Signature of a Two-Phonon State through Its Proton Decay Pattern

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Inelastic scattering of 50 MeV/nucleon ^{40}Ca on ^{40}Ca was measured in coincidence with protons in order to investigate the excitation and decay of highly excited states in ^{40}Ca. The proton decay pattern corresponding to an excitation region around 34 MeV shows the characteristic behavior expected of the direct decay of a two-phonon state. Thus, by using this novel method, the presence of a double-phonon state built with isoscalar giant resonances in ^{40}Ca is demonstrated.

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Collective vibrations such as phonons in solids or plasmons in plasmas are a general feature of macroscopic systems. Such coherent motions survive even in systems with a small number of participants such as metallic clusters or nuclei. In particular, giant resonances (GR) such as the giant dipole resonance (GDR) have been interpreted as collective oscillations of the charged particles and monopole vibrations in nuclei are related to sound modes. It is a unique feature of nuclei to present a large variety of surface modes akin to waves at the interface of two liquids. A GR is understood as the first oscillator quantum (phonon), but until recently the second and higher quanta (multiphonons) remained unobserved. Not only would the observation of multiphonon states reinforce the theoretical interpretation of GRs, but their study would also provide a unique path towards the investigation of hitherto unknown properties of large amplitude collective motion in nuclei. Of particular interest are the energies of multiphonon states which should allow us to gain a handle on the anharmonicities of nuclear excitations [1,2]. Moreover, multiphonons should represent efficient doorway states towards energy dissipation in heavy ion collisions, and thus be a vital ingredient for our understanding of the dynamics of reactions between heavy nuclei [3].

The search for multiphonon excitations must proceed via two steps, the selection of specific reactions favorable for the observation of these modes located amid the high energy nuclear continuum, followed by the measurement of specific observables leading to the signature of the states. The best conditions to excite these multiphonon states are provided by reactions exhibiting large excitation probabilities for the GRs (and consequently for the multiphonons), or by pinpointing highly selective reactions.

In heavy ion scattering, the excitation of multiphonon states is intimately connected to the properties of the excitation of their building blocks, the GRs. Intermediate and high energy heavy ion beams have recently been shown to provide significantly improved conditions for the observation of GRs in nuclei [4], in particular very large differential cross sections and excellent peak to continuum ratios. The choice of the beam is of great importance. For example, the study of the isovector resonances will benefit from the use of high energy heavy beams (e.g., Pb at $E > 1$ GeV/nucleon), due to the large cross section for Coulomb excitation. Such beams will excite both isovector and isoscalar modes. On the contrary, moderate energy "light" heavy probes (e.g., Ca at $E \approx 50$ MeV/nucleon), for which the nuclear interaction dominates, will provide optimal conditions for the investigation of isoscalar modes, since isovector modes will be only weakly excited due to the much lower Coulomb cross section. The large cross section for GR excitation implies a sizable probability for the excitation of multiphonon states [5,6], making heavy ion reactions a privileged tool for their study.

The study of inelastic scattering of various heavy ions at intermediate energies has revealed the existence of structures located between 20 and 60 MeV excitation energy [7–9]. From these data, it was concluded that these structures are due to target excitation and an interpretation in terms of the excitation of multiphonon states built with isoscalar GRs was suggested [6,9]. From the point of view of selectivity, pion double charge exchange reactions are an excellent probe to study double GDR [10,11]. In such reactions the double GDR has been observed over a wide range of nuclei, albeit with very small cross sections on top of a relatively large continuum. Very recently, in exclusive measurements of relativistic heavy ion collisions, strong evidence of the existence of a double GDR excited by Coulomb interaction has been given [12,13].

In this Letter, we report on an experiment in which

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for the first time the typical particle decay pattern for direct decay of a two-phonon state was used to observe the double-phonon state built with the isoscalar giant quadrupole resonance (GQR) excited by the nuclear interaction. The experiment consisted in measuring inelastically scattered 50 MeV/nucleon ^{40}Ca from a 1 mg/cm^2 ^{nat}Ca target in coincidence with protons. It was performed at the GANIL facility using the SPEG spectrometer associated with its standard detection system to measure the ejectiles [14]. Unambiguous identification of $^{40}Ca^{20+}$ was obtained. The energy resolution was about 800 keV. Light charged particles were detected in 30 cesium iodide elements of the multidetector array PACHA [15], positioned in the reaction plane and covering the whole angular domain with the exception of a small wedge of [−15,+7°] around the beam direction (positive angles are on the same side as the spectrometer). The proton energy resolution was about 2%. Thresholds ranged between 1 and 3.5 MeV. In order to be able to add the spectra from various detectors, a software threshold of 4 MeV protons in the center of mass of the recoiling ^{40}Ca nucleus was set during the analysis.

The inclusive inelastic spectrum is displayed in Fig. 1(a) with two different energy binnings (200 keV/channel and 1 MeV/channel). In the first representation, the giant resonance is observed to be split into two components centered at 14 and 17.5 MeV excitation energy with widths of 2 and 3 MeV, respectively. By comparison with distorted wave Born approximation calculations, both components can be mainly attributed, in the studied angular range (from 1.2° to 5° in the laboratory), to the excitation of the GQR [15], which is calculated to have a cross section 5 times larger than either the GDR or the isoscalar giant monopole resonance. When the energy scale is compressed, some small bumps are observed at higher excitation energy, in particular at 34±2 MeV, in agreement with the previous observation of a structure at 37±2 MeV in the ^{40}Ar + ^{40}Ca reaction at 44 MeV/nucleon [8], which was attributed to a two-phonon state. This assignment was based on calculations which predict that the strongest contribution to this region comes from the double GQR [6]. A weaker but sizable contribution from high multipolarity (mainly $L = 3$ and $L = 4$) one-phonon GRs is also expected. The isovector GQR is predicted to be located in the same region; however, its cross section should be very low due to the weak Coulomb interaction in the reaction studied and isospin conservation for the nuclear interaction.

Coincidence measurements of protons emitted at backward angles allow us to select target excitations in the inelastic spectrum, since other mechanisms such as pickup, breakup, and knockout give rise to protons peaked respectively at forward angles and around the direction of the recoiling target [16]. In Fig. 1(b), the ^{40}Ca inelastic spectrum in coincidence with these backward emitted protons is displayed. Such a spectrum must be corrected for the multiplicity of emitted protons [15]. For example,

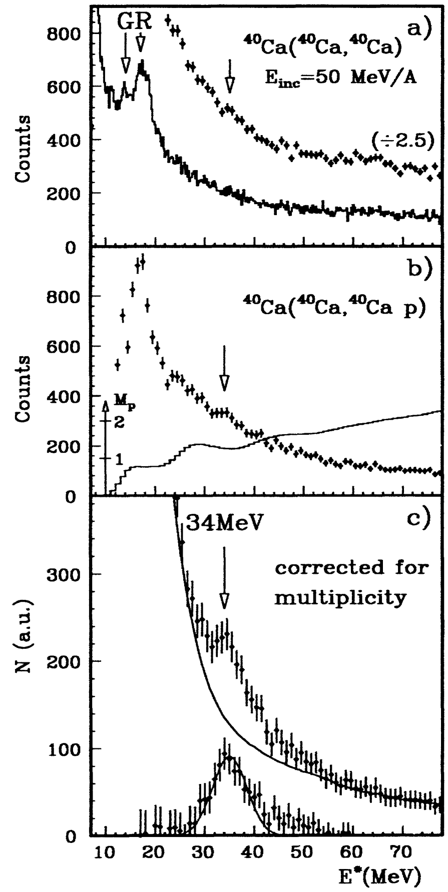

FIG. 1. (a) Inclusive inelastic spectrum with two different binnings (200 keV/channel and 1 MeV/channel). (b) Inelastic spectrum in coincidence with one proton emitted backwards, displayed along with the multiplicity correction. (c) Inelastic spectrum corrected for the proton multiplicity. The solid line corresponds to a polynomial fit of the background. The result of the background subtraction is shown below, fitted by a Gaussian.

when the two-proton decay channel is open, the probability to detect a coincidence event will be greater than when only the one-proton channel is accessible. When the solid angle for particle detection is small, as in the present experiment, this probability goes simply as the multiplicity of protons above the detection threshold. The correction was performed by calculating the proton multiplicity as a function of excitation energy, taking into account the detector thresholds, using two statistical codes (CASCADE [17] and LILITA [18]), and dividing the measured spectrum by this multiplicity. The result depends very little on the choice of the evaporation code. The multiplicity function calculated with the code LILITA is shown in Fig. 1(b). The corrected spectrum is displayed in Fig. 1(c). In such a correction, the main assumption is that particle emission is purely statistical and the direct contribution is neglected. This will tend to slightly overestimate the proton multiplicity. We estimate the systematic error using this assumption to be about 20%. In this coincidence spectrum a very prominent structure at twice the GQR excitation energy shows up, which is barely visible in the inclusive spectrum.

To roughly estimate the characteristics of this structure, several polynomial fits of the background were subtracted. An example is shown as a solid line in Fig. 1(c), and the result, fitted by a Gaussian, is displayed in the bottom of the figure. The width of the structure is estimated to be 9±2 MeV. Concerning the cross section, a ratio of 8±2 between the giant resonance and the structure at 34 MeV was extracted. These characteristics are compatible with the multiphonon model [6] which predicts a ratio of 15 and a width for the two-phonon state equal to $\sqrt{2}$ times the width of the one-phonon state [19]. However, theoretical calculations for this energy region predict the presence of both the two-phonon state and other high lying giant resonances. Therefore, it is difficult to demonstrate the existence of the two-phonon state simply by studying the characteristics of the observed structure.

The main point of this Letter is to present a new method to sign the presence of multiphonon strength through its decay. For this, a detailed study of the decay of the structure and a comparison with the direct decay pattern of the GQR is called for. As is well known, particle decay of GRs can occur through various processes [20], mainly the direct decay into hole states of the $A-1$ residual nucleus with an escape width $\Gamma^{\uparrow}$, and the statistical decay leading to the spreading width $\Gamma^{\downarrow}$. Figure 2 sketches the direct decay of a GR and a high lying state in ^{40}Ca through proton emission. The GR decays towards hole states in ^{39}K. If the high lying state is a one-phonon GR, it will also decay into hole states through the emission of one high energy proton (dashed arrows). Conversely, if the high lying state is a two-phonon state, since the mixing with other high lying states and the coupling between phonons is expected to be weak [1], each of the two phonons will undergo a direct decay exhibiting the same features as the direct decay of the GR. Two protons will then be emitted. The first proton will populate the GR (or GR $\otimes$ hole states) in ^{39}K, and the second will deexcite this GR, leading to two-hole states in ^{38}Ar.

It is the direct decay which can give a signature of a multiphonon state.

Experimentally, the direct decay part of the GQR is extracted by constructing missing energy spectrum $E_{\rm miss} = E^*_{^{40}{\rm Ca}} - E_p^{\rm c.m.}$, where $E^*_{^{40}{\rm Ca}}$ is the initial excitation energy in ^{40}Ca and $E_p^{\rm c.m.}$ the proton energy in the center of mass of the recoiling ^{40}Ca target, and comparing with the equivalent spectrum calculated with the statistical decay code CASCADE [17]. Figure 3(a) shows the result when a gate is set on the GQR region, from 12 to 20 MeV excitation energy in ^{40}Ca. The ground state (GS) of ^{39}K as well as a peak at 2.6 MeV which corresponds to the first hole state in ^{39}K are well separated. The CASCADE calculation has been performed, entering, in addition to the continuum, 50 discrete states up to 6.55 MeV for ^{39}K and discrete states up to a few MeV for neighboring nuclei. The code was run for excitation energies between 12 and 20 MeV in 1 MeV steps. A 4 MeV threshold was set for protons as for the data. Missing energy spectra for each excitation energy were weighted according to the GQR

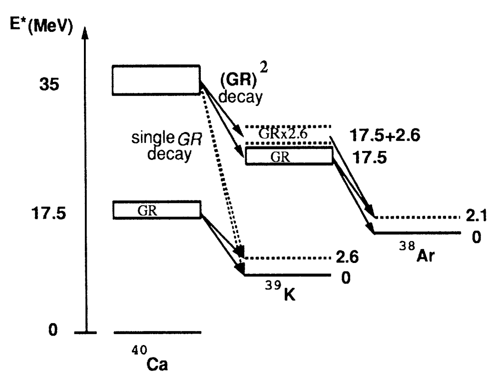

FIG. 2. Schematic diagram of direct decay of the GR and a double phonon at 34 MeV. Also direct decay of a GR at 34 MeV (dashed arrows).

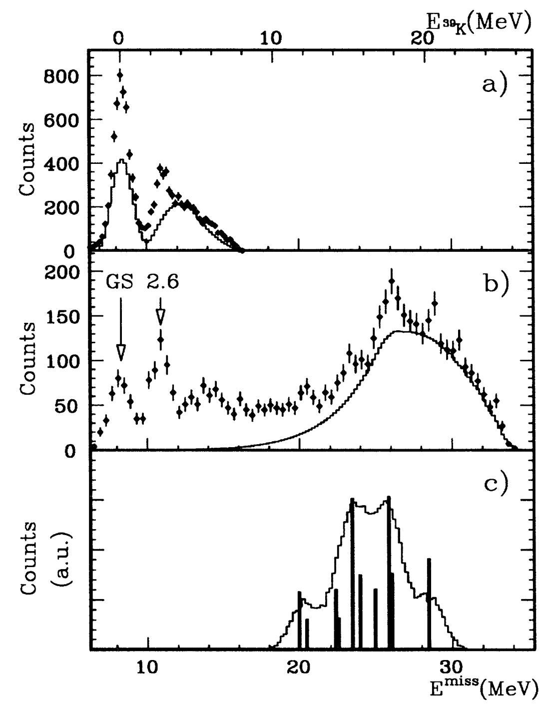

FIG. 3. (a) Missing energy spectrum gated on the GQR (12–20 MeV) for protons emitted in the backward direction between +50° and −110°. The solid line is the result of the CASCADE calculation (see text). (b) Same for the double phonon (30–38 MeV). (c) Simulated missing energy spectrum for the double-phonon direct decay (see text). The upper scale shows the ^{39}K excitation energy.

cross section and summed. The result of the calculation is shown by the histogram in Fig. 3(a). The calculation has been normalized so as to never overshoot the data, in order to obtain the maximum contribution consistent with statistical decay. An excess of cross section for decay to the GS and the first excited hole state is observed, which can be ascribed to direct decay.

For excitation energies in ^{40}Ca around 34 MeV, corresponding to the structure, the missing energy spectrum [Fig. 3(b)] shows peaks at 8.3 and 10.9 MeV corresponding to the population of the GS and the 2.6 MeV state in ^{39}K. Further discussion on these peaks will be presented in a subsequent paper. The most striking feature, however, is the presence of peaks located about 17 MeV above the GS, which corresponds to the GR energy in ^{39}K (see upper scale) superimposed on a broad contribution. The calculated statistical decay spectrum corresponding to this energy region is shown by the histogram. At these large missing energies, two protons can be emitted, while only one is detected. If the first emitted proton is detected, peaks in the missing energy spectrum mean that a small number of states must be preferentially populated in ^{39}K. In the same way, if we detect the second emitted proton, which populates ^{38}Ar, peaks will show up only if the initial excited nucleus, ^{40}Ca, has decayed through particular states in ^{39}K, to well defined low lying states in ^{38}Ar. This is precisely the picture expected for the direct decay of a two-phonon state (cf. discussion of Fig. 2).

A simulation of such a two-phonon direct decay has been done with the following assumptions. The GQR is composed of two peaks centered at 14 and 17.5 MeV with widths (FWHM) of 2 MeV, making up 40% and 60% of the total GQR cross section, respectively. A two-phonon state is constructed by randomly picking each phonon between the two components. As observed for the GR in ^{40}Ca [Fig. 3(a)], the direct decay of each phonon is assumed to populate only the GS and the first excited hole state of the daughter nucleus (^{39}K or ^{38}Ar). The decay probability to the GS and the first excited state were set equal. The experimental resolution of 800 keV was taken into account. The calculation has been done for a 100% direct decay but we checked that the main features remain unchanged for a smaller direct decay branch. The result of the simulation is presented in Fig. 3(c). The various decay combinations should give rise to ten peaks, the positions of which are shown by bars. However, due to the experimental resolution and the GR width, the final result exhibits only four peaks which are in remarkable agreement with those observed in the experimental missing energy spectrum [Fig. 3(b)]. This comparison confirms the picture of the excitation of a two-phonon state.

To summarize, the proton decay of high energy states in ^{40}Ca excited by heavy ion inelastic scattering has been investigated. The coincident inelastic spectrum presents a prominent structure located at 34 MeV excitation energy. Through the observation of its specific direct decay pattern it has been demonstrated that this structure is due to the excitation of the double quadrupole phonon. This is the first signature of a double GQR. The excitation of multiphonon states in such reactions was predicted by calculations coupling the quasiboson approximation for nuclear excitations to classical trajectories [6]. It thus turns out that heavy ion inelastic scattering in combination with coincident decay measurements is a unique tool to investigate multiphonon states built with isoscalar giant resonances in nuclei.

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