.24 and 5.86 MeV, for which a $^9$Be gs + 2n in the sd-shell dominant configuration is reported [21], are among the most excited ones. In addition the structures observed above $S_{2n}$ do not correspond to anything previously reported.

Calculations in the same approach as the one described in the previous section are in progress in order to understand the contribution due to the transfer of two uncorrelated neutrons to the continuum.

![Figure 4.](image-url)
5. Conclusions

The results of the \((^{18}\text{O},^{16}\text{O})\) reaction on \(^{13}\text{C},^{12}\text{C}\) and \(^{9}\text{Be}\) targets at 84 MeV incident energy have been reported. The effects of the two-neutron transfer from the projectile, populating a large region of the continuum of the target plus two-neutron system, have been studied by measuring the missing mass of \(^{16}\text{O}\). Below the \(S_{2n}\) threshold, in the corresponding residual nucleus spectrum, the cross section is mainly concentrated in the bound states and in a number of known sharp resonances emerging above a rather small flat continuous background. A sudden increase of the measured \(^{16}\text{O}\) yield is observed starting from the \(S_{2n}\) threshold, appearing in the shape of previously unobserved large bumps. We note that the states with a known structure of two neutrons coupled with a core exhaust a consistent amount of the measured cross section, with negligible contribution from states with other configuration. This indicates the fundamental role of the n-n correlations in these experimental conditions.

Both the elastic break-up and absorption channels have been analyzed in a consistent way for the \(^{13}\text{C}(^{18}\text{O},^{16}\text{O})^{15}\text{C}\) reaction. In the adopted theoretical model, the scattering of the neutrons independently removed from the projectile as it passes the target nucleus is described by means of an optical potential with a semi-classical approximation for the relative motion. The calculations show that the elastic break-up represents a minor part of the continuous spectra, which are in fact dominated by the absorption of both neutrons. In particular, the bump at 10.5 MeV is described in terms of an enhanced probability, near the \(S_{2n}\) threshold, of exciting \(^{13}\text{C} + n + n\) configurations where the two neutrons are mainly transferred to \(d_{5/2}\) or \(d_{3/2}\) resonances of the resulting \(^{15}\text{C}\) nucleus. The model cannot account for the strong population of narrow resonances with known 2p-3h configuration observed between \(S_{n}\) and \(S_{2n}\), because of the lack of n-n correlations. Also, the bump at 13.6 MeV is missed, which could indicate a similar structure for all these states. An explicit treatment of the full \(^{13}\text{C} + n + n\) interaction, including the n-n pairing, would be required to understand the remaining details of the energy spectra.

The study of the angular distributions and of the decaying products for the systems studied, as well as for similar cases, should allow to shed more light on the role of such n-n correlations.

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