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Search for the giant pairing vibration through (p,t) reactions around 50 and 60 MeV

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The existence of the giant pairing vibration (GPV) in ^{120}Sn and ^{208}Pb was investigated using the (p,t) reaction at incident proton energies of 50 MeV and 60 MeV for the scattering angles 0° and 7°. No clear signature for the GPV was found, providing an upper limit for the cross section of $\sigma_{\max} = 0.2$ mb. Theoretical interpretations for the low cross section of the GPV are discussed.

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Introduction. A giant pairing vibration (GPV) is a collective mode in the two neutron transfer channel [1–3]. From a theoretical point of view, this mode is of fundamental importance since it is analogous to a giant resonance, but in the particle-particle channel. Pairing vibrations manifest themselves as a $L = 0$ transition mode from an A nucleus to a $A \pm 2$ nucleus. The GPV is predicted as a large bump in the excitation energy spectrum around $70A^{1/3}$ MeV. Its collective strength is expected to be maximum for heavy nuclei, such as Sn or Pb isotopes, where numerous nucleons may contribute coherently [1]. Various independent theoretical calculations converge in predicting the GPV as a strong mode (few mb) typically located around 13 MeV in heavy nuclei in the two-neutron $L = 0$ transfer channel [1,2,4].

Pairing vibrations are measured through two-particle transfer reactions. The transfer cross section crucially depends on the pairing interaction at work in the transferred pair [1–3]. Initially, in the 1970–1980s, no microscopic calculation was available to determine the form factor of the transition. The first microscopic calculations have been performed only recently [5], allowing for a strong link to be made between the pairing interaction and pairing vibrations. Several calculations followed [6,7], showing the renewed interest for such studies. It is therefore meaningful to use pairing vibrations as a complementary observable to the masses, in order to constrain the pairing interaction, and study the implications to nuclear matter. Therefore the existence or absence of the GPV may be instrumental in increasing our understanding of the pairing interaction. In Ref. [8] the impact of various pairing interactions on pairing vibration predictions has been analyzed for using a HFB + QRPA approach. A good sensitivity is found from a pure surface interaction compared to mixed interactions, especially in the case of very neutron-rich nuclei such as ^{136}Sn. In the case of exotic nuclei, pairing vibrations are also found to be more sensitive to the surface/volume type of pairing interaction, than in the case of stable nuclei. This may be due to the larger extension of the neutron density in very neutron-rich nuclei.

In the 1970s and the 1980s studies of (p,t) reactions were undertaken on Sn and Pb nuclei in order to measure the GPV [1,2]. However these attempts remained unsuccessful. The following reasons may be invoked: i) The proton incident energy should be high enough to excite a 13 MeV mode. However, if too high (above 80 MeV) the L matching condition hinders the $L = 0$ transfer, and the GPV is not strongly excited [9]. An appropriate energy range for the incident proton is located around 50 MeV. ii) The use of a spectrometer is decisive in order to precisely measure the triton in the exit channel. The only reported search for the GPV with $E_p \sim$ 50 MeV used Si detectors, yielding a strong background [10]. iii) A mode around 8.5 MeV was detected [2], but it finally turned out, after several years of investigation, not to be the GPV, but deep hole noncollective states [11]. This resulted in the experimental efforts during the 80's being exclusively devoted to studying this mode.

It should be noted that it was recently proposed to use exotic nuclei to detect the GPV [2]. As weakly bound projectiles, exotic nuclei could provide a high Q value, as, e.g., in the (^{6}He,α) reaction. However the background is expected to be important, due to the various channels of two-neutron emission from ^{6}He, namely breakup, etc. Moreover the beam intensity is several orders of magnitude lower than for stable beams and therefore it is not possible to detect the GPV with exotic beam intensities, as shown by a recent ^{208}Pb(^{6}He,α) experiment performed at GANIL [12,13].

In summary, an experiment with a well-suited reaction and detection setup to search for the GPV has until now not been undertaken. In this Brief Report we report on measurements of the (p,t) reaction that used an appropriate setup to detect the GPV. This experiment combines a proton beam of energy $E_p \sim$ 50–60 MeV with the use of a magnetic spectrometer to measure the outgoing tritons. Furthermore, as the $L = 0$ cross sections are known to exponentially increase when approaching 0°, this measurement was performed at small angles that include 0°. The aim of this work is to provide a decisive answer to the question of the existence of the GPV.

Experimental setup. The (p,t) experiments were carried out at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), South Africa, using proton beams of 50 MeV and 60 MeV with beam intensities of up to 10 nA from the $K = 200$ Separated Sector Cyclotron (SSC). Self-supporting isotopically enriched (more than 95%) ^{120}Sn

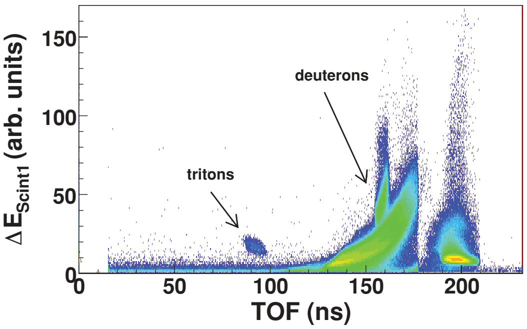

FIG. 1. (Color online) Particle identification spectrum of the pulse height of the first scintillator versus the TOF for a 0° measurement at $E_p = 50$ MeV. Tritons and deuterons are clearly indicated. All the other events represent background at 0° due to the internal beam stop.

and ^{208}Pb target foils were used. The ^{208}Pb target density was 2.1 mg/cm^{-2} whereas two ^{120}Sn targets were used, with densities of 2.1 mg/cm^{-2} and 3.32 mg/cm^{-2}. The outgoing tritons were detected in the focal plane detectors of the $K = 600$ QDD magnetic spectrometer. The detectors consisted of a pair of wire chambers followed by a pair of plastic scintillators. The wire chambers allowed for the reconstruction of particle trajectories in the focal plane while the plastic scintillators were used as trigger detectors and to perform particle identification.

The spectrometer has a 9.7% momentum acceptance and ±2° angular acceptance. A spectrometer magnetic field setting that selects the central triton energy of 36 MeV allows for a measurement over and excitation energy range of ~6.6 MeV. Since this range is beyond the maximum expected width of the GPV, data were acquired for different spectrometer field settings in order to cover the whole excitation energy range of 0–21 MeV for the $E_p = 60$ MeV data set and 0–17 MeV for the $E_p = 50$ MeV data set.

At 7° the measurements were performed with both ^{120}Sn and ^{208}Pb target nuclei using an incident proton beam of 60 MeV. The energy of the tritons was sufficient to allow coincidence signals from both scintillators to generate a trigger for the data acquisition system.

A small overlap in energy loss in the scintillators resulted in deuteron contamination of the (p,t) spectra. However, deuteron events could easily be distinguished from triton events due to their different ion optical characteristics, resulting in easily discernible deuteron loci in a plot of the focal plane position versus focal plane angle. At $\theta_{K=600} = 7^\circ$ the measurements were performed with both ^{120}Sn and ^{208}Pb target nuclei using an incident proton beam of 60 MeV. The energy of the tritons was sufficient to allow coincidence signals from both scintillators to generate a trigger for the data acquisition system. Rigidity calculations indicate that deuterons constitute the only particle background in the triton spectrum, and that it consists of a few discrete states for excitation energies higher than $E^* \sim 17.1$ MeV in ^{120}Sn and $E^* \sim 17.5$ MeV in ^{208}Pb. However, deuteron events could easily be distinguished from triton events due to their different ion optical characteristics, resulting in easily discernible deuteron loci in a plot of the focal plane position versus focal plane angle.

The measurements at 0° were performed for the ^{120}Sn target at $E_p = 50$ MeV and 60 MeV. In this experimental configuration both the particles of interest as well as the primary proton beam enter the magnetic spectrometer. Due to the difference in rigidity the proton beam was collected at an L-shaped brass beam stop placed midway between the two dipole magnets of the spectrometer, while the tritons were focused on the focal plane. This resulted in a considerable increase in background contamination seen in the focal plane, especially for measurements with the lower beam energy ($E_p = 50$ MeV) since the trigger was generated by the first scintillator only. The background rate was as much as 500 times higher than that of the tritons of interest. This background consisted of protons scattering off the beam stop with the combinations of angles and magnetic rigidities so that their trajectories reached the focal plane detectors. However, the combination of trajectories and energies of this low energy background resulted in significantly longer flight times than that experienced by the tritons. The accelerator was therefore operated in pulse selection mode (using one in five), thereby increasing the time between beam pulses sufficiently to allow clean identification of the tritons. A plot of the relative time of flight (TOF), measured between the SSC radio-frequency (RF) signal and the scintillator trigger, versus energy deposited in the first scintillator is shown in Fig. 1. Without the pulse selection mode the triton locus would clearly be lost amidst the background events, considering that the ordinary beam packet separation for $E_p = 50$ MeV would have been only 69.3 ns. Reasonable data acquisition dead time of less than 10% was achieved by vetoing a portion of the TOF range which corresponded to the majority of the background events.

Figure 2 displays a typical excitation energy spectrum obtained, and shows the very low background. Peaks were observed in both data sets for the ^{16}O(p,t) and ^{12}C(p,t) reactions due to target contamination. Energy calibration of the spectra at the various field settings was achieved by comparing the relative positions of known discrete states in the target

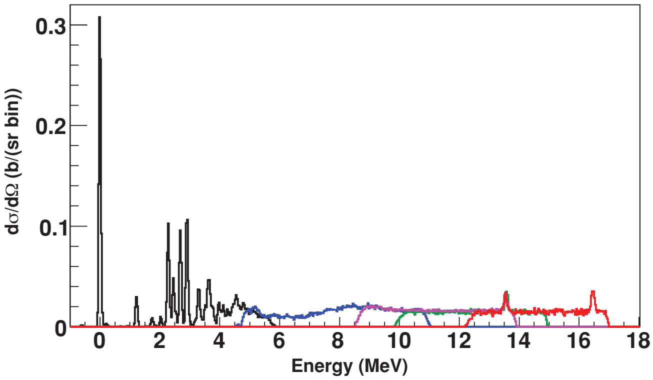

FIG. 2. (Color online) Excitation energy spectrum of ^{118}Sn for the 0° measurement at $E_p = 50$ MeV. The bin width is 30 keV/bin. The data acquired for various spectrometer field settings are displayed in different colors.

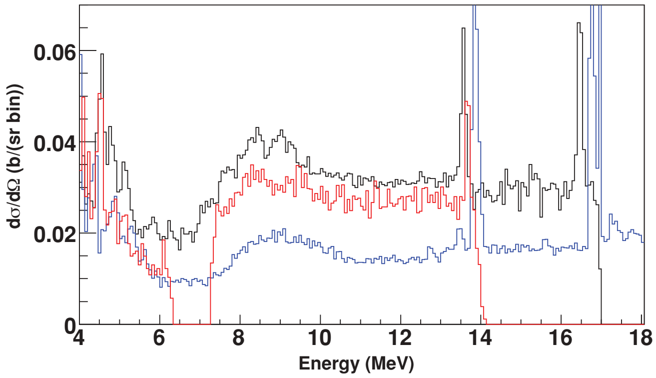

FIG. 3. (Color online) Excitation energy spectrum of ^{118}Sn for the 0° measurement at $E_p = 50$ MeV (upper curve) and $E_p = 60$ MeV (middle curve) and the 7° measurement at $E_p = 60$ MeV (lower curve). The bin width is 67 keV/bin. The data are taken for the 0° measurement at $E_p = 60$ MeV stops at 14 MeV excitation energy.

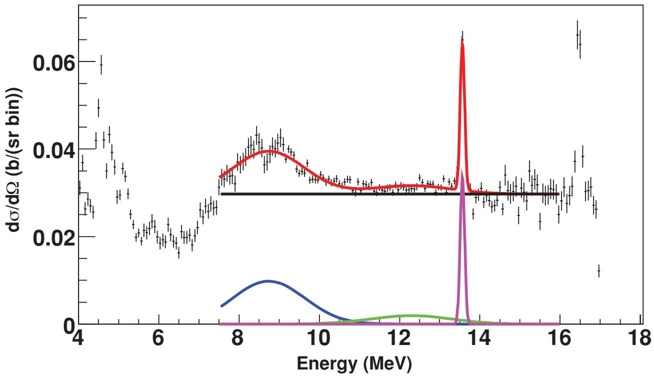

FIG. 4. (Color online) Excitation energy spectrum of ^{118}Sn for the 0° measurement at $E_p = 50$ MeV. The linear background, deep-hole states (around 9 MeV), fit for a possible GPV (around 12 MeV), oxygen contaminant (around 13.5 MeV) and total fitting function are shown. The bin width is 67 keV/bin and a GPV width of $\sigma = 800$ keV was assumed.

nuclei from the ^{58}Ni(p,t) reaction, which has a more negative Q value (−13.984 MeV) as well as contamination peaks.

Results. No clear evidence of the GPV was found at 7°, for either the ^{120}Sn or ^{208}Pb targets for a proton beam of 60 MeV. The results are shown in Fig. 3. The excitation energy spectrum from ^{120}Sn shows the deep hole states between 8 and 10 MeV as well as low-lying states, in agreement with previous measurements [2,9,10]. At higher energies, apart from a sharp peak due to oxygen contamination of the target, a small bump may be visible in the expected GPV area around 12 MeV. However, the statistics are not good enough to give a clear answer to the existence of the GPV. This is mainly due to the low $L = 0$ selectivity of the experiment, performed at 7°. Therefore the recent availability of the zero degree mode at iThemba Laboratories allowed us to perform the experiment with a higher $L = 0$ selectivity.

The excitation energy spectra of ^{118}Sn for the 0° measurement at $E_p = 50$ MeV and $E_p = 60$ MeV and the 7° measurement at $E_p = 60$ MeV are plotted in Fig. 3. As mentioned above, the peaks at low energy correspond to low-lying states of ^{118}Sn, whereas the sharp peak above 13 MeV originates from the oxygen contamination in the target. All these peaks are found at the correct energy, validating our method of analysis. A bump is observed for E^* between 8 and 10 MeV, which corresponds to the deep hole states. A larger background is clearly observed in the 0° case when compared to 7°, indicating the possible low L composition of this background.

In the case of the spectrum at 0° with a 50 MeV proton beam, a linear background was assumed from the average background level between 14 and 16 MeV. The fit of the spectrum from 7 to 14 MeV above the background allows possible structures to be studied. This fit to data in the GPV area (E^* between 12 and 14 MeV) depends on the width of the Gaussian fitting function that is chosen. In the absence of straightforward theoretical considerations, one could tentatively put forward a value between 0.6 and 1 MeV [2]. A large bump is observed in the deep-hole area (E^* between 8 to 10 MeV) whereas a much smaller bump is extracted in the GPV area. The corresponding analysis is displayed in Fig. 4. The integral of this last bump provides an upper limit for the GPV cross section. It is estimated at $\sigma_{\max} = 0.13$ mb and 0.19 mb for a GPV width of 600 keV and 1 MeV, respectively. This cross section corresponds to an integration over the angular acceptance of the spectrometer (±2°).

The typical cross section predicted for the GPV is of the order of a few mb [4]. The present study suggests that the GPV cross section is at least one order of magnitude lower than the predicted theoretical value, which may explain the difficulty in detecting it. The weak but nonvanishing signal obtained for the GPV may provide encouragement to perform this reaction with more optimal conditions, such as with a lower incident proton energy of around 35 MeV. Work along these lines is in progress.

Discussion on the GPV. The present results address the question of the existence of the GPV. It should be noted that various calculations predict the existence of the GPV [1,2,4,5]. The GPV question is also raised for light systems: are heavy nuclei really more adapted for the GPV than light ones? In Refs. [5,7] the GPV is predicted in ^{20}O using both QRPA and TDHFB approaches. However it should be noted that TDHFB calculations in a heavier system, such as calcium isotopes, do not exhibit the GPV as a distinct bump [7]. Experiments are also performed at LNS-Catania on light nuclei to investigate if the GPV is more likely in light nuclei, such as carbon and oxygen, than in heavy nuclei [14]. However for light systems the optimum kinematic conditions for pair transfer are different from that of a heavy system [15].

Another explanation for the possible low cross section observed for the GPV is that the two-particle transfer mechanism may quench high-energy collective states such as the GPV. This effect should not be disregarded, because several structure models predict a large GPV strength, whereas the cross section of the GPV seems to be low. There is also the possibility that the two neutron stripping cross section may be different to that of two-neutron pickup. Therefore (t,p)-like experiments, such as (^{12}C,^{10}C) may also be useful to investigate. Finally recent investigations involving continuum effects predict that the GPV may be located at higher energy than 13 MeV in heavy nuclei, with a 10 MeV width, making it difficult to be detected [16]. The two proton channel as well as the neutron-proton one might be more promising.

Conclusion. The possible existence of the giant pairing vibration has been investigated through (p,t) reactions around 50 MeV on ^{120}Sn and ^{208}Pb targets for small angles including zero degree measurements. No clear signal of the GPV was found, although a possible bump with a cross section $\sigma_{\max} = 0.2$ mb is extracted. This value is one order of magnitude lower than the one usually predicted, which could explain the historical difficulty to detect the GPV. More advantageous experimental conditions are looked for, such as a proton beam energy of about 35 MeV so that $L = 0$ modes are preferentially increased.

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