Vol. 47 (2016) ACTA PHYSICA POLONICA B No 3

COLLECTIVE EXCITATIONS IN THE ^{14}C NUCLEUS POPULATED BY THE ^{12}C(^{18}O,^{16}O) REACTION AT 84 MeV*

D. Carbone[a], C. Agodi[a], F. Cappuzzello[a,b], M. Cavallaro[a]
A. Foti[b,c], E. Khan[d]

[a]INFN — Laboratori Nazionali del Sud, Catania, Italy
[b]Università degli Studi di Catania, Catania, Italy
[c]INFN — Sezione di Catania, Catania, Italy
[d]Institut de Physique Nucleaire, Université Paris-Sud, Orsay, France

(Received November 25, 2015)

The ^{12}C(^{18}O,^{16}O)^{14}C reaction at 84 MeV incident energy has been explored up to high excitation energy of the residual nucleus thanks to the use of the MAGNEX spectrometer to detect the ejectiles. In the region above the two-neutron separation energy, a resonance at 16.9 MeV has been observed. Continuum quasi-particle random phase approximation calculations of the response function, corresponding to the transfer of a neutron pair to the ^{12}C nucleus, have been performed to investigate the possible presence of the Giant Pairing Vibration in that energy region.

DOI:10.5506/APhysPolB.47.937

1. Introduction

Two-neutron transfer reactions induced by heavy ions offer a number of possibilities and specific features, which have allowed significant progress in the study of dynamical pairing correlations with respect to the more traditional transfer reactions induced by light projectiles, as the recent discovery of the Giant Pairing Vibration (GPV) [1, 2]. The elementary excitation mode known as GPV was predicted by the theory in the 70s [3] and should lie at energies about two times the single particle harmonic oscillator quantum. The excitation of the GPV should be induced by two-nucleon transfer reactions where the angular momentum transfer is $L = 0$ and a correlated pair of nucleons in a relative S-wave is transferred. In the past, many experimental attempts were performed using (t, p) or (p, t) transfer reactions on tin and

* Presented at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 6–13, 2015.

lead isotopes [4, 5]. However, these attempts remained unsuccessful until the ^{12}C(^{18}O,^{16}O)^{14}C and ^{13}C(^{18}O,^{16}O)^{15}C reactions at 84 MeV incident energy were explored [1, 2]. One of the successful choices in these measurements was the use of the MAGNEX large acceptance magnetic spectrometer to detect the ^{16}O ejectiles, since it conjugates good energy and angular resolutions with a large acceptance both in solid angle and momentum [6].

One of the indications in favour of the population of the GPV in these reactions was provided by continuum quasi-particle random phase approximation (cQRPA) calculations for the ^{12}C response to the monopole p–p operator to predict the 0^+ two-neutron addition strength, which suggested the presence of a collective bump at high excitation energy. The results of such calculations are presented and discussed in the present paper.

2. The experiment

The ^{18}O^{6+} beam at 84 MeV incident energy, produced and accelerated by the Tandem Van de Graaff facility of INFN — LNS in Catania, impinged on a 49 ± 3 g/cm^2 self-supporting ^{12}C. The ^{16}O ejectiles were momentum analysed by the MAGNEX spectrometer [6] working in the full acceptance mode (solid angle $\Omega \sim 50$ msr and momentum range $\Delta p/p \sim 24\%$). The ejectiles were identified event-by-event in atomic number (Z), atomic mass (A) and charge (q) by combining two techniques [7]: the standard ΔE–E correlation plot for the Z identification and the correlation between the horizontal position at the focal plane ($X_{\rm foc}$) and the ejectile residual energy ($E_{\rm resid}$) for the mass identification, which exploits the properties of the Lorentz force. The horizontal and vertical position and angles of the ^{16}O ejectiles at the focal plane were used as the input for a 10$^{\rm th}$ order ray-reconstruction based on the differential algebraic method implemented in MAGNEX [8]. The ray-reconstruction technique allows an effective compensation of the high-order aberrations connected with the large acceptance of the spectrometer. As a result, the initial phase space parameters at the target point are obtained, which are directly related to the momentum modulus and the scattering angle of the detected ejectiles. The corresponding Q-values, or equivalently the excitation energy $E_x = Q_0 - Q$ (where Q_0 is the ground-to-ground state Q value), were obtained by a missing mass determination using relativistic energy and momentum conservation laws, assuming a binary reaction. An example of the reconstructed energy spectrum for the ^{14}C nucleus is shown in Fig. 1. An overall energy resolution of $\sim$ 160 keV is obtained from Gaussian fit of the observed transition to bound states. Several known bound and resonant states of the ^{14}C nucleus are identified, the same populated in (t,p) reactions [9]. In the region above the two-neutron separation energy (S_{2n} = 13.122 MeV), a new resonance appears, recently identified as the GPV [1, 2]. The spectroscopic features of such resonance are deduced by a best-fit procedure with Gaussian shapes on a locally adjusted linear model for the 3-body continuum background (as shown in the insert of Fig. 1). Taking into account also the two known resonances at $E_x = 16.43$ and 16.72 MeV, the resonance is identified at $E_x = 16.9 \pm 0.1$ MeV with a full-width at half-maximum (FWHM) $= 1.2 \pm 0.3$ MeV.

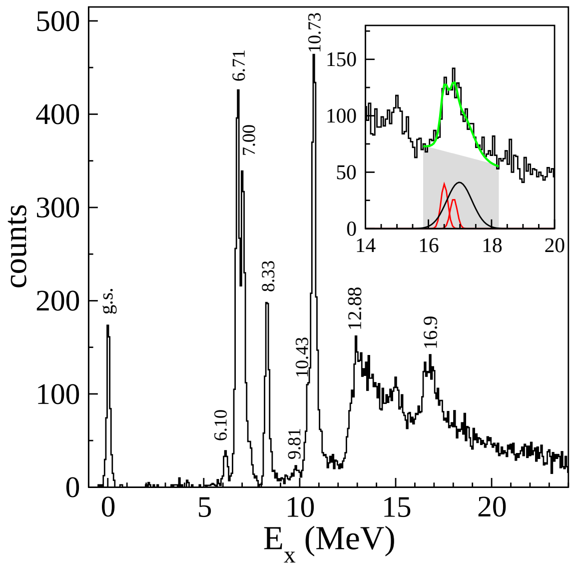

Fig. 1. Excitation energy spectrum of the $^{12}C(^{18}O,^{16}O)^{14}C$ reaction at $10^\circ < \theta_{\rm lab} < 11^\circ$. In the insert: zoomed view of the spectrum above the two-neutron separation energy. The modelled 3-body continuum (grey area), the fitted resonances at 16.43 and 16.72 MeV (dark grey/red Gaussians), the fitted GPV (black Gaussian) and the sum of them (light grey/green curve) are shown.

3. cQRPA calculations

One of the indications of the presence of the GPV in the energy region where the ^{14}C bump is observed comes from the cQRPA calculations of the 0^+ excitations in the energy spectra.

The two-particle transfer modes are usually described using the *pp*–RPA [10, 11] in the case of closed shell nuclei and the QRPA [12, 13] in open shell nuclei. In the present case, the calculations of the response function corresponding to the transfer of a neutron pair to the ^{12}C nucleus were done following the same approach of Refs. [14, 15]. The first step of the calculations is to determine the ^{12}C ground state within the Hartree–Fock–Bogoliubov approach [16]. The HFB equation were solved in coordinate space assuming spherical symmetry. The mean field quantities were evaluated using the Skyrme interaction SLy4 [17] while for the pairing interaction, a zero-range density-dependent interaction was taken given by

$$V_{\rm pair} = V_0 \left[1 - \left(\frac{\rho(r)}{\rho_0}\right)^{\alpha}\right] \delta(r_1 - r_2)\,, \tag{1}$$

where V_0, ρ_0 and α are the parameters of the force. Due to its zero range, this force should be used in the HFB calculations with a cutoff in *qp* energies. Using the same prescriptions of Ref. [15], a *qp* cutoff of 60 MeV was chosen and the obtained value is $V_0 = -570$ MeV fm^{-3}. The parameter ρ_0 is set to the usual saturation density, 0.16 fm^{-3}. The value of the α parameter was chosen in order to reproduce the trend of the experimental pairing gap and it was found $\alpha = 1$. The obtained HFB *qp* energies corresponding to the $1p_{1/2}$, $1d_{5/2}$, $2s_{1/2}$, $2p_{3/2}$, $2p_{1/2}$, $1d_{3/2}$ and $1f_{7/2}$ states are listed in Table I.

TABLE I

^{12}C single-quasiparticle neutron energies calculated in the HFB model.

	Single-*qp* energy [MeV]
$1p_{1/2}$	4.51
$1d_{5/2}$	10.89
$2s_{1/2}$	10.96
$2p_{3/2}$	13.19
$2p_{1/2}$	13.25
$1d_{3/2}$	13.80
$1f_{7/2}$	14.79

The results for the $L = 0$ strength function corresponding to a neutron pair transferred to the ^{12}C nucleus are shown in Fig. 2. The zero of the energy scale refers to the ^{12}C$_{\rm gs}$. As in the cases of the oxygen isotopes [14, 15], a collective structure associable to the GPV mode is appearing at ~ 20 MeV with respect to the ^{12}C$_{\rm gs}$. In order to compare this value with the experimental energy centroid of the ^{14}C bump, it is necessary to compute the excitation energy compared to the target ground state as

$$E_x^t = E_x + M_{\rm r} - M_{\rm t}\,, \tag{2}$$

where $M_{\rm t}$ and $M_{\rm r}$ represent the mass of the target and of the residue, respectively. When applying such a scaling of the experimental excitation energies, a value $E_x^t = 16.9 + 3.0 = 19.9$ MeV is obtained for the ^{14}C bump, which is consistent with the present calculations. This finding is compatible with the population of the GPV.

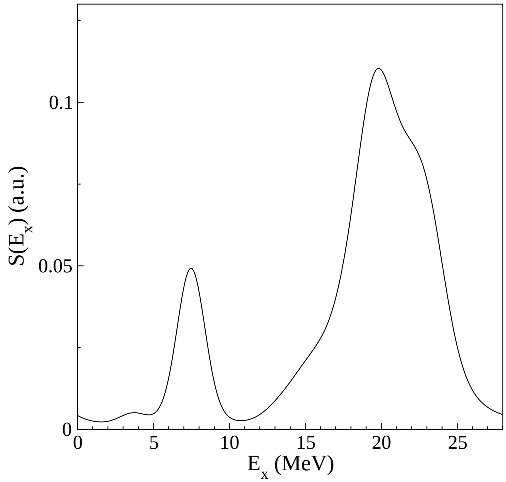

Fig. 2. The $L = 0$ cQRPA response function for the transfer of a neutron pair on ^{12}C. The results are displayed as a function of E_x, the excitation energy with respect to the ^{12}C ground state.

REFERENCES

[1] F. Cappuzzello *et al.*, *Nat. Commun.* **6**, 6743 (2015).

[2] D. Carbone, *Eur. Phys. J. Plus* **130**, 143 (2015).

[3] R.A. Broglia, D.R. Bes, *Phys. Lett. B* **69**, 129 (1977).

[4] B. Mouginot *et al.*, *Phys. Rev. C* **83**, 037302 (2011).

[5] G.M. Crawley *et al.*, *Phys. Rev. C* **23**, 589 (1981).

[6] F. Cappuzzello, D. Carbone, M. Cavallaro, A. Cunsolo, *Magnets: Types, Uses and Safety*, Nova Publisher Inc., New York 2011, pp. 1–63.

[7] F. Cappuzzello *et al.*, *Nucl. Instrum. Methods A* **621**, 419 (2010).

[8] F. Cappuzzello, D. Carbone, M. Cavallaro, *Nucl. Instrum. Methods A* **638**, 74 (2011).

[9] S. Mordechai *et al.*, *Nucl. Phys. A* **301**, 463 (1978).

[10] A. Boussy, N. Vinh Mau, *Nucl. Phys. A* **224**, 331 (1974).

[11] G. Ripka, R. Padjen, *Nucl. Phys. A* **132**, 489 (1969).

[12] R.A. Broglia, O. Hansen, C. Riedel, *Adv. Nucl. Phys.* **6**, 287 (1973).

[13] L. Fortunato *et al.*, *Eur. Phys. J. A* **14**, 37 (2002).

[14] E. Khan *et al.*, *Phys. Rev. C* **69**, 014314 (2004).

[15] E. Khan *et al.*, *Phys. Rev. C* **66**, 024309 (2002).

[16] M. Grasso *et al.*, *Phys. Rev. C* **64**, 064321 (2001).

[17] E. Chabanat *et al.*, *Nucl. Phys. A* **635**, 231 (1998).