On the Structure of Two-Quasiparticle States in Even-$A$ Xe Isotopes

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The excitation energies of proton and neutron two-quasiparticle states in even-$A$ xenon isotopes are studied within the shell-model framework. The results suggest that in the lighter isotopes ($A \leq 126$) the proton excitations might be yrast, whereas in the heavier ones ($A \geq 130$) the neutron-hole excitations dominate at lower energies. This finding would then explain the complex excitation spectra found in $^{126,128,130}$Xe, where the two excitation modes occur at comparable energies.

1. Introduction

The xenon isotopes belong to the $Z>50$, $N<82$ transitional region and they show yrast excitation spectra which are typical for an anharmonic vibrator. However, even far from the $N=82$ neutron shell closure they display distinct two-quasiparticle excitations [1-4].

In Fig. 1 the behavior of some negative-parity two-quasiparticle states and the yrast $10^+$ states in Sn, Te, Xe and Ba isotopes are shown together with some relevant low-lying vibrational states. A very clear difference in behaviour for these two excitation modes is apparent: With increasing proton number the excitation energies of the vibrational states ($J^e=2^+, 4^+, 6^+$ and $8^+$, except $6^+$ in Te) decrease with decreasing neutron number, whereas the energies of the yrast $5^-$, $7^-$ and $10^+$ states in Sn and Te increase with decreasing neutron number. However, the $7^-$, $8^-$ and $9^-$ states in Xe, and $7^-$ in Ba behave differently. When going from the $N=82$ the energy increase to about $N=74-76$ but then stays constant or decreases slightly with decreasing neutron number. Of these states the $5^-$, $7^-$ and $10^+$ states in e.g. $^{132}$Xe have been attributed to the $v(h_{11/2}^1s_{1/2}^1)s^-$, $v(h_{11/2}^1d_{5/2}^1)s^-$ and $v(h_{11/2}^2)^6$ configurations [1], whereas the $6^+$ states in the Te isotopes have been attributed to the $\pi(g_{7/2}^2)^6$ and/or $\pi(g_{7/2}^1d_{5/2})^6$ configurations [10].

Quite recently measurements of magnetic moments in $^{134}$Ce [11] and $^{128}$Xe [12] have revealed very pure neutron configurations for the isomeric states in question ($10^+$ and $8^-$, respectively).

The aim of the present work is thus to investigate whether it is possible in a simple two-quasiparticle approach, to reproduce at least qualitatively the behaviour of the non-band states (Fig. 1) in even-$A$ xenon isotopes, and further, to elucidate whether the observed quasiparticle states are of neutron or proton nature.

2. Shell-Model Considerations

2.1. General

A description of two-quasiparticle states in the xenon isotopes might be allowed provided the nuclear shape is rather spherical and the orbits are not very much admixed. The quadrupole deformation parameter $\beta_2$ has a smooth behaviour as a function of neutron number for Sn to Ba isotopes (we also include $^{140}$Ce and $^{142}$Nd). From a linear fit to the data [13, 14] the average value of $\beta_2$ at $N=82$ is found to be $\langle \beta_2 \rangle = 0.105(10)$. If this value is accepted as the "spherical" value then the effective Nilsson parameter $\epsilon$ is about 0.1 or less in the xenon isotopes. Note that $\epsilon \sim 0.95\beta_2$ for small deformations [15]. Thus the $\Omega$-splitting on a Nilsson diagram is
Probable rather small and we neglect it for simplicity. Further, that the states probably have rather pure configurations can be inferred from e.g. g-factors in \(^{121}\) Te, \(^{127,128}\) Xe [12], \(^{112,113}\) In [17] and \(^{134}\) Ce [11], from close-lying levels with the same spin-parity in \(^{124}\) Xe, or from theoretical calculations

in Sn [18], \(^{121}\) I [16] or \(^{133}\) La, \(^{131,133}\) Ba [19]. It is thus argued that the shell-model approach should be a valid approximation for the present two-quasiparticle study.

In the shell-model framework the excitation energy of a two-quasiparticle state of total spin \(J\) is given by

\[
E_{2\text{qp}}(J) = \varepsilon(i) + \varepsilon(j) + A(ij; J)
\]

where \(\varepsilon(i)\) are the one-quasiparticle energies and \(A(ij; J)\) is the interaction energy of two quasiparticles in orbitals \(i\) and \(j\) coupled to spin \(J\) (in the \(j - j\) sense).

The orbitals included in the present study are

- protons: \(d_{5/2}, g_{7/2}\) and \(h_{11/2}\)
- neutrons: \(s_{1/2}, d_{3/2}, d_{5/2}, g_{7/2}\) and \(h_{11/2}\).

Thus the deep-lying neutrons hole \(g_{9/2}\) is not included, neither are proton \(1p - 1h\) excitations across the \(Z = 50\) shell closure considered.

2.2. One-Quasiparticle Energies \(\varepsilon(i)\)

The excitation energies of the odd protons are known in most of the odd-Z isotopes, but not in all of them [9, 20–25]. We thus obtain the effective energies in the xenon isotopes in the following manner. Using the odd-particle values and performing a smooth interpolation both in isotopic and isotonic directions, the missing even-\(N\) values are deduced. Subsequently the values in the isotonic direction are read off at \(Z = 54\) (Xe); these values are then adopted as the proton one quasiparticle values in xenon, as presented in Table 1. The energies of the neutron-hole states are known in all the odd Xe isotopes [9, 21, 26–30]. Since the energies change only slowly as a function of neutron number, the effective energies in the even isotopes are readily obtained from the odd neighbours (Table 1). The uncertainties in the proton energies are of the order of some tens of keV, while the neutron energies are accurate to some keV, being the empirical values.

2.3. Two-Quasiparticle Interaction Energies \(A(ij; J)\)

The interaction energies of two nucleons \(i\) and \(j\) in total spin \(J\) are neither empirically nor theoretically well known around the doubly closed core nucleus \(^{132}\) Sn. We thus use the method of scaling in nuclear matter [31], as detailed in e.g. [32]. In this approach the two-nucleon matrix elements are presumed to be proportional to \(1/N \sim 1/A\). Thus the tin

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Fig. 1. Systematical behaviour of some yrast negative-parity and intruder \(10^+\) states in even-\(A\) SnTe, Xe and Ba isotopes with 2–16 holes in the \(N=82\) shell. Some relevant vibrational states are included for comparison.