The Giant Pairing Vibration in Carbon isotopes

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Abstract. The ^{13}C(^{18}O,^{16}O)^{15}C and ^{12}C(^{18}O,^{16}O)^{14}C reactions at 84 MeV incident energy were 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 has been observed in both nuclei, attributed to the Giant Pairing Vibration (GPV). The neutron decay of the ^{15}C resonances, including the GPV, populated via the two-neutron transfer reaction has been studied using an innovative technique, which couples MAGNEX with the EDEN neutron detector array. The data show that the ^{15}C GPV mainly decays via two-neutron emission.

1. Introduction

In the last few years, a study of the structure of different nuclei was pursued at the Catania INFN-LNS laboratory by the (^{18}O,^{16}O) two-neutron transfer reaction at 84 MeV on different targets using the MAGNEX large acceptance magnetic spectrometer to detect the ejectiles. Thanks to its high resolution and large acceptance, high quality inclusive spectra were obtained, even in a largely unexplored region above the two-neutron emission threshold in the residual nucleus. New phenomena appeared, such as the dominance of the direct one-step transfer of the two neutrons [1] and the presence of broad resonances at high excitation energy in the ^{14}C and ^{15}C spectra [2]. These structures were recently identified as the first experimental signature of the Giant Pairing Vibration (GPV) [3], [4], [5] predicted long time ago [6].

The GPV is a giant collective mode in the atomic nuclei. Its microscopic origin is the coherence among elementary particle-particle excitations generated by the addition or removal to/from an atomic nucleus of two nucleons in a relative S-wave (motion component characterized by an orbital angular momentum L = 0). This quantum mechanism is analogous to that feeding the Giant Resonances (GR) observed in the inelastic nuclear excitation. The link between GPV and GR is the symmetry between single-particle states above (particle) and below (hole) the Fermi level. In both cases, the only required condition is a system whose minimum energy structure is governed by a mean field. GR are collective states, manifestation of a coherence mechanism of the particle-hole (p-h) excitations connecting major shells of the harmonic oscillator like nuclear mean field. In a similar way, the GPV represents the

particle-particle (p-p) or the hole-hole (h-h) counterpart of the GR. The main component of the p-p or h-h residual interaction is the pairing field. The introduction of such a field explains why at the minimum energy the nuclei with an even number of neutrons and protons are more tightly bound than the neighbouring even-odd or odd-odd ones.

Despite the existence of the GPV mode has been theoretically suggested and several evidences of p-h giant modes have been observed, like the GR, no resonances with the properties defining the GPV has been identified in any nucleus so far. This is probably due to the reaction mechanism required for populating the GPV. The addition or removal of two nucleons can be obtained in the laboratory by two-nucleon transfer reactions. These processes are typically characterized by a sizeable exchange of linear momentum at the surface of the colliding nuclei. Consequently, the angular momentum transferred in the reaction tends to be large and the cross section for the L = 0 modes is expected to be suppressed. This feature is more evident for reactions induced by heavy-ion projectiles and characterized by large negative Q-values. In Ref. [3] we reported on a new experimental approach to investigate the GPV mode, based on heavy-ion induced two-neutron transfer reactions on light nuclei.

2. Experiments and results

In the experiment conducted at INFN-LNS laboratory, a beam of $^{18}O^{6+}$ ions at 84 MeV incident energy impinged on a 49 ± 3 μg/cm^2 self-supporting ^{12}C and a 50 ± 3 μg/cm^2 self-supporting 99% enriched ^{13}C targets. The runs with ^{12}C were used also for estimating the background coming from ^{12}C impurities in the ^{13}C target. The ^{16}O ejectiles produced in the collisions were momentum analysed by the MAGNEX spectrometer working in full acceptance mode (solid angle 50 msr and momentum acceptance Δp/p ~ 24%).

The neutron decay of the ^{15}C resonances up to 16 MeV excitation energy, populated via the $^{13}C(^{18}O,^{16}O$ n) reaction was studied using a new method to determine the neutron kinetic energy by time-of-flight (TOF) in exclusive experiments [7]. It involves the use of MAGNEX coupled to the EDEN neutron detector array [8], [9]. A schematic view of the used set-up is shown in Figure 1.
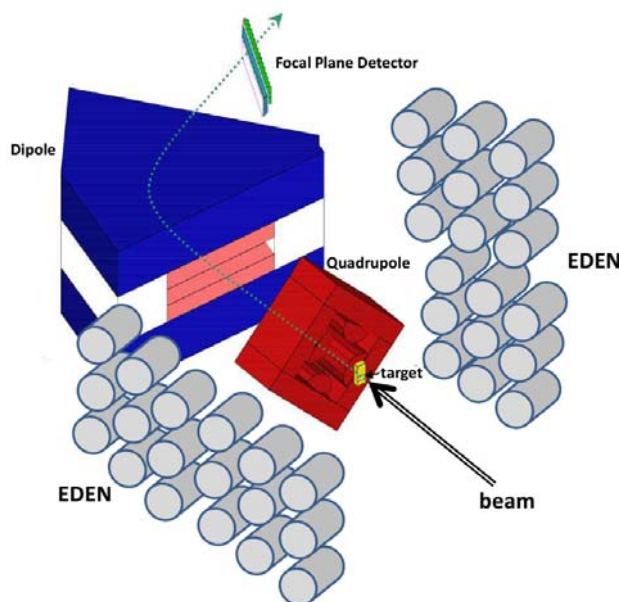

Figure 1. Schematic layout of the MAGNEX-EDEN facility.

The reconstructed excitation energy spectra $E_x = Q_0 - Q$ (where Q_0 is the ground to ground state Q-value) were obtained by the missing mass determination by MAGNEX applying an algebraic ray-

reconstruction technique [10], [11]. An example for the ^{15}C case is shown in Figure 2. The background contribution, which mainly comes from impurities of ^{12}C in the ^{13}C target, was evaluated and subtracted in the spectrum. Several narrow peaks corresponding to well-known low-lying bound and resonant states are observed.
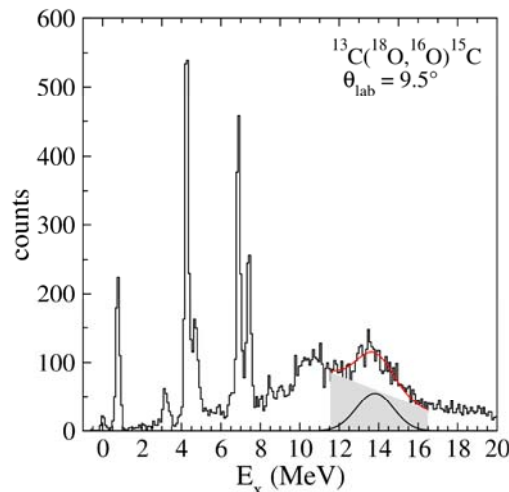

Figure 2. Energy spectra for the ^{13}C(^{18}O,^{16}O)^{15}C reaction. The linear background model, the fit of the GPV bump and their sum are shown as the grey area, the black Gaussian and the red line, respectively.

A sudden increase of the yield is found just above the two-neutron separation energy (S_{2n}= 9.394 MeV). In particular, a large bump, superimposed to the continuum background, is observed in the spectrum. A best fit procedure with Gaussian shapes and a locally adjusted linear background model gives an energy E_x = 13.7 ± 0.1 MeV (FWHM 1.9 ± 0.3 MeV). A similar spectrum is obtained in the case of ^{14}C, showing the presence of an unknown bump at 16.9 ± 0.1 MeV. The centroids and widths are confirmed by a supplementary experiment performed at 270 MeV bombarding energy studying the same reactions by the same experimental set-up.

The absolute cross section angular distributions of the two bumps were extracted, according to the procedure described in Refs. [12], [4]. The background underneath each peak was modelled by a linear function and the possible overlap between close peaks was treated by a least squared analysis assuming Gaussian shapes. The angular distribution for the bump at 13.7 MeV in ^{15}C is shown in Figure 3. A clear indication of an oscillating pattern is present.
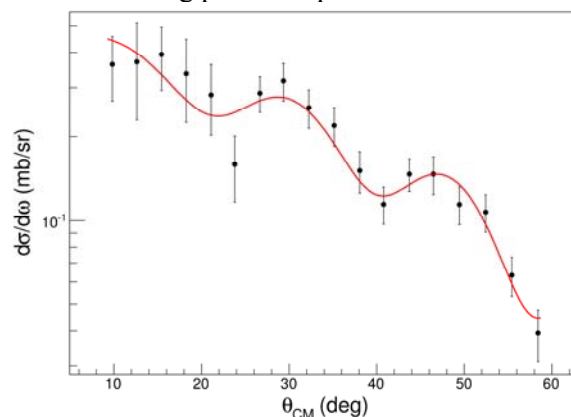

Figure 3. Experimental ^{14}C GPV angular distribution and comparison with the L = 0 Bessel function folded with the experimental resolution.

3. The GPV properties

A first important information is to identify the various components of the projectile break-up present in the inclusive excitation energy spectra, in order to isolate the spectral characteristics of the resonant-like excitations observed in the ^{15}C and ^{14}C nuclei. An extreme semi-classical model was used to describe the removal of two neutrons from the projectile and to analyse the measured energy spectra of ^{15}C in the region above S_{2n} [2], [13]. In this model, the specific treatment of nucleon-nucleon correlations beyond the residual nucleus mean field, as, for example, those due to the neutron-neutron pairing in the sd-shells were not included. The calculations give a good account for the continuum background in the excitation energy spectra. Both bumps in ^{14}C and ^{15}C are not explained within this approach. Similarly, approaches based on the towing mode of the 2n cluster [14] fail in accounting for the observed bumps [3]. These results indicate that a more complete description of the ^{12,13}C + n + n systems, including the n-n correlations, is required to describe these structures.

Another important aspect is investigation of the possible common origin of the two observed structures in ^{15}C and ^{14}C. To this aim, the excitation energy compared to the target ground state was computed as $E^t_x = E_x + M_r - M_t$, where M_t and M_r represent the mass of the target and of the residue, respectively. E^t_x is a more suitable parameter when comparing the data with theoretically derived p-p excitations built on the target mean field. When applying such a scaling of the excitation energies, the energy of the two resonances is found at about the same value in both nuclei. This is consistent with the results of ref. [15], where Quasi-particle Random Phase Approximation (QRPA) calculations predicted a GPV mode at ~ 20 MeV in oxygen isotopes. The same kind of calculations were performed for the ^{12}C response to the monopole p-p operator to predict the 0^+ two neutrons addition strength [3]. A broad distribution connected to the superposition of the $2p_{3/2}$, $2p_{1/2}$, $1d_{3/2}$, $1f_{7/2}$ and orbitals above is identified in the response function at 17 MeV with respect to the $^{14}C_{g.s.}$, a value consistent with the experimental centroid of the bump. A certain degree of collectivity is observed in such a bump when the residual interaction is taken into account.

A model independent approach to investigate the multipolarity of the observed resonances is the analysis of the oscillating behaviour of the experimental angular distributions. A well-known phenomenon in heavy-ion induced transfer reactions above the Coulomb barrier is the presence of oscillations in the angular distributions only for the L = 0 transitions [16]. The distinctive feature of the L = 0 angular distributions provides a model independent identification of L = 0 among the other multipolarities. This phenomenon was experimentally observed for the same ^{12}C(^{18}O,^{16}O)^{14}C reaction at 84 MeV in ref. [1] for transitions below S_{2n}. The oscillating pattern observed in the angular distributions of the two broad resonances in ^{14}C and ^{15}C (see Figure 3 in the case of ^{14}C) supports their dominant L = 0 nature.

Another observable defining the GPV is the cross section, which was predicted to be comparable with that of the L = 0 transition to the ground state pairing vibration. In the present case, it was found $\sigma(^{14}C_{g.s.}) = 0.92$ mb and $\sigma(^{14}C_{GPV}) = 0.66$ mb integrated in the same angular range. This indicates the high-collectivity of the GPV. This property was also confirmed in terms of the strength, in order to remove trivial Q-value effects.

To summarize, the MAGNEX data showed the clearest signal compatible with the long searched GPV so far. The resonances at $E_x = 16.9 \pm 0.1$ MeV in ^{14}C and at $E_x = 13.7 \pm 0.1$ MeV in ^{15}C show properties consistent with those defining the GPV mode. These results were recently published in [3]. The study of the decaying features of these resonances, partially presented in the next section, could reveal further information on the nature of the neutron-neutron correlation in the giant mode.

4. Neutron decay spectroscopy

The investigation of the decay modes of nuclear states populated in direct reactions is a powerful tool for understanding their microscopic structure. When the reaction populates unbound or weakly bound neutron-rich systems, the neutron emission is the dominant decay mode of the excited states

and sometimes of the ground state itself. In these cases, the coincidence detection of the emitted neutrons and charged ejectiles and the high-resolution measurement of the neutron energy are crucial tasks for spectroscopic investigations of the residual nuclei.

Above the one-neutron separation energy of ^{15}C, S_n = 1.218 MeV, the neutron decay of the observed resonances was studied using the EDEN array of neutron detectors [8] in coincidence with MAGNEX, as described in Ref. [12]. The technique consists in measuring the ion energy spectra (see Figure 2) using MAGNEX, then gating on the different peaks of the ^{15}C excitation energy spectrum (E_x) and plotting the corresponding neutron energy spectra (E_n) (see Figure 4) measured by EDEN in coincidence. An analysis of the neutron decay ratios was also performed. More details and the obtained results are presented in Ref. [7]. The resulting neutron emission probability for the whole ^{15}C spectrum above Sn is 101% ± 8%. Thanks to the high energy resolution in the ^{15}C spectrum, it was also possible to determine for the first time the neutron emission probability for each excited state.

Considering for example the ^{15}C excited state at E_x = 4.220 MeV, the neutron energies obtained by gating the excitation energy spectrum in the region 3.8 MeV < E_x < 4.4 MeV is shown in Figure 4a. A structure in the neutron spectrum at around 3 MeV appears well visible. Such an energy corresponds, within the uncertainty, to the energy of the neutrons decaying from the ^{15}C excited state at E_x = 4.220 MeV to the ^{14}C ground state, which is E_n = E_x - S_n = 3 MeV. This means that such ^{15}C resonance decays to the ^{14}C ground state. A branching ratio of 88 ± 16% was measured. The analysis of the other states of ^{15}C below S_n is reported in ref. [7].

The neutron decay of the ^{15}C resonance at E_x = 13.7 MeV, associated to the Giant Pairing Vibration, to the ^{14}C ground state is shown in Figure 4. The measured neutron energy spectrum rules out the emission of single neutrons which are expected to have energy distributed around $E_n = E_x - S_n$ = 13.7 - 1.22 = 12.5 MeV. The high energy part of the neutron spectrum can be described as the decay to the group of ^{14}C excited states between $E'_x(^{14}$C) = 6.094 MeV and $E''_x(^{14}$C) = 7.341 MeV, which would produce neutrons with energies distributed between 5 and 6.4 MeV. However, the most intense neutron distribution in coincidence with the GPV peak of ^{15}C can be explained by the decay to the ^{13}C ground state via a two-neutron emission. In this case, neutron energies ranging from zero to $E_n = E_x - S_{2n}$ = 4.3 MeV are expected and, indeed, observed. Due to the low yield, two-neutron coincidences were not observed in the present experiment. A dedicated run is foreseen as the next step of this research program.
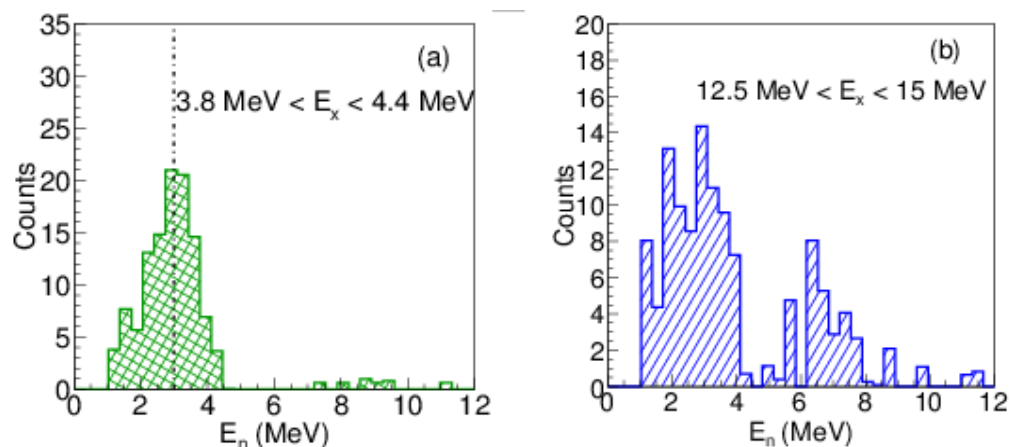

Figure 4(a) Neutron energy spectrum gated on the ^{15}C excitation energy 3.8 MeV < E_x < 4.4 MeV. (b) Neutron energy spectrum gated on the ^{15}C excitation energy 12.5 MeV < E_x < 15 MeV. In both plots the background neutron spectra are subtracted as described in ref. [7].

5. Conclusion

The Giant Pairing Vibration has been observed for the first time in the ^{14}C and ^{15}C nuclei populated via (^{18}O, ^{16}O) reactions at 84 MeV incident energy at excitation energy $E_x = 16.9 \pm 0.1$ MeV and $E_x = 13.7 \pm 0.1$ MeV, respectively. We performed a further run at 270 MeV and the results confirm the presence of the two new structures in ^{14}C and ^{15}C with the same centroid and width, within the error bars. The properties of the GPV, such as the excitation energy, the $L = 0$ angular momentum transfer, the width and the collective nature have been studied and are consistent with those defining the GPV mode. This observation confirms the basis of the particle-hole quantum symmetry in a system of interacting fermions and can provide benchmark information on the role of the pairing field in nuclear structure.

The decay by neutron emission of the states of ^{15}C above the one-neutron emission threshold and of the GPV resonance have been measured by coupling the MAGNEX magnetic spectrometer to the EDEN array of neutron detectors. The results show that the ^{15}C GPV mainly decays to the ^{13}C ground state emitting two neutrons sharing the available energy, while the decay to the ^{14}C ground state via single neutron emission is ruled out by the measured neutron energy spectrum. This is a further confirmation of the presence of large components with two correlated neutrons on a ^{13}C core for this state.

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