Pairing and collectivity of the first $2^+$ state in light Sn isotopes

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Abstract. In recent experiments [1–4] the E2 strengths have been measured in the neutron deficient $^{106−112}$Sn isotopes. Using different models [5–8] a lot of theoretical effort was devoted in order to understand the effect of different aspects of the nuclear structure on the $B(E2;0^+ \rightarrow 2^+_1)$ strength in the Sn chain. In those works a large decrease of the $B(E2)$ values in $^{102,104}$Sn in comparison to the heavier Sn isotopes $^{106−112}$Sn has been predicted. Here we concentrate on the effect of the pairing on the E2 strength in the Sn nuclei chain. We analyze the correlation one could observe between the pairing gap and the $B(E2)$ strengths to the first $2^+$ excited state. The theoretical results on the $B(E2)$ strengths are obtained within a QRPA model. These predictions are analyzed and compared to the experimental results.

1. Motivation

The $B(E2;0^+ \rightarrow 2^+_1)$ values provide one of the most sophisticated tool to examine the shell structure of nuclei. In this work we try to convince the reader that these values are also correlated with the pairing in the nuclei. For our investigation we have chosen the Sn isotopic chain as it provides the longest chain of semi-magic nuclei, well studied both experimentally, and theoretically. What is of importance for us, is the well established, for almost the whole chain, experimental value of $B(E2;0^+ \rightarrow 2^+_1)$. Recently, new measurements in $^{106,108}$Sn [4] have been done. They show a reduction in $B(E2)$ strength when one goes towards the neutron deficient $^{106}$Sn. Still it is uncertain, what would one expect when going towards the $^{100}$Sn doubly magic nuclei. In this work we assume a simple model for the description of the ground state and the excited state of the nuclei, still we would like to point out the good description of the experimental data available up-to-date, and to show the prediction of such a model for the $^{102,104}$Sn. We use a Skyrme-Hartree-Fock scheme for the description of the ground state, on top of which pairing in constant gap approximation is included. The excited state is represented in Quasi-particle Random Phase Approximation. In this scheme we would like to emphasise the role of the pairing on the structure of the excited state, and thus its influence on the $B(E2)$ strengths.

2. Theoretical Framework

We have used the Separable Quasi-particle Random Phase Approximation [9] in order to describe the excited states of the Sn nuclei. The single-particle spectrum has been calculated within a
Skyrme-Hartree-Fock approximation, a SIII [10] parameterization of the force has been adopted. The pairing has been taken in a constant gap approximation. The pairing strength is used as a constant for the whole isotopic chain. Still it is taken as independent parameter and it is not fitted on the experimental gap values. The continuous part of the single-particle spectrum is discretized by diagonalizing the HF hamiltonian on a harmonic oscillator basis. The single quasi-particle basis has been chosen in such a way that the Energy-weighted Sum Rule is depleted by 100% up to 30 MeV. In the model we use the residual particle-hole interaction, taken in a Landau-Migdal form, which in coordinate representation reads:

$$V_{ph} = N_0^{-1} \sum_l F_l + G_l \sigma_1 \cdot \sigma_2 + (F_l + G_l \sigma_1 \cdot \sigma_2) \tau_1 \cdot \tau_2 \delta(r_1 - r_2)$$  

(1)

here $N_0 = \frac{2k_F m^*}{\pi^2 \hbar^2}$. In this expansion only the $l = 0$ terms are non zero. The Hamiltonian used for the QRPA calculations includes the average HF field, pairing interactions and the isoscalar and isovector particle-hole residual interaction in a N-rank seperable form. The exact form of the Hamiltonian could be found in [9,11].

3. Results

In the Sn isotopes the protons form a closed shell subsystem. This of course affects the proton particle-hole excitations (PPHE), which could be excited only across the $Z=50$ gap. Because of this feature of the structure of the nuclei the PPHE are at a relatively high energy. On the other hand, the neutron particle-hole excitation (NPHE) in the semi-magic Sn nuclei could be excited in the valence shell, thus the NPHE are lower in energy. From this observation one would expect that the dominant contribution in the low-lying $2^+$ excitations would be neutron. This would be especially important in the first $2^+$ state. The proton contribution to the excited states has a strong effect on the B(E2) strengths, thus one would expect that even a small change in the structure of the first excited state would lead to a change in the observed B(E2)s. On the left-hand-side of Fig. 1 showing the neutron pairing gap behavior with the mass number, we can see that with the increasing of the mass number, the neutron pairing gap, first gets bigger, then it remains almost unchanged, and then falls again when one goes towards the doubly magic $^{132}$Sn. These changes influence the energy of the neutron particle-hole excitations, which are lower close to the doubly magic Sn isotopes. The neutron component in the first $2^+$ excited state is affected by the energy of NPHE, the lower the energy is the higher is the contribution from the neutrons on the $2^+_1$ state. The considerations above are only qualitative. To get a quantitative result we have used the QRPA model to describe the first excited state in the Sn isotopic chain. The strength of the particle-hole interaction, has been fitted in such a way that the energy of the $2^+$ state corresponds to the experimental value. The obtained results on the B(E2) strengths, corresponds well to the experimental values, as one could see from the right-hand-side of Fig. 1. Let us focus our attention on nuclei belonging to the steep slopes where the neutron pairing gap is small and the energy of the NPHE goes down. In those nuclei the contribution of the PPHEs in the structure of the first $2^+$ excited state goes down to (3 - 5%), compared to (6 - 8%) $^{108-124}$Sn. The latter has an imminent effect on the B(E2) strength, which falls rapidly, with the decreasing of the proton component of the wave function of the first excited $2^+$. This could be clearly seen on the right-hand-side of Fig. 1. One could see that a drastic reduction of the B(E2) strength is expected for the $^{102-104}$Sn. From the figure it could also be seen that in these calculations the subshells closures are somehow smeared, and for example at the $2d_{5/2}$ closure in $^{106}$Sn one cannot observe sharp increase in the NPHE, thus the B(E2) strength changes smoothly within the closed shell.
4. Conclusion

The results from our calculations could be summarized in two points. The first result is a prediction on the B(E2) strengths, as one goes towards the neutron deficient Sn nuclei. We could expect a drastic reduction of the B(E2) strengths in the $^{102,104}$Sn isotopes as compared to the nearby nuclei $^{106,108}$Sn. The reduction we observe is only due to the increasing role of the neutron particle-hole excitation $2\delta_{5/2}^p 2\delta_{5/2}^h$ which is 430keV lower in energy in $^{102,104}$Sn nuclei as compared to $^{106}$Sn. This of course increase its contribution in the structure of the first excited state by more than 8% which reduces the proton contribution in the preceding 2 nuclei by 3, 2% as compared to the last.

The second interesting result is presented on the left hand side of Fig. 1 and it supposes that the overall behavior of the B(E2) strength of the transitions to the first excited $2^+$ states is correlated with the neutron pairing gap in these nuclei. If confirmed experimentally, such a result would emphasize the crucial role of pairing also in nuclei deviating from the stability line.

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