

Multitude of 2^+ discrete states in ^{124}Sn observed via the $(^{17}\text{O}, ^{17}\text{O}'\gamma)$ reaction: Evidence for pygmy quadrupole states

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A multitude of discrete 2^+ states in ^{124}Sn with energy up to 5 MeV were populated and identified with the $(^{17}\text{O}, ^{17}\text{O}'\gamma)$ reaction at 340 MeV. Cross sections were compared with distorted wave Born approximation predictions and in general a good agreement was found. The measured energy and intensity distributions of the 2^+ states are very similar to the predictions based on self-consistent density functional theory and extended QRPA approach accounting for multiphonon degrees of freedom. This provides evidence of the excitation of the pygmy quadrupole resonance in skin nuclei.

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I. INTRODUCTION

Among the most interesting findings of nuclear structure physics there are those concerning the nuclear dipole response at energies below and close to the particle emission threshold in stable and unstable nuclei with charge asymmetry $N/Z > 1$ where a new excitation mode called the pygmy dipole resonance (PDR) has been observed [1]. That mode was intensively investigated in many experimental and theoretical studies in which unknown aspects on the isospin dynamics of the nucleus have been revealed (see [1] and [2] for reviews and, e.g., the recent experiments [3–5]). Typically, the PDR appears as an additional dipole strength situated on top of the low-energy tail of the giant dipole resonance (GDR) [6]. Theoretically, the PDR is explained as excitations of excess neutron or proton matter (depending on the isospin asymmetry of the nucleus) from the nuclear surface layer which corresponds to a vibrational motion of the nuclear skin against the core [7,8]. The total PDR strength was found to be closely correlated with the neutron skin thickness [1,7].

An obvious question, arising immediately in this context, is to what extent the presence of a neutron or proton skin will affect excitations of other multipolarities and vice versa. Promising candidates are low-energy 2^+ states. Theoretical predictions using the Hartree-Fock-Bogoliubov (HFB) and quasiparticle random phase approximation (QRPA) plus multiphonon approach [9] for the Tin isotopic chain show a concentration of low-energy electric quadrupole strength located much below the isoscalar giant quadrupole resonance (ISGQR) which is identified with new mode of nuclear excitation named pygmy quadrupole resonance (PQR). The explanation is based on the detailed analysis of spectroscopic features and transition rates. Thus, the microscopic structure of the QRPA 2^+ states with excitation energy less than about $E_x = 5$ MeV in Sn nuclei with $N/Z > 1.1$, is predominantly of neutron character dominated by neutron two-quasiparticle states located close to the Fermi surface. An important part of the correlations is given by the quadrupole pairing interaction. The states are clustered in a comparatively small energy interval, thus giving rise to a neutron PQR. The most convincing evidence for the connection between PQR and neutron pairing is the disappearance of the PQR in the double magic ^{132}Sn nucleus [9]. In this connection, the PQR states are containing important information on the structure of the valence shells and their evolution with the nuclear mass number. Furthermore, the correlation between the PQR and the neutron or proton skin thickness manifests itself via a transition from a neutron PQR to a proton PQR in ^{104}Sn . Similar effect of increased

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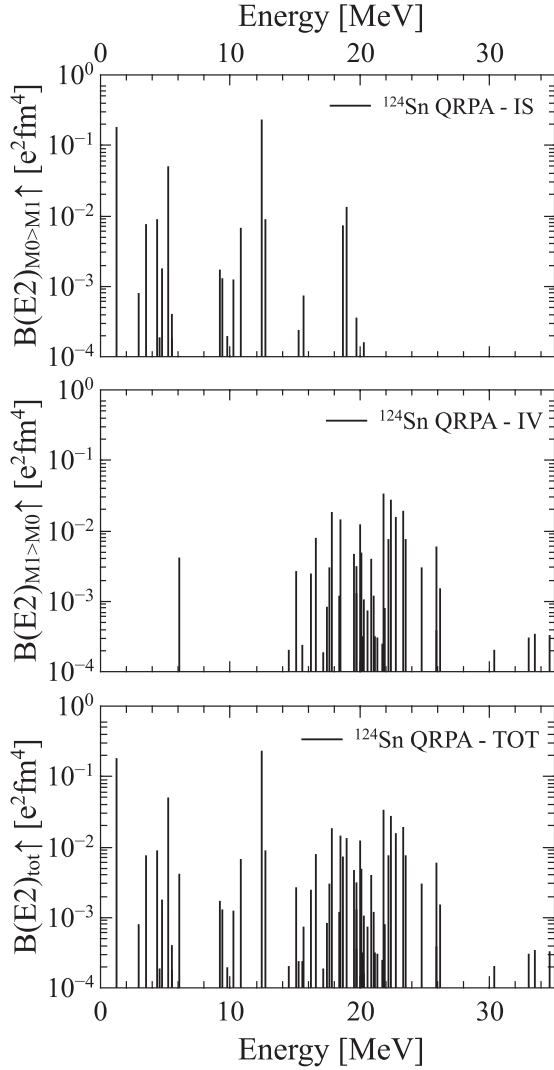


FIG. 1. QRPA calculations for the isoscalar and the isovector partial contributions as well as the total electric quadrupole strength in ^{124}Sn .

low-energy $E2$ strengths correlated with increasing neutron number is observed as well in QRPA calculations of lighter mass nuclei $^{33}\text{Al}/^{35}\text{Al}$ and $^{32}\text{Mg}/^{34}\text{Mg}$ [10]. The dominance of neutrons or proton transitions implies immediately a strong mixture of isoscalar and isovector contributions, because it is related to the particle projector, $P_q = \frac{1}{2}(1 \pm \tau_3)$, where $\tau_3 = \pm 1$ for neutrons and protons, respectively.

The work presented in this paper concerns the search for a concentration of 2^+ states below the neutron separation energy in the nucleus ^{124}Sn . The QRPA predictions based on HFB theory [7] of the quadrupole response in terms of $B(E2; \text{g.s.} \rightarrow 2^+)$ transition probabilities, calculated up to an excitation energy of 35 MeV for this nucleus, are shown in Fig. 1. The theoretical results indicate the presence of a group of low-energy closely situated 2^+ states which resembles a ‘resonance-like’ structure which is also similar to the observations of the PDR [1]. The isospin character of the QRPA 2^+ excited states is examined by calculation of the multipole transition matrix elements $M_I(\lambda\mu)$ for multipolarity $\lambda = 2$

defined in [9] where $I = 0$ corresponds to isoscalar and $I = 1$ to isovector contributions into the $E2$ transitions. Quadrupole states of predominantly isoscalar ($M_0 > M_1$) and isovector ($M_1 > M_0$) character, respectively, are presented also in Fig. 1. It is clearly seen that the 2^+ states below 5 MeV are mostly isoscalar. The calculations describe well the properties of the collective lowest-lying 2^+ state as well the ISGQR and isovector giant quadrupole resonances (IVGQR) [11]. Similar to the PDR case, the transition densities of 2^+ states below the separation energy are characterized by a correlation between this quadrupole excitation and the neutron skin.

Experimentally, only a few 2^+ states were well identified so far in ^{124}Sn while a number of states in the excitation energy region 4–5 MeV were found but their multipolarity was not uniquely determined [12,13]. With the experiment discussed in this paper it was possible to infer the multipolarity of these 2^+ states below 5 MeV. In the present case for the states for which the $B(E2) \uparrow$ was not yet measured, values of $B(2)$ were deduced via a DWBA analysis of the excitation cross sections.

This work provides the first experimental evidence for the existence of pygmy quadrupole states in the neutron rich nucleus ^{124}Sn .

II. THE EXPERIMENT

The 2^+ states in ^{124}Sn were populated via inelastic scattering of ^{17}O at 340 MeV. In a previous paper, data on pygmy dipole states in ^{124}Sn obtained with the same experiment, were reported [5]. The same reaction and set up was used for the study of the pygmy states in ^{208}Pb [3], ^{90}Zr [4], and ^{140}Ce [14].

The experiment was performed at Legnaro National Laboratory of INFN (LNL, Italy) with a beam from the TANDEM-ALPI accelerator complex and using a self-supporting target of ^{124}Sn with a thickness of 3 mg/cm². The beam energy of 340 MeV was chosen because it enhances the contribution of the nuclear isoscalar part in the interaction [15]. In order to detect the scattered ions an array of segmented silicon detectors was used [16,17]. The two ΔE - E silicon telescopes consisted of a thin ‘ ΔE ’ detector placed in front of a thick ‘ E ’ detector. Each of the ΔE detectors was 200- μm thick, corresponding to an energy loss of about 70 MeV for ^{17}O ions at the present beam energy. The E detectors were 1-mm thick and stopped the ^{17}O ions completely. The overall energy resolution was around 0.3% at 340 MeV. The subsequent γ -ray decay was detected by the detection system AGATA (Advanced Gamma Tracking Array), the new generation HPGe array based on the techniques of pulse shape analysis and γ -ray tracking [17,18]. In this experiment the AGATA array consisted of five triple clusters (configuration called Demonstrator) and was placed 132 mm from the target. The segmentation of the AGATA detectors and the use of the tracking algorithms allowed the γ -ray interaction position to be identified with a precision of about 1°. The use of the telescopes of silicon detectors allowed to measure a wide region of excitation energy and allows the study of the low-lying $E2$ response in addition to the low-energy $E1$ response (lying in energy above the $E2$ response). The ^{17}O - γ coincident measurements are a powerful tool to investigate the low-lying 1^- and 2^+ states.

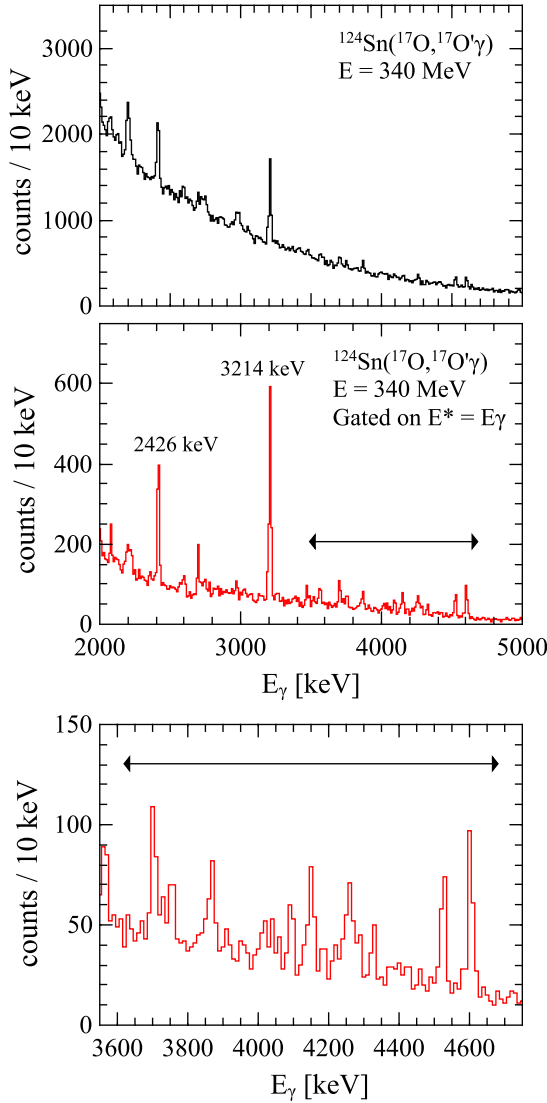


FIG. 2. (Color online) Top panel: γ -ray energy spectrum in the 2–5 MeV interval, measured with the AGATA array and corresponding to the ^{17}O inelastic scattering channel. Central panel: γ -ray energy spectrum in the 2–5 MeV interval, measured with the AGATA array and corresponding to the ^{17}O inelastic scattering channel with the additional condition of selecting the kinetic energy loss of the scattered ions with a gate at $E_x = E_\gamma$. Lower panel: γ -ray energy spectrum in the 3.5–4.8 MeV energy interval with the same conditions of the central panel. The horizontal arrows in the middle and bottom panels are indicating the region of interest for the present work.

Indeed, the correlation between the excitation energy measured by the silicon telescopes and the γ -ray energy measured with the AGATA demonstrator allows the suppression of the background and the selection of specific decaying paths. The top panel of Fig. 2 shows the γ -ray energy spectrum measured with the AGATA array in coincidence with the inelastically scattered ^{17}O ions. An additional gating condition was imposed in order to select the transitions to the ground state and the corresponding γ -ray energy spectrum is shown in the middle panel of Fig. 2. Indeed, by requiring the excitation energy measured in the silicon detectors (E_x) to be equal

to the γ -ray energy (E_γ) measured in the AGATA array only the γ -ray transitions to the ground state were enhanced. The bottom panel shows the energy region between 3.5 and 4.8 MeV where the low-lying $E2$ strength is located.

III. THE OBSERVED 2^+ STATES

In the present experiment several 2^+ states were populated and the subsequent γ decay was observed in the energy region between 3.5 and 5 MeV. Up to now, only a few 2^+ states in ^{124}Sn were identified via photon, proton, and α -scattering as well as β -decay experiments [12,13]. This is the first time that several 2^+ states above 3.5 MeV and below the neutron separation threshold are identified and, thanks to the measurement of their γ decay, it was possible to assign for them a well-defined multipolarity. Figure 3 shows the part of level scheme of ^{124}Sn nucleus with the γ transitions observed in the present experiment. The black solid arrows

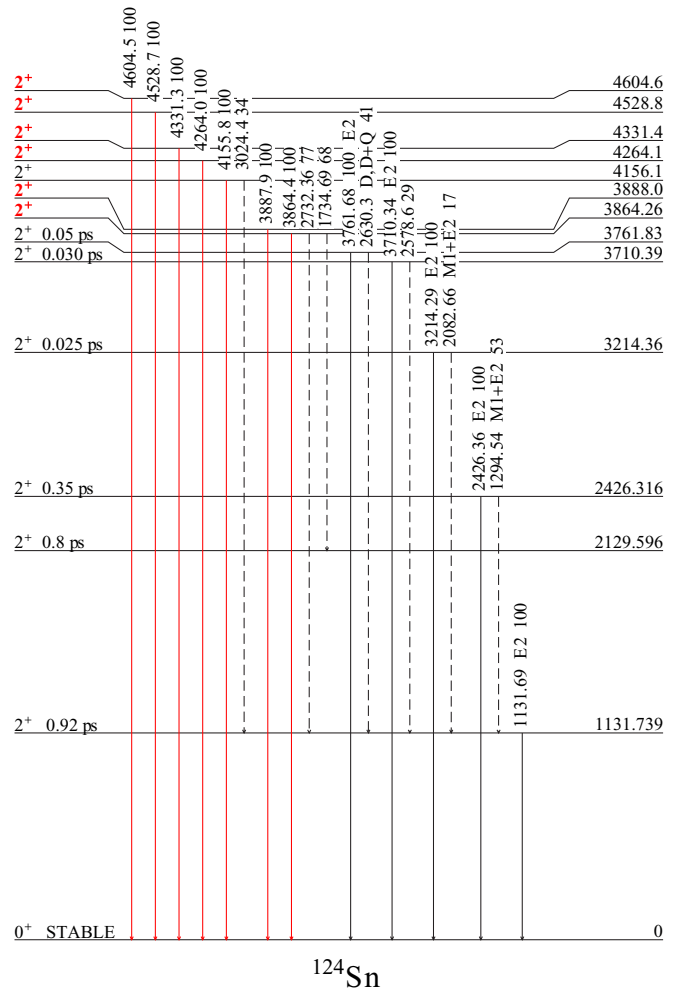


FIG. 3. (Color online) The part of the level scheme of ^{124}Sn relevant to this measurement showing the γ transitions observed in the present work. The black solid arrows correspond to the known $E2$ ground-state transitions while the red arrows correspond to the unknown $E2$ ground-state transitions observed in this work. The black dashed arrows show the γ decay of the populated 2^+ states to other excited states.

correspond to the known $E2$ ground-state transitions while the red arrows correspond to the unknown $E2$ ground-state transitions. The black dashed arrows, instead, show the γ decay of the populated 2^+ states to different excited states.

In order to deduce the multipolarity of the observed transitions, the angular distribution of the emitted γ rays were extracted. Indeed, since the excited states were populated through the inelastic scattering of heavy ions we expect a certain degree of alignment of the nuclear spin in this experiment and consequently the study of the angular distribution of the emitted γ rays gives information on the multipolarity of the excited state [19]. This is an important issue since in the case of heavy ions scattering, in contrast with proton and α scattering, the differential angular distribution does not have specific patterns characterizing the transferred angular momentum. In addition, the coincidence of inelastically scattered particles with γ rays reduces the contribution from population of states with higher multipolarity, because the γ ray proceeds mainly via multiplicities 1 and 2.

Exploiting the position sensitivity of the AGATA Demonstrator and the segmented silicon detectors, an almost continuum angular distribution for all the transitions, with respect to the direction of the recoiling nucleus, was obtained. The AGATA array was treated as a continuum HPGe detector and for each γ ray the angular position of the first interaction point with respect to the recoil direction was considered. The γ -ray detection efficiency of the AGATA array was simulated with the GEANT4 code for the γ -ray energy in the interval relevant for this analysis [20].

Figure 4 shows the angular distribution obtained for several transitions of interest in the angular interval 0° – 90° . The results for the unknown transitions are depicted with red dots while the black dots represent the known $E1$ ground-state transition from the first 1^- state at 1.471 MeV (top left panel) and the known $E2$ ground-state transition from the 2^+ state at 3.214 MeV (top right panel), respectively. It is clear from the study that the unknown transitions supposed to be of electric quadrupole multipolarity are as a matter of fact identified as $E2$ ground-state transitions. The ratio between the counts in the angular range 60° – 90° over the ones in 30° – 60° was also calculated for all the observed transitions and it is shown in Fig. 5. Even from this plot it is evident that the only $E1$ transition among those selected is the transition from the 1.471 MeV state and that a $E2$ multipolarity can be assigned to all the transitions located in the region between 3.5 and 5 MeV.

Since the population cross section was measured at different angles a DWBA analysis of the data was performed for all the excited states observed in our experiment. The calculated differential cross sections are shown in Figs. 6 and 7 in comparison with the data for the excitation of the different 2^+ states. The cross sections corresponding to the already known states are shown with black dots while for the unknown states red dots are used. The cross section predictions within the DWBA approach were obtained using the FRESKO code [21]. In the calculations of the excited state cross sections the optical model parameters obtained from the analysis of the elastic scattering reported in [5] were used. In addition, the total normalization factor including the combined effect

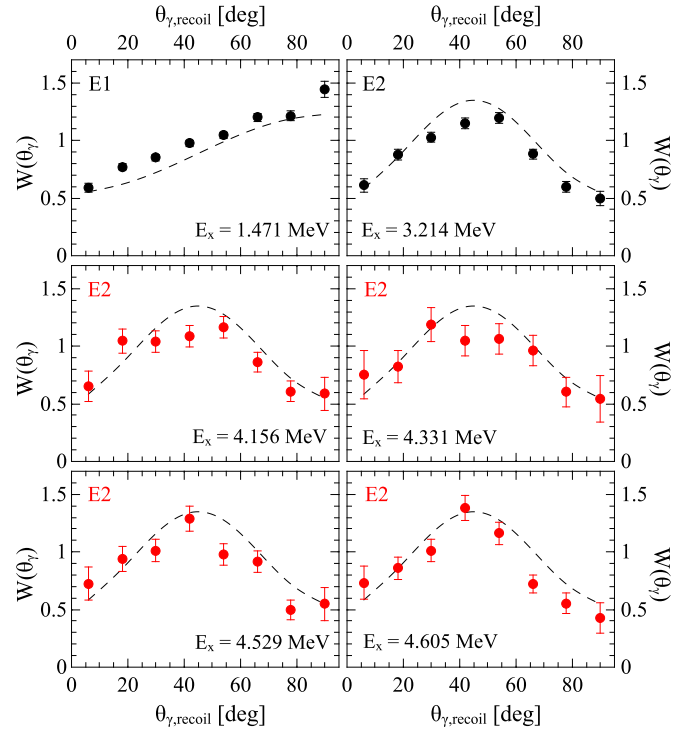


FIG. 4. (Color online) Angular distribution of the measured γ rays in the angular interval 0° – 90° obtained for the observed transitions. The red dots indicate the results for the transitions for which the multipolarity was not yet known.

of target thickness and integrated beam particles was the same deduced from the analysis of the elastic scattering data (see [5]). For the present analysis of the 2^+ states the vibrational collective form factor was used and it was assumed that the ratio of the neutron and proton transition matrix elements is $M_n/M_p = N/Z$. Although the fulfillment of this condition is often considered as a manifestation of isoscalar

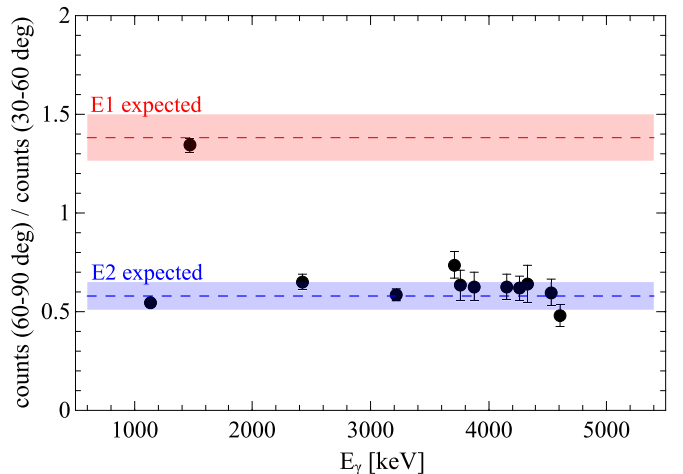


FIG. 5. (Color online) The ratio between the counts in the angular interval 60° – 90° over the ones in 30° – 60° was deduced for all the observed transitions. The blue and the red regions highlight the ratio predicted for pure $E2$ and $E1$ transitions, respectively.

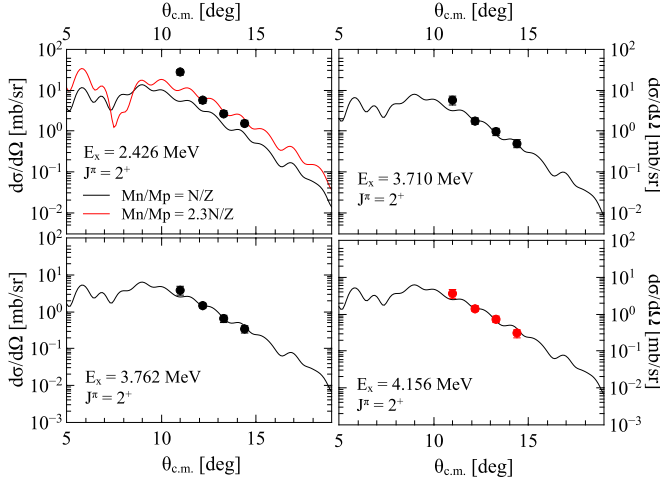


FIG. 6. (Color online) Inelastic scattering cross section $^{124}\text{Sn}(^{17}\text{O}, ^{17}\text{O}')^{124}\text{Sn}^*$ at 340 MeV for several 2^+ states. The black dots represent the results of excited states with known multipolarity while the red dots are related to states for which the multipolarity was previously unknown. The error bars are the statistical errors. The lines show DWBA calculations. The black solid curves are the calculations with the standard phenomenological form factor and assuming $M_n/M_p = N/Z$. The red solid line, instead, represents the calculations for which $M_n/M_p = 2.3 \times N/Z$ was assumed.

character of the transition (according to the hydrodynamical model), it is important to make a clarification on this point. Indeed this relation implies a pure isospin character only for $N = Z$ nuclei and in the other cases one has an admixture of an isoscalar transition amplitude [in general being the dominating term which decreases with $(N - Z)/A$] with a nonzero isovector transition amplitude. This can be easily understood by recalling that $M_1 = M_n - M_p$ and $M_0 = M_n +$

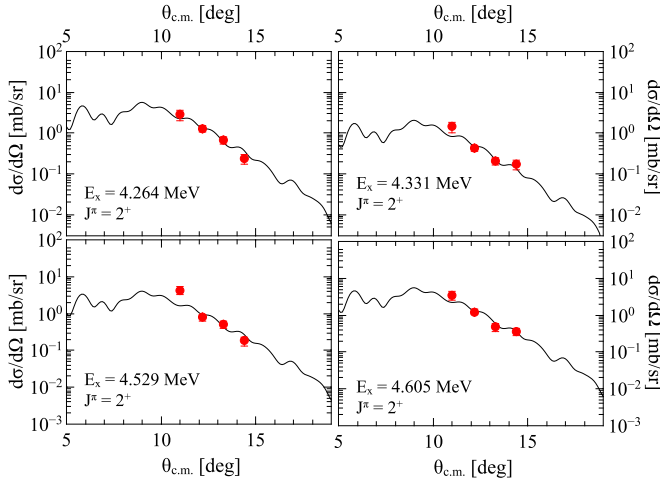


FIG. 7. (Color online) Inelastic scattering cross section $^{124}\text{Sn}(^{17}\text{O}, ^{17}\text{O}')^{124}\text{Sn}^*$ at 340 MeV for several 2^+ states. The red dots represent the results related to states for which the multipolarity was previously unknown. The error bars are the statistical errors. The lines show DWBA calculations. The black solid curves are the calculations with the standard phenomenological form factor and assuming $M_n/M_p = N/Z$.

M_p and thus $M_p = (M_0 - M_1)/2$ and $M_n = (M_0 + M_1)/2$. Therefore the finding for a nucleus $A(N, Z)$ of $M_n/M_p = N/Z$ implies $[(Z - N)M_0 + (N + Z)M_1]/2 = 0$ and thus $M_1 = 0$ for $N = Z$ nuclei and in the other cases one has $M_1/M_0 = (N - Z)/A$. The $B(E2) \uparrow$ used for the known states are the ones reported in literature [12,13] while for the unknown states a tentative assignment of the corresponding $B(E2) \uparrow$ was done. This was obtained from the relation between $B(E2) \uparrow$ and M_n/M_p [22,23] and assuming $M_n/M_p = N/Z$. It was already seen in [5] that the deformed potential model is able to reproduce well the experimental data, with the exception of the 1^- states. In the case of the known 2^+ states treated in this work, the data are well reproduced by calculations with the exception of the state at 2.426 MeV. To fit the experimental data the DWBA calculations were performed with the standard phenomenological form factor but with the condition $M_n/M_p = 2.3 \times N/Z$ (displayed with the red curve in Fig. 6). With the use of $M_n/M_p = 2.3 \times N/Z$, increasing the nuclear contribution, the corresponding predictions move closer to the experimental points and are much different than the calculations assuming $M_n/M_p = N/Z$ (black curve in the top left panel in Fig. 6). To have found for this state $M_n/M_p = 2.3 \times N/Z$ (namely that $M_n/M_p = xN/Z$ with $x \gg 1$) one deduces the presence a strong dominance of the neutron component which in turn implies strong isospin mixing. To understand this one has to recall that $xNM_n - ZM_p = 0 = [(Z - xN)M_0 + (xN + Z)M_1]/2$ with $M_1/M_0 = [1 - (Z/N)/x]/[1 + (Z/N)/x]$. In leading order in $\xi = (Z/N)/x \approx 1/(2x) < 1$ one has $M_1 \approx M_0(1 - 2\xi)$, thus $M_1 \approx M_0$ and according to the above relations $M_p \approx 0$ and the transition strength is carried predominantly by neutron particle-hole configurations.

Since the $B(E2) \uparrow$ transition probability of several observed states was not known, a tentative assignment of $B(E2) \uparrow$ was made assuming these states (similarly to what found for a number of other 2^+ states in this nucleus) to fulfill the relation $M_n/M_p = N/Z$ (and according to what said to have a dominant isoscalar character). This assumption is supported by the presented QRPA calculations and Ref. [9] where the electric quadrupole response was investigated theoretically by HFB and three-phonon quasiparticle-phonon model (QPM) calculations along the Sn isotopic chain. The QRPA results for ^{124}Sn are presented in Fig. 1 where the predicted predominantly isoscalar and isovector $E2$ transitions as well as the total electric quadrupole $B(E2) \uparrow$ strength in ^{124}Sn are shown. As we mentioned already in the Introduction, one can easily observe from the QRPA calculations that the dominant character of the quadrupole excitations in the lower excitation energy region is mainly isoscalar while at higher excitation energy is mostly isovector. However, one should also take into account that the interaction of quasiparticles and phonons leads to mixing of the pairing vibrational quadrupole QRPA states with two- and three-phonon states [24]. This effect is known to produce the fragmentation of the single-particle strength to many nuclear excited states. As a result the low-energy quadrupole states have a complex structure and only few of them are of one-phonon character. The two- and three-phonon contributions to the state vectors of the low-energy quadrupole states are due to couplings of the

TABLE I. Values of the $B(E2) \uparrow$ extracted by the comparison of the data with the calculations assuming $M_n/M_p = N/Z$ (i.e., pure isoscalar character for the state) together with the $B(E2) \uparrow$ already known from literature [12,13] and the cross sections measured in the experiment (at $\theta_{c.m.} = 12^\circ$). For the state at 2.426 MeV a value of $M_n/M_p = 2.3 \times N/Z$ was used in order to reproduce the data. The errors for the extracted $B(E2)$ values reflect the uncertainty in the cross sections.

E [MeV]	$B(E2) \uparrow$ [$e^2\text{fm}^4$]	$\frac{d\sigma}{d\Omega_{c.m.}}$ [mb/sr]	$B(E2) \uparrow$ extracted [$e^2\text{fm}^4$]
1.132	1660	47.5(8.3)	—
2.426	95	5.63(83)	—
3.214	275	9.3(1.3)	—
3.710	75	1.78(30)	—
3.762	60	1.49(24)	—
3.864–3.888	—	2.36(37)	90(14)
4.156	—	1.43(24)	60(10)
4.264	—	1.27(22)	55(10)
4.331	—	0.43(7)	20(3)
4.529	—	0.78(15)	40(8)
4.605	—	1.23(21)	55(9)

lowest-lying 2^+ and 4^+ QRPA phonons which are mostly of isoscalar character. Consequently, the total transition strength obtained by the QPM $\sum_{2 \text{ MeV}}^{5 \text{ MeV}} B(E2) = 392.7 e^2\text{fm}^4$ is about twice larger than that calculated from the QRPA. Based on these results the DWBA analysis performed for this experiment was made considering a standard phenomenological form factor and assuming $M_n/M_p = N/Z$ for all the unknown states. The results of this analysis are shown in Figs. 6 and 7. The values of the $B(E2) \uparrow$ extracted from the comparison of the data with these calculations are reported in Table I. In this table the values of the $B(E2) \uparrow$ already known from literature [12,13] and of the cross sections measured in this experiment are also reported.

In Fig. 8 the present cross section measurements of the states (middle panel) are compared with the $B(E2) \uparrow$ experimental value from previous experiments (top panel) and with the QPM calculations. Altogether the present experimental and theoretical results show the presence of a number of 2^+ states grouping together in the energy region 3–5 MeV supporting the prediction of the HFB+QPM model [9]. This quadrupole strength clustering appears to be similar to the known PDR at 5–7 MeV. The microscopic analysis of these 2^+ states reveal that they have a unique structure closely connected with excitation of the neutron skin. In the future it will be important to obtain information on the transition densities of these states, on $B(E2) \uparrow$ and to study other isotopes to learn more on the quadrupole degree of freedom of the neutron skin.

IV. SUMMARY

The low-lying part of the quadrupole nuclear response in ^{124}Sn was here studied using data from the inelastic scattering of ^{17}O at 340 MeV. With this work we have measured for the first time the γ decay from a group of states with excitation energy at 3–5 MeV for which only the energy (and not the spin) was

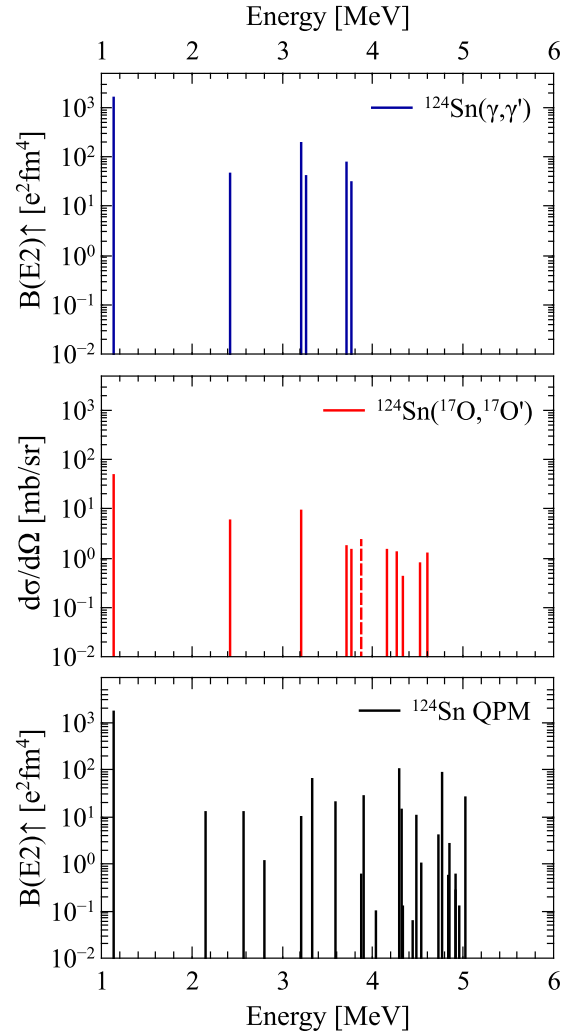


FIG. 8. (Color online) Comparison between the transition probabilities known from previous experiments [12,13] (top panel), the one theoretically calculated [9] (bottom panel), and the cross sections measured in our experiment (middle panel).

previously known. The spin assignment was unambiguously made via the measurement of the angular distribution of the γ rays de-exciting these states. The measured cross sections populating this multitude of 2^+ states was analyzed within the framework of the DWBA. This analysis, made under the assumption of pure isoscalar nature of these states has allowed to infer values of the $E2$ transition probability. The comparison with the QPM calculations show that data and calculations have similar features for the $E2$ strength up to 5 MeV in excitation energy. The $B(E2) \uparrow$ strength estimated from the data up to 5 MeV is $2485 e^2\text{fm}^4$, which is 13.6% of the value of the sum rule strength for the ISGQR. The QMP calculations show that these 2^+ excited states are due to excitations of neutrons from the skin.

In conclusion we have provided the first evidence for excitation of pygmy states of quadrupole character in ^{124}Sn and thus that the neutron skin can also have vibrations of quadrupole type. Further work also on the form factor of these states and on other isotopes will be very enlightening to pin down the neutron skin properties and its degrees of freedom.

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