Study of isomers in neutron-rich magic $^{132}$Sn region

S. Sarkar
Department of Physics, The University of Burdwan, Golapbag, Burdwan -713104

M. Saha Sarkar
Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Kolkata - 700064

Abstract. Shell model calculations have been done for interpreting two representative isomeric states in neutron rich $^{132}$Sn region using SMN and SMPN Hamiltonians. They are, (i) 2.91 min isomer in $^{138}$Cs and (ii) the 0.57 µs isomer in $^{136}$Sb nuclei. The results are compared with those obtained with KH5082 and CW5082 Hamiltonians. How the results clearly distinguish the most appropriate interaction has been discussed.

Keywords. A=132, Shell model, Isomers

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1. Introduction

Few-valence-particle neutron- rich nuclei above the doubly magic $^{132}$Sn are of recent interest. It is well known that after $^{16}$O, the strongest shell closure occurs at $^{132}$Sn, and nuclei with few valence particles in the proton $\pi$(gdsh) and neutron $\nu$(hfpi) orbitals above the $^{132}$Sn core are appropriate systems inviting applications of the spherical shell model. The region closely resembles the region above the $^{208}$Pb core. But nuclei above the $^{132}$Sn core, particularly the isotopes of Sn, Sb, Te, I, Xe and Cs are comparatively neutron-rich and close to the dripline. For example, the last stable isotope of Sn is $^{124}$Sn and therefore the Sn isotopes with $A=134-138$ are already more than 10 neutrons away from the line of stability. Study of these very n-rich nuclei both experimentally as well as theoretically are important not only for the nuclear structure, such as for the knowledge of empirical N-N interaction in the neutron-rich exotic environment, but also for the applications in the astrophysical r-process model calculations.

These nuclei are located far from the line of stability and are very difficult to produce. Thermal - neutron - induced fission and the spontaneous fission sources of $^{252}$ Cf and $^{248}$Cm initially played the most important role in populating these nuclei. More recently, deep inelastic, fragmentation and fission at intermediate and relativistic energies have also been used. Different complementary experimental techniques are used to study the nuclear structure of these neutron-rich nuclei. Among them the search for microsecond isomers and the study of their decay schemes are very powerful tools, and in many cases it is
the only way to get nuclear structure information for nuclei very far from the stability line. Specially, the microsecond isomer spectroscopy is complementary to prompt gamma measurements using large detector arrays or β decay experiments as discussed recently in Ref [1].

Near the doubly magic nuclei, isomers, specially the microsecond ones are very abundant and these isomers are generally yrast traps carrying considerable amounts of angular momentum. The isomers may be studied using recoil-fragment spectrometers which are efficient for the selection of the reaction products. The detection is based on event-by-event time correlation between the fragments and the delayed gamma-rays or conversion electrons de-exciting the isomers. Recoil-fragment spectrometer allows one to detect the microsecond isomers produced at a very low rate. This is the most frequently used technique in recent experiments. The measured energies and half-lives of the isomeric transitions allow one to deduce the electromagnetic transition rates which are important to test theoretical models.

In the present work shell model calculations have been done for interpreting two representative isomeric states in this mass region. They are, (i) 2.91 min isomeric state in $^{138}$Cs [2] nuclei and (ii) the 0.57 $\mu$s isomer in $^{136}$Sb [3]. It is shown clearly, how theoretical prediction of the half-lives of the isomeric states sensitively depends on the parametrization of the shell model Hamiltonian and how the results distinguish the most appropriate interaction.

2. Shell model valence space and the (1+2)-body Hamiltonians

The shell model valence space considered for this calculation consists of $\pi (1g_{7/2}, 2d_{5/2}, 2d_{3/2}, 3s_{1/2} \text{ and } 1h_{1/2})$ proton orbitals and $\nu (1h_{9/2}, 2f_{7/2}, 2f_{5/2}, 3p_{3/2}, 3p_{1/2} \text{ and } 1i_{13/2})$ neutron orbitals with $^{132}$Sn as the inert core. As mentioned above, because of its resemblance with the valence space above the $^{208}$Pb core, effective interaction derived for the well studied Pb-region has been used in the shell model calculations for nuclei in the $^{132}$Sn region by the appropriate scaling. KH5082 is one such a Hamiltonian obtained from the Pb-region by $A^{1/3}$ scaling of the two-body matrix elements (tbme) to take in to account the different sizes of the nuclei in the two regions. With the availability of experimental data on the binding energies and low-lying spectra for $^{134}$Sb and $^{134}$Te, which provided information on the n-p and p-p tbmes respectively, the KH5082 was modified by Chou and Warburton to obtain CW5082 (1+2)-body Hamiltonian [4]. In the recent years improved experimental data on the binding energies and low-lying spectra for A=134, Sb and Te have been available. It may be noted that now data on $^{134}$Sn have also become available and these can provide valuable information on n-n tbmes for this n-rich region. With these new data on A=134, Sn and Sb, further modification of the CW5082 Hamiltonian has been done recently [5] to obtain SMN Hamiltonian. $^{134}$Te which provides proton-proton tbmes, has been studied extensively. It is expected that the inclusion of new experimental data would further improve the SMN interaction. We have initiated this effort by changing only four proton-proton tbmes of the SMN interaction. The binding energies of $^{134}$Te with respect to $^{132}$Sn core (-20.56 MeV) and its three low-lying excited levels with $J^\pi = 2^+, 4^+, 6^+$ at energies 1279, 1576 and 1692 keV, respectively, predominantly from the $\pi (1g_{7/2})^2$ multiplet, have been used to modify only four relevant proton-proton tbmes and SMN was renamed as SMPN. These two empirical Hamiltonians have been found to be remarkably
successful in predicting binding energies, low-lying spectra and electromagnetic transition probabilities for the nuclei in the range A=134-138 and 50 ≤ Z ≤ 55. In the present work we use these two Hamiltonians along with KH5082 and CW5082 in the shell model calculations for $^{136}$Sb and $^{138}$Cs nuclei, employing the code OXBASH [6].

3. Results and discussions

3.1 $^{138}$Cs

Not much information is available on the $^{138}$Cs nucleus. This nucleus though neutron-rich, is not very exotic (N/Z = 1.51). A few levels are observed [2]. But for most of them spin-parities are not assigned. Only three levels including the $3^-$ ground state and a 2.91 min $6^-$ isomeric state have definite spin-parity assignment. It is therefore of interest to apply shell model with the newly constructed SMN and SMPN Hamiltonians for this region to predict the level structure and calculate the half-life of the isomer for comparison with the measured value. Calculated level structure and electromagnetic transition probability may further act as guidance for future experiments on this nucleus.

![Figure 1. Calculated and experimental $^{138}$Cs spectra.](image)

In Fig.1, calculated spectra with SMN and SMPN Hamiltonians are compared with the experimental one. In Set I, for both SMN and SMPN Hamiltonians the calculation over the valence space mentioned above is slightly truncated. Only 0-2 protons are allowed to occupy the $1h_{11/2}$ orbital, otherwise no truncation is made. It correctly reproduces a $3^-$ ground state with both SMN and SMPN Hamiltonians.
In calculation with SMPN, the first 2− excited state comes at 15 keV whereas the observed level is at 10.86 keV. The next observed level at 15.74 keV excitation has been assigned (1)− and we get a 1− level at 31 keV. In the untruncated calculation, SMPN (Set II), 2− comes at 13 keV and the 6− comes at 20 keV, the first excited 1− now comes at 29 keV. The most interesting is that both the calculations correctly reproduce the isomeric nature of the 6− level though its excitation energy is underpredicted to be at 15 keV (SMPN Set I), and 20 keV (SMPN Set II). The measured excitation energy of this state is 79.9 keV. The only favourable transition is (SMPN Set I), and 20 keV (SMPN Set II). The measured excitation energy of this state is 29 keV. The most interesting is that both the calculations correctly reproduce the isomeric state as above the first 6− state. For most of the yrast states from 7− to 0−, except 1− and 6−, the dominant components of the wave functions are π1g7/232d5/2ν2f7/2 and π1g7/25ν2f7/2, the former one is 28-38% and the later is 13-30%. We name these two configurations C1 and C2. For 1− the C1 configuration is 28% with an admixture of 16% of π1g7/242d5/2ν2f7/2. The wave function structure of the 6− isomeric state is, as one may expect, quite different than other yrast states. Its dominant components are not C1 and C2 but π1g7/22d5/2ν2f7/2(55.2%) and π1g7/232d5/23ν2f7/2(16.1%). It should be mentioned here that the results of the untruncated calculation (Set II) validate the results of the slightly truncated one (Set I) by showing that the occupation of the intruder orbital πh11/2 is small.

For the calculations with SMN interaction, all the yrast states including 6−, C2 is most dominant (30-50%) and C1 is 23-30%. Moreover, in calculation with SMN, while 3− is still the ground state but the 1− state is pushed up in energy whereas 2− and 4− come below the 6− level. So in this calculation 6− apparently does not look like an isomer.

Half-life of the isomeric state is then calculated with the wavefunctions of both SMN and SMPN (both Sets) calculations. Calculated half-life for the 6− → 4− E2 transition with the wavefunctions of the SMN Hamiltonian is of μs order. The measured half-life is 2.91 min. Thus SMN calculation fails to predict the longlived isomer. For calculation with the wavefunctions of the SMPN Hamiltonian, 6− → 3− (gs) M3 transition gives a half-life of about 12 min. Bare values of the g-factors have been used. E4 half-life for the same transition is extremely large. Thus SMPN Hamiltonian correctly predicts a long lived isomer in 138Cs. The result also indicates a need for larger B(M3) value implying thereby different g-factors than the bare ones.

### 3.2 136Sb

At present very little is known about the nuclear structure of 136Sb. The ground state of this nucleus is argued to be 1− by Hoff et al [7]. Their argument was based mainly on the strong beta transitions of the 136Sb ground state to the Iπ = 0+ ground state and the excited 2+ states in 130Te. They also used the analogy of 136Sb with the 212Bi of the 208Pb region, the two regions being similar. The ground state of 212Bi is Iπ = 1−. The ground state in 136Sb arises predominantly from the π1g7/2 ν(2f7/2)3 configuration. So it must have negative parity. A 0+ ground state would imply a highly improbable scenario where several states below 3 MeV in 136Te are populated by relatively strong first forbidden unique beta transitions. Hoff et al. also ruled out the possibility of a 2− ground state only on the ground that it demanded an exceptionally fast log ft1u =8.2 first forbidden unique beta transition to the 0+ ground state of 136Te. They used, in favour of their argument, the smallness of
the unique forbidden matrix elements from the beta decay of $^{134}Sb$ and $^{135}Sb$.

In our calculations with both CW5082 and SMN Hamiltonians, we get a $2^-$ ground state for $^{136}Sb$. The first excited $1^-$ state comes at an excitation energy of 125 keV and 47 keV, respectively. With KH5082 Hamiltonian, the ground state comes out to be $1^-$. The first excited $2^-$ state comes at 126 keV. Since KH5082 predicts incorrectly a $1^-$ ground state instead of $0^-$ in $^{134}Sb$, and fails badly compared to CW5082 and SMN, for $^{135}Sb$ and other $N=84$ isotones, the prediction of a $1^-$ ground state for $^{136}Sb$ by KH5082 (and its different variations [8]), which agrees with the assignment of Hoff et al., seems to be questionable.

The only information available on $^{136}Sb$ are, a beta delayed neutron-emission half-life of 0.923(14)s, a beta delayed neutron-emission probability of 16.2(32)% per decay and a $\mu$s isomeric state with a half-life of 0.565(50)$\mu$s observed recently through a 173 keV gamma transition by Mineva et al [3]. They examined several probable scenarios for this isomeric transition. The most probable scenario they advanced was that the isomer originated from the small energy spacing between the $6^- \text{and } 4^- \text{levels of the } \pi(1g_7/2) \nu(2f_7/2)^3 \text{multiplet.} \text{This was based on their shell model calculations with Kuo-Herling interaction (KH5082 and its variations, like Khn [8]) and the non-observation of a high-spin (6^-) beta-decaying isomer. According to them the observed 173 keV } \gamma\text{-ray was the result of E2 transition from the } 4^- \text{to } 2^- \text{level and the low energy } 6^- \text{to } 4^- \text{and } 2^- \text{to } 1^- \text{(ground state) transitions were not observed due to conversion and/or absorption in the aluminum catcher. In deducing their theoretical B(E2) value, for comparison with that from the measured half-life, they, however, did not mention the effective charges used.}

Our calculation of half-life for the excited states also favour the $6^-$ level as the probable isomeric state. It seems that a $2^-$ assignment to the ground state spin-parity makes the discussion of the isomeric transition easier, compared to the $1^-$ assumption. From the measured half-life of 565 $\pm$ 50 ns of the isomeric state one can deduce a value for the $B(E2)=4.11^{+0.40}_{-0.33}$ W.u. with transition energy 47 keV (not observed) between $6^-$ to $4^-$ levels. This energy for the gamma-ray is obtained in our shell model calculation with SMN Hamiltonian. The $4^- \text{to } 2^- \text{(ground state) transition energy 148 keV observed as 173 keV transition experimentally. The calculated half-life of the } 4^- \text{state is much shorter compared to 565 ns. The effective charges for reproducing experimental half-life of the } 6^- \text{isomeric state are proton effective charge } = 1.00 \text{ and neutron effective charge } = 1.00^{+0.06}_{-0.05} \text{ (in unit of e), seem reasonable when compared with those for the } N=84 \text{ isotones [5].}

4. Conclusion

Only SMPN Hamiltonian in the mass region can reproduce correctly the $6^-$ isomeric state in $^{138}Cs$. Recalling the fact that the SMPN differs from the SMN only by four important $\pi-\pi$ tbmes, it shows how sensitively the wavefunctions depend on certain important tbmes.

Thus changes in the $\pi-\pi$ tbmes in SMPN is significant and more $\pi-\pi$ tbmes should be modified in the light of new experimental data to improve the prediction for the energy eigenvalues of low-lying yrast levels. Origin of the isomeric transition in $^{136}Sb$ has been discussed and effective charges for N=85 Sb has been derived. The question of the ground state spin of $^{136}Sb$ can be resolved only through further experimental investigation on this
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nucleus. Work is in progress to compare the shell model prediction of beta-delayed n-emission half-life with the measured value. This will further help in inferring about the quality of the shell model wave functions.

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