NATURAL PARITY STATES EXCITED VIA (^{18}O,^{16}O) TWO-NEUTRON TRANSFER REACTION*

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The ^{12}C(^{18}O,^{16}O)^{14}C and ^{13}C(^{18}O,^{17}O)^{14}C reactions were studied at INFN-LNS laboratory in Catania. The experiments were performed using an ^{18}O Tandem beam at 84 MeV incident energy. Charged ejectiles produced in the reactions were momentum analyzed and identified by the MAGNEX spectrometer. Q-value spectra were extracted with a remarkable energy resolution (FWHM $\sim$ 150 keV) and several known bound and resonant states were identified. In particular, states with relevant 1p–3h configuration with respect to the ^{16}O core are mainly populated by the reaction (^{18}O,^{17}O) while states with known 2p–4h configuration are excited by the (^{18}O,^{16}O) one. Exact Finite Range Coupled Reaction Channel calculations based on a parameter free double-folding optical potential were performed to reproduce the measured absolute cross-section angular distributions. The (^{18}O,^{16}O) is found to be an important probe to study pair configurations in nuclear states.

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1. Introduction

Two-neutron transfer reactions are useful probes to study details of the neutron–neutron correlations beyond the nuclear mean field, in particular,

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they play an important role to test the pairing interaction between the nucleons [1–3]. In this context, the (^{18}O,^{16}O) reactions are good spectroscopy probes to study the pairing interaction. The reason is the existence of a preformed pair of neutrons coupled to angular momentum $L = 0$ and the very low polarizability of the ^{16}O core. Moreover, the ^{18}O stable beam can be produced with high intensities. We have chosen to study ^{14}C as a benchmark residual nucleus because many excited states have well known configurations and a vast literature is available [4, 5].

2. Experimental setup and data reduction

The experiment was performed at the INFN-LNS laboratory in Catania. A Tandem beam of ^{18}O at 84 MeV incident energy impinged on a 49 μg/cm^2 self supporting ^{12}C target and a 50 μg/cm^2 self-supporting 99% enriched ^{13}C target. The outgoing ejectiles were momentum analyzed by the MAGNEX spectrometer [6–8] and detected by the focal plane detector (FPD) [9, 10]. The spectrometer was located at three different angular settings, with $\theta_{\rm lab}^{\rm opt} = 8°, 12°, 18°$. Due to the large angular acceptance of MAGNEX (-0.090 rad, $+0.110$ rad horizontally, ± 0.125 rad vertically in the spectrometer reference frame), this setting covers an angular range of about $3° < \theta_{\rm lab} < 24°$. The magnetic fields were set in order to transmit the ^{16}O$_{8+}$ ejectiles at kinetic energies corresponding to excitation energies of ^{14}C from 0 to 20 MeV.

The Z identification was obtained using a standard ΔE–E technique. For mass identification, a technique based on the relation between the ion kinetic energy and the horizontal position, measured in the FPD, was used. With this identification technique a mass resolution as high as 1/160 has been reached [11, 12].

The horizontal and vertical positions and angles of the oxygen ions, measured at the focal plane, were used as input of a 10$^{\rm th}$ order ray reconstruction of the scattering angle and kinetic energy, based on a differential algebraic method implemented for MAGNEX [12]. This allows an effective compensation of the high order aberrations of the spectrometer and allows the reconstruction of interesting physical quantities like the scattering angle and the excitation energy of the residual nucleus.

An energy resolution of 150 keV (full width at half maximum) in energy and 0.3° in angle was obtained in the laboratory frame, mainly due to the multiple scattering in the target and the beam divergence. Examples of the obtained energy spectra and angular distributions are shown in Fig. 1 and Fig. 2, respectively.

The absolute cross-section angular distributions were extracted, according to the procedure described in Ref. [13].

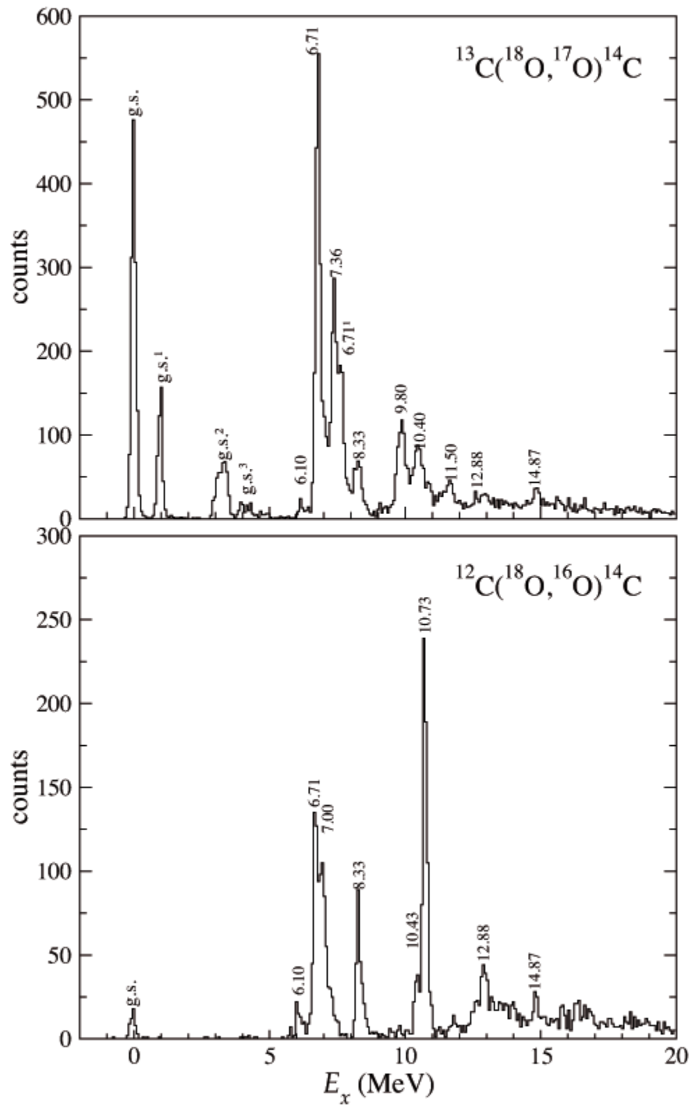

Fig. 1. ^{14}C energy spectra for the one- (top panel) and two- (bottom panel) neutron transfer for $4° < \theta_{\rm lab} < 5°$. In the top panel, the peaks marked with ^{1}, ^{2}, ^{3} represent the transition to the excited states of ^{17}O ejectiles at 0.87, 3.06, 3.84 MeV, respectively.

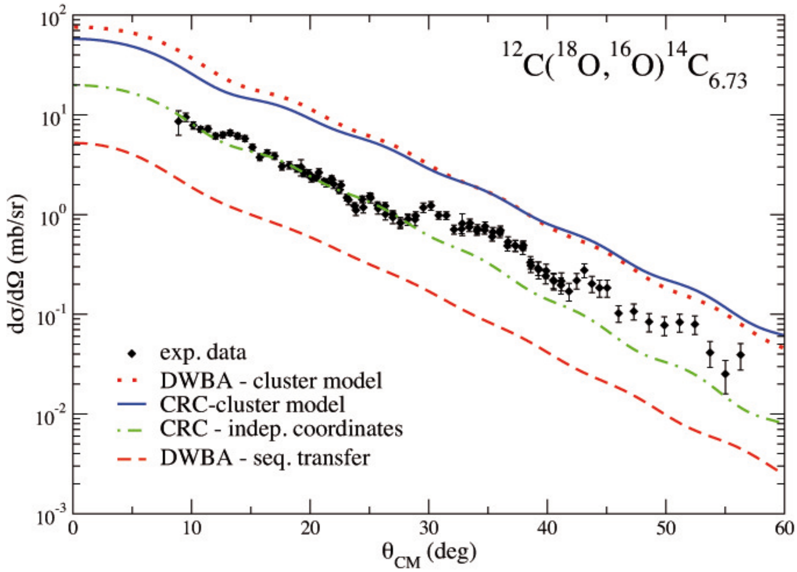

Fig. 2. (Color on-line) Comparison of the experimental angular distributions with theoretical calculations for the ^{12}C(^{18}O,^{16}O) transition to the 6.73 excited state of the ^{14}C nucleus.

3. The ^{14}C spectrum via one- and two-neutron transfer

In order to study the selectivity of the (^{18}O,^{16}O) reaction, it is interesting to compare the ^{14}C spectra populated via two- and one-neutron transfer. The ^{14}C spectrum obtained from the ^{13}C(^{18}O,^{17}O)^{14}C reaction (shown in the top panel of Fig. 1) is very similar to those measured in the ^{13}C$(d,p)^{14}$C one [4, 14, 15]. This reaction excites especially states with dominant single-particle configuration. The most excited are in the doublet at 6.73 MeV (3^-) and 7.34 MeV (2^-) with $|(^{13}\mathrm{C_{gs}})^{1/2^-} \bigotimes (1d_{5/2})_v^{5/2^+}]^{2^-,3^-} >$ single particle configuration.

States with well known dominant configuration of two neutrons in the sd-shell coupled with ^{12}C core (such as 8.33 MeV (2^+) and 10.74 MeV (4^+)), are weakly populated. In the case of (^{18}O,^{17}O), these states can be populated only by a two step mechanism where one neutron is transferred to sd-shell and the $p_{1/2}$ neutron of $^{13}\mathrm{C_{gs}}$ is promoted to the same shell. The low population of these states indicates that this two-step mechanism is suppressed in the (^{18}O,^{17}O) reaction.

On the other hand, the ^{14}C spectrum populated by (^{18}O,^{16}O) reaction (bottom panel of the Fig. 1) shows the same states strongly excited in the ^{12}C$(t,p)^{14}$C [4, 14].

It is worth noting, the behavior of the doublet 3^-, 2^- in the case of two-neutron transfer reaction. Here, the 3^- level at 6.73 MeV, is strongly excited whereas the neighboring 2^- level at 7.34 MeV is almost not observed. Both of these levels are strongly excited in the single particle transfer on ^{13}C. Starting from an ^{18}O projectile, the unnatural 2^- state could be populated in two-neutron transfer reaction only through a second-order mechanism, such as a spin–flip process followed by a neutron-pair transfer process, while the 3^- state can be excited through a single-step transfer of the neutron pair. This result indicates that the existing neutron pairing correlation ($S = 0$, isospin $T = 1$), present in the ^{18}O projectile, is preserved in this transfer reaction.

4. Cross-section calculations

We carried out Exact Finite Range (EFR) DWBA and CRC cross-section calculations for the ^{12}C(^{18}O,^{16}O) transition to the 6.73 excited state of the ^{14}C nucleus using the Fresco code [16]. The Sao Paulo double folding potential (SPP) was used as real part in the optical potential [17, 18], taking into account a matter diffuseness of 0.61 fm for ^{18}O and ^{17}O nuclei [21, 22]. The imaginary part of the optical potential had the same SPP shape. As reported in the Ref. [20], we used a scaling factor for the imaginary part of 0.6 for the entrance partitions and 0.78 for the outgoing one.

The wave functions, used in the form-factor calculations, were generated by a Woods–Saxon shaped potential, whose parameters reported in Ref. [20] allow to produce the exact binding energies for one and two neutrons. The deformation parameters for the collective excitation in the entrance partition were taken from Ref. [23]. The EFR, prior, full real remnant approximation was used. The spectroscopic amplitudes were calculated by shell-model in the $1p_{1/2}$, $1d_{5/2}$ and $2s_{1/2}$ model space using a modified version of the *zbm* effective interaction [24, 25]. The calculated spectroscopic amplitudes and the adopted coupling schemes are listed in Ref. [20].

According to the perturbative formalism of two-particle transfer, the total transition amplitude up to the second order should contain three contributions: the simultaneous transfer, the sequential transfer and the non-orthogonality term. In our approach, we carried out two separate calculations for simultaneous and sequential transfer. The non-orthogonality terms are included in both CRC one-step and DWBA sequential transfer.

The calculations were performed using both the extreme cluster model and the independent coordinate scheme to calculate the two-particle wave functions in the CRC.

In the extreme cluster approach, the two neutrons are paired anti-parallel and coupled to a zero intrinsic angular momentum ($S = 0$) (L–S coupling). In this case, the wave function of the cluster respect to the core is described by the principal quantum number N and the angular momentum L. These are deduced from the conservation of total number of quanta in the transformation of the wave functions of the two independent neutrons in orbits n_i, l_i into a cluster [19]

$$\sum_{i=1}^{2} 2(n_i - 1) + l_i = 2(N-1) + L\,.$$

The $N = 3$, $L = 0$ configuration is used for the cluster in ^{18}O ground state with a spectroscopic amplitude, inferred from shell-model, equal to 0.945.

In the independent coordinates scheme, the transfer of two neutrons is described taking into account single-particle information obtained by shell-model calculations in the available model space, as shown in the Ref. [20].

In the independent coordinates CRC calculations the cross section for the transition to the 3^- state at 6.73 MeV is accurately reproduced. It does confirm the expected $L = 3$ $(1p_{1/2}, 1d_{5/2})$ angular momentum transferred [4, 5].

A larger cross section is obtained in the CRC extreme cluster model calculation. An amplitude of 0.58 is estimated by scaling the CRC calculated cross section with $N = 1$, $L = 3$ to fit the experimental data. Negligible differences are found when using DWBA results. This result can be interpreted considering that the $N = 1$, $L = 3$ configuration takes into account not only the major $(1p_{1/2}, 1d_{5/2})$ configuration, but also others, such as the $(1p_{1/2}, 2s_{1/2})$ one, which increase the calculated cross section even if they do not give a large contribution to the true 3^- state wave function.

The two-neutron sequential transfer was treated with two-step DWBA formalism, introducing the intermediate partition ^{13}C+^{17}O. The used Wood–Saxon parameters and the coupling scheme are taken from Ref. [20]. We find that the sequential calculation accounts only for a minor contribution to the measured absolute cross section.

5. Conclusions

The one- and two-neutron transfer reaction induced by ^{18}O beam at 84 MeV incident energy were studied with high energy and angular resolution. The energy spectra measured for the ^{13}C(^{18}O,^{17}O)^{14}C and the ^{12}C(^{18}O,^{16}O)^{14}C reactions indicate a strong selectivity in populating states with well known single- and two-particle configurations respectively.

Exact Finite Range (EFR) DWBA and CRC cross-section calculations allow to distinguish states with main j–j coupling configuration from the cluster one. In the angular distribution for the 6.73 MeV state populated via (^{18}O,^{16}O) reaction, reported in this work, an important role of the j–j coupling was found.

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