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## Low-lying excited states in $^{17,19}\text{C}$

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### Abstract

$^{17,19}\text{C}$  nuclei have been investigated by proton inelastic scattering on a liquid hydrogen target at intermediate energies. Two peaks were observed in the Doppler-corrected  $\gamma$ -ray spectra with energies of 210(6), 331(6) keV in  $^{17}\text{C}$  and 72(4), 197(6) keV in  $^{19}\text{C}$  corresponding to the decay of two excited states in both nuclei. Analyzing the reaction cross sections, tentative spin values were determined for the states. The experimental results are in reasonable agreement with the predictions by shell model calculations.

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Several interesting new effects have already been found and are expected in the structure of nuclei lying close to the driplines. In recent years, the ground state properties of the neutron-rich proton  $p$ -shell nuclei were extensively studied and their neutron skin or halo properties were shown in many cases. Special attention was given to  $^{19}\text{C}$  to establish the one-neutron-halo feature of its ground state. A large interaction radius [1] and a narrow longitudinal momentum distribution of the halo neutron has been proved for this nucleus [2–6]. On the basis of measurements of different quantities associated with neutron-removal reactions, the spin  $1/2^+$  of the ground was proposed [5,7,8] and the  $s$ -wave spectroscopic factor of about  $C^2S = 0.5$ –1 was deduced [5,8]. To describe a group of the experimental findings in a reasonable manner, the assumption of a neutron separation energy larger than the one deduced from mass measurements is needed [5,7–10], while the Glauber model analysis of the data suggests the existence of an enlarged core [6,11]. Posing other assumptions, different ground state spin assignments might also be possible [11]. The study of the excited states of these nuclei, the properties of which may give further information on correlations between the nucleons, were not in the spotlight.

Theoretical calculations predict two low-lying excited states in both  $^{17,19}\text{C}$  [5,12,13], but only one excited state was found in  $^{17}\text{C}$  [14–16]. Recently, two  $\gamma$  transitions in  $^{17}\text{C}$  were reported [17] suggesting that both predicted excited states are bound in this nucleus. In addition, a  $\gamma$ -ray peak in  $^{19}\text{C}$  was also observed [17] indicating that in spite of the very low value of the neutron separation energy ( $S_n = 160 \pm 110$  keV deduced from direct mass measurement [18]), at least one excited state is bound in  $^{19}\text{C}$ . To investigate the properties of these excited states, to confirm their existence, to check whether a second excited state is bound in  $^{19}\text{C}$  and to determine the deformations of both nuclei, we have studied them via the  $(p, p'\gamma)$  process in inverse kinematics at intermediate energy. The  $(p, p'\gamma)$  method can exploit the large target thickness and the large number of target nuclei in a liquid hydrogen target. In this way, it can be very efficient in populating excited states in exotic nuclei by use of radioactive beams of intensities of 1 particle/s (pps) or even lower [19,20]. In addition, it provides information on the collectivity of the nuclei based on the DWBA analysis of the cross sections. It may be interesting since recently

the shell model calculations used for the analysis of the one-neutron knock-out reaction on these nuclei [5] raised the possibility of deformed ground state of the  $^{17}\text{C}$  isotope.

The experiment was carried out at the RIKEN radioactive isotope separator RIPS [21]. A  $^{22}\text{Ne}$  primary beam of 100 pnA intensity and 110 A MeV energy hit a  $^9\text{Be}$  production target of 0.8 cm thickness. Optimizing for a  $^{19}\text{C}$  beam, after momentum and mass analysis, using a  $1.36$  g/cm<sup>2</sup> thick aluminum wedged degrader at the momentum dispersive focal plane (F1), the secondary cocktail beam included 20%  $^{19}\text{C}$  and 25%  $^{17}\text{B}$ . Tuning the  $^{17}\text{C}$  beam, the same conditions were used with different magnetic field settings and practically 100% purity could be produced. The momentum acceptance of the fragment separator was set to a maximum value of 6% to have as high a beam intensity as possible. In this way, around 800 pps total rate of  $^{17}\text{C}$  was achieved. On an event-by-event basis, an identification of the incoming beam was performed by energy-loss, time-of-flight (TOF) and magnetic rigidity ( $B\rho$ ) measurement. The  $B\rho$  was determined using a parallel plate avalanche counter (PPAC) with an area of  $15 \times 10$  cm<sup>2</sup> at F1 focal plane covering the total momentum range of the secondary beam. Plastic scintillators of 0.5 mm thicknesses were placed at the second and third focal planes (F2 and F3) measuring the TOF while for the energy-loss information, two silicon detectors of 0.35 mm were put at F2 and F3. With this method, the incident  $^{17,19}\text{C}$  particles could be well distinguished from other beam species.

The secondary beams bombarded a liquid hydrogen target of 3 cm diameter at F3, the thickness of which was 24 mm and it was closed by 6.6  $\mu\text{m}$  thick Aramid foils [22]. The hydrogen was cooled down under 22 K having an average areal density of 190 mg/cm<sup>2</sup>. Based on their incident energy and on the energy-loss information, the mean energy of the reaction induced by  $^{17}\text{C}/^{19}\text{C}$  isotopes was calculated to be 43.3/49.4 A MeV. The position and shape of the incident beams was monitored by two PPACs placed at F3. The horizontal spot size of the beams was 20 mm while the vertical one was 18 mm in FWHM. In order to reduce the background, the events produced by the beam particles hitting the target holder were filtered out by putting a gate on the projected image of the beam on the target.

The DALI2 setup consisting of 158 NaI(Tl) scintillators [23] surrounded the liquid hydrogen target to detect the de-exciting  $\gamma$ -rays. Since we aimed to observe very low-energy radiation, the calibration and threshold setting—made by standard sources of  $^{137}\text{Cs}$ ,  $^{60}\text{Co}$  and  $^{133}\text{Ba}$ —was crucial. Finally, we could adjust the array to be able to detect  $\gamma$ -rays with energies higher than 20–30 keV taking into account the Doppler effect, as well. (Similar threshold was achieved with the DALI setup earlier in Ref. [24].) The energy resolution was 10% at 662 keV.

A silicon telescope with layers of 0.5, 2, 2 and 0.5 mm thicknesses was inserted in air at about 80 cm downstream of the target to identify the scattered particles. (The target chamber was closed by a thin Al plate of 1.5 mm.) The active area of the silicon detectors was  $48 \times 48 \text{ mm}^2$  covering scattering angles between  $0\text{--}1.7^\circ$  in laboratory frame with 100% detection efficiency. The inelastically scattered  $^{17,19}\text{C}$  particles stopped in the second and third layers and could be separated by the  $\Delta E\text{--}E$  method from other carbon nuclei emerged in the liquid hydrogen target by neutron-removal reactions. The separation was done by requiring  $\gamma$  coincidence with the telescope events, linearizing the  $\Delta E\text{--}E$  curves with second degree polynomials similar to [20]. As it is seen in Fig. 1,  $^{16,17,18,19}\text{C}$  nuclei from neutron-removal reactions in the target are reasonably well separated.

To produce the  $\gamma$ -ray spectra, one-fold events in the NaI(Tl) array were selected. A time gate was put on the calibrated time spectrum of the NaI(Tl) detectors to select the prompt events. A low energy continuous background radiation was emitted from the thick Al/Si stack at the downstream direction. In order to eliminate them, the spectra taken without the target were subtracted from the spectra when the target was inserted. Fig. 2 shows the subtracted, Doppler corrected spectra of  $\gamma$ -rays for  $^{19}\text{C}$  and  $^{17}\text{C}$  nuclei. As a by-product, the first excited states of  $^{16}\text{C}$  and  $^{18}\text{C}$  were also populated in the one-neutron knock-out channels with  $282 \pm 28 \text{ mb}$  and  $47 \pm 5 \text{ mb}$  cross sections integrated for  $0\text{--}1.7^\circ$  laboratory angle region, respectively, not shown in the figure. The Doppler correction is done using the average energy of the beam particles in the middle of the target and the geometrical center of the NaI(Tl) detectors. This introduces about 4% error for the velocity and about  $1^\circ$  uncertainty for the position of the detectors, which corresponds to about

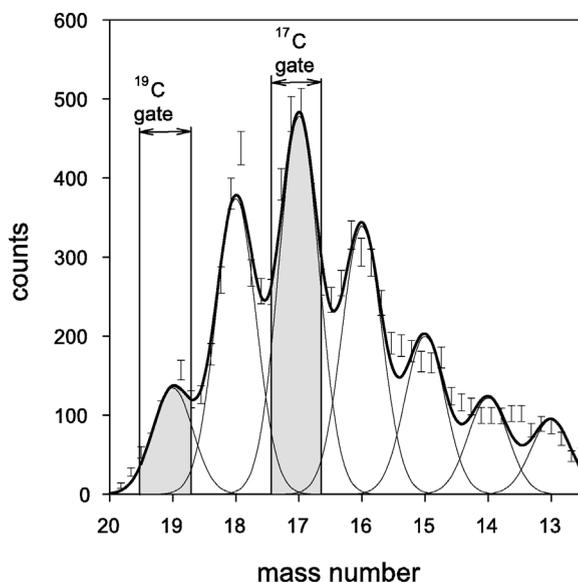


Fig. 1. Separation of carbon isotopes using  $\Delta E\text{--}E$  information in the silicon telescope. The bold solid line is a fit with 7 Gaussians. The individual curves are also plotted as thin solid lines.

0.5% and 0.8% errors in the peak positions, respectively.

To draw the line shape of the peaks observed, first, their positions were determined by fitting the spectra with Gaussian functions and constant backgrounds. During the fitting process the widths of the peaks were fixed to the expected values including the intrinsic resolution and Doppler effect. After the peak positions had been determined they were fed into the detector simulation software GEANT4 [25] and the resultant response curves with small constant backgrounds are plotted in Fig. 2.

In panel (a), two peaks are clearly visible at 72(4) and 197(6) keV which can be associated with the prompt decays of excited states in  $^{19}\text{C}$ . Fig. 2(b) shows two strong peaks at 210(4) and 331(6) keV establishing two low-lying excited states in  $^{17}\text{C}$ . In panel (c) of the  $^1\text{H}(^{17}\text{C}, ^{17}\text{C})$  reaction, the higher energy peak is clearly visible, while the 210 keV peak sitting on the Compton background of the 331 keV peak is very weak, if it exists at all. A 201(15) keV peak was also seen in the  $\gamma$  spectrum of  $^{19}\text{C}$  in a recent GANIL experiment [17], while the 72 keV peak was observed for the first time. The 331 keV peak of  $^{17}\text{C}$  was detected in the fragmentation reaction [17], too, and there were

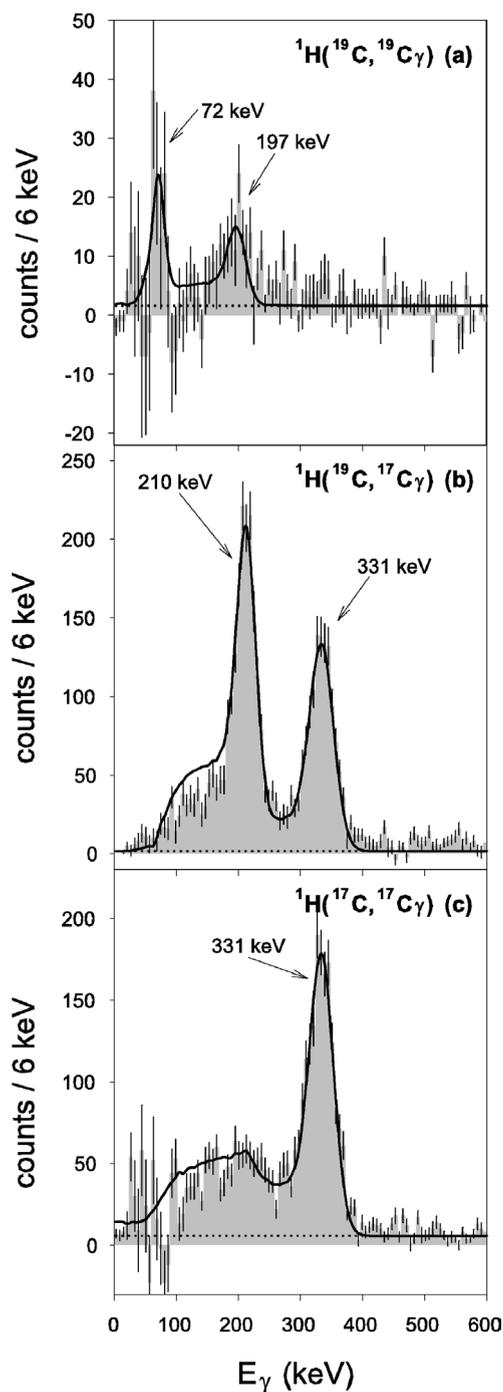


Fig. 2. Doppler-corrected spectra of  $\gamma$ -rays emerging from  $^1\text{H}(^{19}\text{C}, ^{19}\text{C})$  (a),  $^1\text{H}(^{19}\text{C}, ^{17}\text{C})$  (b) and  $^1\text{H}(^{17}\text{C}, ^{17}\text{C})$  (c) reactions. The solid line is the final fit including the spectrum curves from GEANT4 simulation and additional constant backgrounds plotted as separate dotted lines for each nucleus.

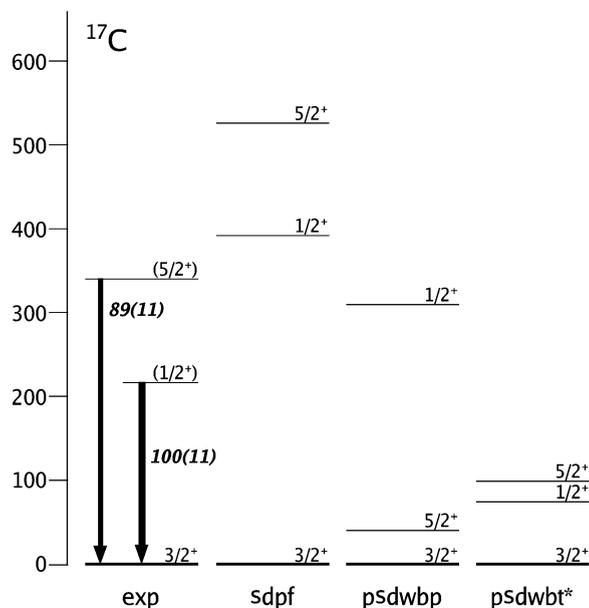


Fig. 3. Experimental level scheme for  $^{17}\text{C}$  nucleus plotted together with *sdpf* [13], *psdwbp* [31] and *psdwbtp\** [32] theoretical predictions. The arrows indicate the relative  $\gamma$  transition strengths observed in the  $^{19}\text{C} \rightarrow ^{17}\text{C}$  two-neutron removal reaction.

also indications on the existence of a 207 keV transition sitting just at the  $\gamma$  detection threshold. The energies of the  $\gamma$ -rays significantly differ from the energies of the states measured in multi-nucleon transfer reactions: 295(10) keV [15] and 292(20) keV [14]. Due to the poor resolution in those studies ( $\sim 200$  keV FWHM), the two states at about 1/2 FWHM energy difference may have been identified as a single peak with an averaged energy.

The counting statistics in Fig. 2(b) allowed us to perform a  $\gamma$ - $\gamma$  coincidence analysis which showed that the observed two transitions in  $^{17}\text{C}$  are not in coincidence. Thus, the two  $\gamma$ -rays are parallel in the level scheme establishing two excited states at 210(4) and 331(6) keV, respectively, as it is shown in Fig. 3.

The quoted uncertainties of the peak positions are the square roots of the sum of the squared uncertainties including two main errors namely the statistical one and the one due to Doppler correction. (The error coming from the energy calibration of the NaI(Tl) detectors were checked by a  $^{133}\text{Ba}$  radioactive source in the energy region in question and found to be negligible (less than 1 keV) compared to the above uncertainties.)

In the two-neutron removal reaction process using  $^{19}\text{C}$  incident beam, both states in  $^{17}\text{C}$  are populated almost with the same intensity:  $37 \pm 4$  mb and  $33 \pm 4$  mb integrated for  $0\text{--}1.7^\circ$  laboratory angle region. However, the difference observed in the  $\gamma$  transition strengths of the two states for the  $^{17}\text{C}(p, p')$  reaction is remarkable (compare panels (b) and (c) in Fig. 2). The strength of the  $0 \rightarrow 210$  keV transition is 1/9th of that of the  $0 \rightarrow 331$  keV transition at the most. This deviation may indicate that the transition matrix element between the ground and first excited state is relatively small. The ground state has a spin parity of  $3/2^+$ , which can arise as a mixture of  $d_{5/2}^3$  and  $s_{1/2} \otimes [d_{5/2}^2]_2$  neutron configurations. In single-step (particle-hole) excitation, it is forbidden to go from a  $[d_{5/2}^3]_{3/2}$  state to the  $[d_{5/2}^2]_0 \otimes s_{1/2}$  state. The low transition probability to the first excited state in the  $(p, p')$  reaction suggests that the 210 keV state is the  $1/2^+$  state, which has a small  $[d_{5/2}^3]_{1/2}$  admixture, while the ground state has a dominant  $[d_{5/2}^3]_{3/2}$  component mixed with a small  $s_{1/2} \otimes [d_{5/2}^3]_2$  component. The arguments on the configurations are mainly based on Ref. [5]. As a consequence of the above considerations, the 331 keV state can be assigned to the  $d_{5/2}$  state. This observation is in accordance with the result of a simultaneous shell model analysis of the  $^{17}\text{C}$  and  $^{17}\text{N}$  experimental data [26], where the state of  $^{17}\text{C}$  strongly excited in the heavy ion reactions was assigned to the spin  $5/2$  state. The level scheme and the relative intensities for the  $\gamma$  transitions in the two-neutron removal reaction are shown in Fig. 3.

In  $^{19}\text{C}$ , we have two  $\gamma$  transitions of nearly the same intensity. According to Maddalena et al. [5], the spin  $1/2$  state is mainly formed by  $d_{5/2}^4 \otimes s_{1/2}$  configuration while the spin  $3/2$  state is a mixture of  $d_{5/2}^5$ ,  $d_{5/2}^3 \otimes s_{1/2}^2$  and  $d_{5/2}^4 \otimes s_{1/2}$  configurations. If we assume—based on the instance of  $^{17}\text{C}$ —that the  $d_{5/2}^4 \otimes s_{1/2}$  component is small in the spin  $3/2$  state, the  $3/2 \rightarrow 1/2$  transition is forbidden in first order in both direction. In addition, in case of  $^{15}\text{C}$  the  $5/2 \rightarrow 1/2$   $\gamma$  transition is a slow single particle E2 transition. Scaling the 2.6 ns half life of the 740 keV state by  $E_\gamma^5$ , the half lives of the 197 keV and 72 keV transitions would result in 1.9  $\mu\text{s}$  and  $\sim 3$  ms, respectively. Even if there is a significant change in the structure of these states allowing for a much (1–2 orders of magnitude) faster transition rate, the  $5/2 \rightarrow 1/2$   $\gamma$

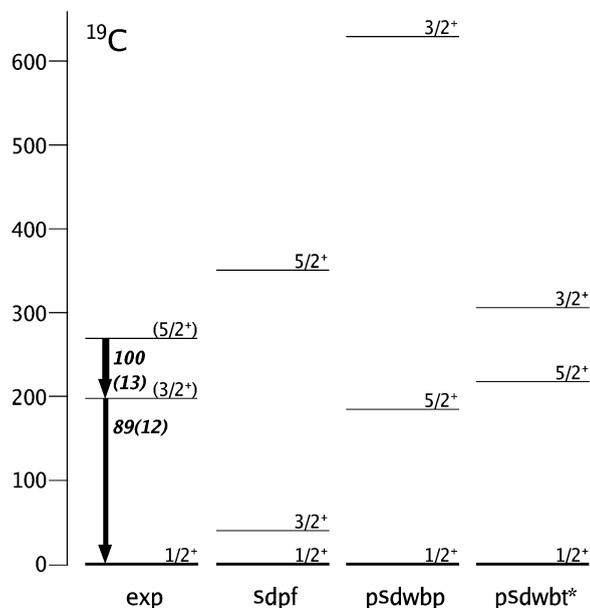


Fig. 4. Experimental level scheme for  $^{19}\text{C}$  nucleus plotted together with *sdpf* [13], *psdwbp* [31] and *psdwbt\** [32] theoretical predictions. The arrows indicate the relative  $\gamma$  transition strengths observed in  $(p, p')$  reaction.

transition would have such long a lifetime that we could not observe it with the present setup. Thus, none of observed transitions should correspond to the  $5/2 \rightarrow 1/2$   $\gamma$  transition. Therefore, having only the three predicted states, this means that the two transitions must be in cascade, and the only possible spin sequence is the  $5/2 \rightarrow 3/2 \rightarrow 1/2$ . Considering the retarded feature of the  $3/2 \rightarrow 1/2$  transition and the prompt nature of the observed  $\gamma$ -rays, the assignment of the higher energy to this transition may be more probable. The tentative level scheme constructed for  $^{19}\text{C}$  together with the relative intensities for the  $\gamma$  transitions in the  $(p, p')$  process can be seen in Fig. 4. Note that the discussion above is based on the assumption of a ground state spin  $1/2$  for  $^{19}\text{C}$ —which is also strongly suggested by other studies [1,5,7,8,10]—our data still leave lower possibility of other ground state spin assignment.

Comparing the experimental energies with those predicted by the shell model, it is seen that the shell model gives a qualitative description of the results by predicting two excited states below 600 keV independently of the effective interactions applied. Although in Figs. 3, 4 large deviations of the experimental and

calculated level schemes can be observed, it is only due to the expanded energy scale; the description of the energy spectrum is within the typical  $\sim 300$  keV uncertainty. This means that the energy spectrum of bound excited states in  $^{17,19}\text{C}$  is well described in terms of the shell model.

The cross section of the inelastic scattering process carries information on the amount of collectivity in these nuclei and indirectly on the deformation of their ground states. Analyzing the cross sections, a distorted wave calculation was performed by use of the ECIS79 [27] code. During the analysis, the standard collective form factors were used deriving the “matter” deformation parameters ( $\beta_2$ ) for the different transitions. The optical potential parameters were taken from the global phenomenological set CH89 [28].

For the second excited state in  $^{19}\text{C}$ , the integrated experimental cross section is  $\sigma(269 \text{ keV}; 0^\circ\text{--}1.7^\circ) = 4.2 \pm 0.5$  mb. Due to its large uncertainty, the middle level with spin  $3/2$  can hardly pose any restriction on the calculation. As a result of the distorted wave analysis, it can be concluded that having an  $1/2^+$  ground state and excited states of  $3/2^+$  197(6) keV and  $5/2^+$  269(8) keV results in  $\beta_2(269 \text{ keV}) = 0.29 \pm 0.03$ . This quite small deformation parameter suggests a basically single particle nature for the transition with some collective component, which is in accordance with the shell model calculation in Ref. [5].

In  $^{17}\text{C}(p, p')$  reaction, practically one state is excited with the cross section  $\sigma(331 \text{ keV}; 0^\circ\text{--}1.7^\circ) = 13.8 \pm 1.5$  mb. To reproduce this value starting with a  $3/2^+$  ground state, a  $\beta_2 = 0.52 \pm 0.04$  value is needed if the excited state has a spin  $5/2$ . This suggests that the  $^{17}\text{C}$  nucleus is strongly deformed with its deformation similar to the values obtained for other neutron-rich nuclei in this region like  $^{16}\text{C}$ :  $\beta \sim 0.5$  [29] or  $^{17}\text{B}$ :  $\beta \sim 0.57$  [30].

It is interesting to mention that a large deformation in the intrinsic frame leads to a virtual increase of the size of the nuclear matter distribution in the laboratory frame. The  $\beta \sim 0.5\text{--}0.6$  deformation results in 5–7% increase of the nuclear radius, which exhausts about two third of the increase of the nuclear radius observed experimentally in  $^{16,17}\text{C}$  [1]. Since an ellipsoid with  $\beta = 0.6$  deformation has a 2 : 1 axis ratio in the intrinsic frame, in the laboratory frame nucleons are found even at a distance of twice of the nuclear radius with a finite probability. Accordingly, the nuclear

density goes to zero in laboratory frame in these nuclei in a much slower way than usual for a spherical nucleus.

Summarizing our results, we have studied the  $^{17,19}\text{C}(p, p'\gamma)$  reactions. In spite of the low beam intensity, two  $\gamma$  peaks could be observed in both nuclei indicating two bound excited states in  $^{17,19}\text{C}$  nuclei in agreement with the theoretical expectations. We have determined the energies of the excited states and made tentative spin assignments to them on the basis of the systematics of transition strengths. From the analysis of the excitation cross sections, the  $\beta_2$  deformation parameters of the 331 keV transition in  $^{17}\text{C}$  and the 269 keV one in  $^{17,19}\text{C}$  have been deduced. The  $^{17}\text{C}$  nucleus was found to be strongly deformed. This fact is in agreement with the shell model calculations suggesting a strongly mixed Nilsson orbit-like ground state wavefunction [5].

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