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MAGNETIC PROPERTIES OF SUPERDEFORMED ^{193}Hg AND ^{195}Tl NUCLEI

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MAGNETIC PROPERTIES OF SUPERDEFORMED ^{193}Hg AND ^{195}Tl NUCLEI

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Abstract:

Recent data from the EUROGAM array have revealed dipole transitions linking signature partner superdeformed bands in ^{193}Hg and ^{195}Tl nuclei. Measurements of the photon decay branching ratios, taken together with the average quadrupole moment measured in neighboring superdeformed nuclei, enable the absolute M1 strengths to be determined. From these data and using the strong coupling model, we find that four from the six superdeformed bands in ^{193}Hg involve the excitation of the single 113^{th} neutron into the [512]5/2$^-$ and the [624]9/2$^+$ orbitals and that the two superdeformed bands in ^{195}Tl are due to the 81^{st} proton being in the [642]5/2$^+$ orbital.

Introduction

One of the currently most interesting research areas in nuclear physics is the study of superdeformed (SD) nuclei. Such nuclei are associated with extremely large quadrupole deformations, typically $\beta_2 = 0.6$ in the mass 150 region [1,2] and $\beta_2 = 0.47$ in the mass 190 region [3,4]. Hence, they are expected to have a completely different structure than normal deformed nuclei, leading to the possibility of exotic new modes of excitation. It is therefore of great importance to identify and characterise as fully as possible the active single-particle orbitals in SD nuclei. In such studies, the electromagnetic properties play a crucial role. While the electric quadrupole moment is completely determined by the nuclear shape, the magnetic properties should provide new insights into the structure of the SD single-particle states and may reveal new and interesting features. Because of the large quadrupole deformations the decay sequences in the SD bands were found to be completely dominated by stretched E2 transitions. However, in the heavier mass-region of observed SD nuclei, around ^{192}Hg, the decay extends to considerably lower spins, $I_0=8\hbar$ compared to $I_0=24\hbar$ in the A=150 region, and to correspondingly smaller transition energies. Thus, the M1/E2 branching ratio becomes larger. In this contribution we report on results obtained from the EUROGAM array. Several M1 transitions have been found to compete strongly with E2 transitions in several SD bands in the ^{193}Hg and ^{195}Tl nuclei. As it will be shown, unambiguous intrinsic configurations can be assigned to those SD bands from the extracted M1 strengths.

Experiments and results

Two different experiments were carried out at the Tandem accelerator at the Nuclear Structure facility, Daresbury Laboratory, using the EUROGAM array. It consists of 45 large-volume Compton suppressed germanium detectors [5,6]. In the first experiment, the nucleus ^{193}Hg was populated using the ^{150}Nd(^{48}Ca,5n)^{193}Hg reaction at a beam energy of 213 MeV. A total of 10^9 events were recorded with an unsuppressed fold ≥ 5, where an event is defined as a coincidence between any number of suppressed γ-rays. In the second experiment, the nucleus ^{195}Tl was populated using the ^{186}W(^{15}N,6n)^{195}Tl reaction at a beam energy of 105 MeV. A shorter beam time was used for this reaction, and only 300 x 10^6 events were recorded with an unsuppressed fold ≥ 5. In both experiments targets consisting of thin self-supporting foils were used, in order to have the residual nuclei emitting their γ-rays with the full recoil velocity. In the following, the results concerning ^{193}Hg [7] and ^{195}Tl [8] will be presented separately, after a brief reminder of the known properties of the SD bands in those nuclei (prior to the EUROGAM experiments) :

^{193}Hg

Up to five SD bands have been observed [9] in this nucleus. Comparison with theoretical calculations leads to the suggestion that the two pairs of signature partner

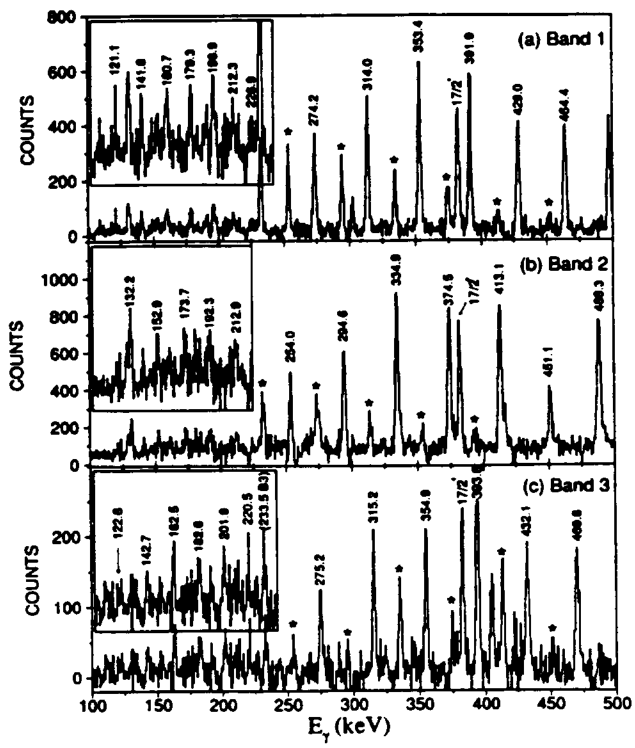

Fig. 1 - Spectra of superdeformed bands 1,2 and 3 in ^{193}Hg. These spectra are from quadruple coincidences showing γ rays in coincidence with three γ rays that are in the band of interest. (a) Band 1 with members of band 2 (2a) denoted *, and interband dipoles (inset). (b) Band with members of band 1 denoted *, and interband dipoles (inset). (c) Band 3 with members of band 2 (2b) denoted *, and interband dipoles (inset).

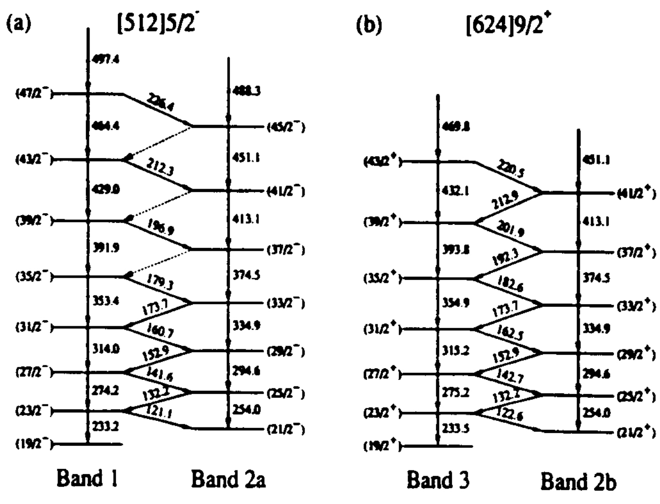

Fig. 2 - Level schemes for the negative and positive parity structures. The energies of the dipoles are assigned maximum errors of 0.5 keV : (a) Bands 1 and 2a showing interband dipoles and (b) bands 3 and 2b showing interband dipoles.

bands are based on the [512] 5/2 and [624] 9/2 neutron orbitals. An additional band was thought to have the favored $j_{15/2}$ single-particle configuration. This latter band interacts strongly with one signature of the [512]5/2 pair of SD bands allowing their parity and signature to be deduced. An intriguing property of the [512] 5/2 signature partner bands was the observation of cross talk from one partner to the other. This cross talk had originally [9] only been observed in one direction and the connecting transitions were not seen. Very recently, it has been established [10] that the cross talk goes both ways. It has also been suggested that the connecting dipole transitions have M1 multipolarity. This assignment is consistent with the recent measurement of the X-ray yield [11].

In order to study the cross talk between SD signature partners in ^{193}Hg, spectra requiring triple gates in each known SD band have been constructed. Figure 1a exhibits such a spectrum for band 1. In this spectrum, transitions in band 2 can be clearly seen, up to 451 keV. This confirms the observation of cross talk by Cullen et al. [9]. In addition, dipole transitions connecting band 1 to band 2 are observed at low energy (see insert). In fig. 1b, the situation is reversed and the triple-gated spectrum on band 2 exhibits the low-lying transitions of band 1. Once more, interband γ–rays are observed at low energy (insert of fig. 1b). These data enable us to connect bands 1 and 2a as shown in Fig. 2a. A spectrum of band 3 is shown in fig. 1c, gated on transitions above the crossing, where it is no longer identical to band 1. In this spectrum, transitions belonging to band 2 are observed up to 450 keV. At low energies, transitions linking these SD bands are observed (in the insert of fig. 1c). Because of the gating procedure necessary to separate band 3 from band 1, these transitions are very weak. The level scheme shown in fig. 2b illustrates how band 3 and band 2 are connected. At this level of the discussion, it appears that we are making the conclusion that band 2 consists of two unresolved bands (identical within the detector resolution). This conclusion is confirmed by comparing the width of the peaks for band 2 with those of band 1 (see fig. 3). It is clear from this figure that band 2 is indeed two SD bands, with an average γ-ray separation of 1.4 ± 0.3 keV. Measurement of the widths of the component 2a of band 2 (marked with stars in fig. 1a), observed by gating on band 1, are also shown in fig.3. These widths are the same as the widths for band 1. These data constitute the first experimental evidence for identical superdeformed bands in the same nucleus.

In order to measure the nuclear g factor, the γ-ray photon M1/E2 branching ratios have been measured. Theoretically [12], the branching ratio is given by the formula :

$$R\gamma\,(M1/E2) = 14556.0 \times \frac{E\gamma^3\,(M1)}{E\gamma^5\,(E2)} \times \frac{B(M1)}{B(E2)}$$

where at strong coupling, B(E2) is propotional to Q_0^2 and B(M1) is proportional to $(g_K - g_R)^2 \times K^2$. The Rγ branching ratios for levels in band 1 are shown in fig.4, where they are fitted as a linear function of A, where A represents the dependence on energy and Clebsch-Gordan coefficients of the branching ratio :

$$A = \frac{E\gamma^3(M1)}{E\gamma^5(E2)} \times \frac{\langle I\ K\ 1\ 0 \mid I\text{-}1\ K\rangle^2}{\langle I\ K\ 2\ 0 \mid I\text{-}2\ K\rangle^2}$$

The quadrupole moment Q_0 =19 ± 2 eb of band 1 is assumed to be the same as that measured for the core nucleus ^{192}Hg [13,14]. A least square fit is made to the data

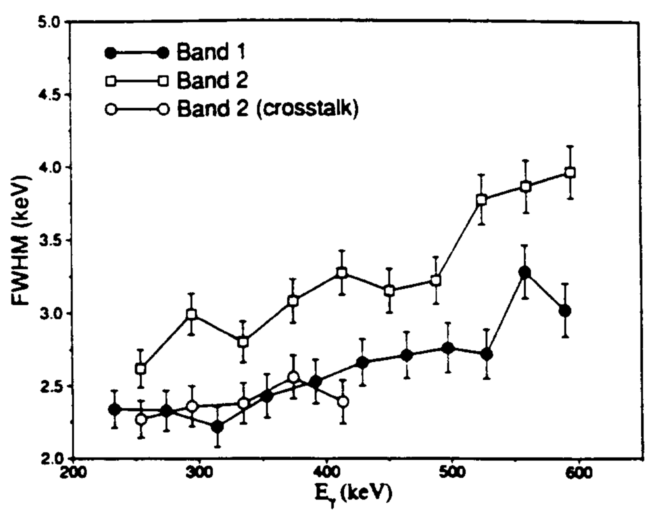

Fig. 3 - Measurements of the full width half maxima (FWHM) of band 1 and band 2. Errors are assigned through consideration of the statistical variation of similar measurements made on all the superdeformed bands present in ^{193}Hg which have very similar widths to those of band 1.

giving $(g_K-g_R)K/Q_0 = -0.14 \pm 0.01\ (eb)^{-1}$ so that $g_K = -0.65 \pm 0.14$ (g_R is taken equal to Z/A). The measured g factor is in good agreement with $g_K = -0.61$ given by the strong coupling model for the proposed $[512]5/2^-$ neutron orbital [12]. As pointed out earlier, the reduced number of gates in band 3 free of contamination from very close γ-transitions in band 1, prevent us from performing a conclusive g-factor measurement for the positive parity structure. However, if these connecting transitions were M1 and the observed cross talk was to the signature partner of band 3, then the larger Ω=K in this case would result in a larger M1 strength than is observed in the case of band 1. This would result in the intensity of the E2 transitions of band 3 in the region of the cross talk decreasing more rapidly, with decreasing γ-ray energy, than in the case of the band 1.

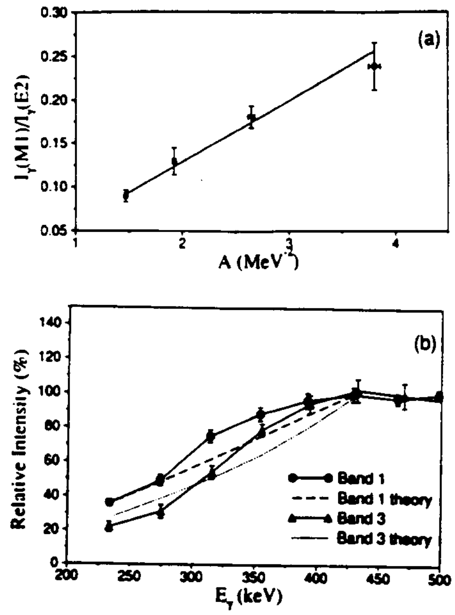

Fig. 4 - (a) Measurements of the M1/E2 branching ratios taken on band 1 only, plotted as a function of A (see text).
(b) Intensity measurements of bands 1 and 3 measured relative to the 429 keV and 432 keV transitions respectively.The variation in intensity down bands 1 and 3, using theoretical branching ratios determined from their respective single parity assignments of $[512]5/2^-$ and $[624]9/2^+$, is also included.

Relative intensity measurement of both bands 1 and 3 are shown in fig.4b, and it can be seen that this is indeed the case. Also shown in fig. 4b are the results of estimating the variation in E2 intensity in bands 1 and 3, using the theoretical branching ratios for both the negative and positive parity band pairs, assuming neutron orbitals $[512]5/2^-$ and $[624]9/2^+$, respectively, and assuming that there is no decay from the SD minimum to normal states until the bottoms of the bands are reached. Theoretical electron conversion coefficients used in this analysis are taken from ref. [15]

195Tl

Two SD bands have been reported in ^{195}Tl [16]. They have been interpreted as signature partners which exhibit some signature splitting for rotational frequencies above 0.2 MeV. This was found to be in agreement with a configuration where the single proton is occupying the $i_{13/2}$ (Ω=5/2) intruder orbital. A similar pair of SD bands was found in each of ^{191}Tl and ^{193}Tl nuclei [17,18], which illustrates the role of this orbital located in between the two SD proton shell gaps (Z=80 and Z=82).

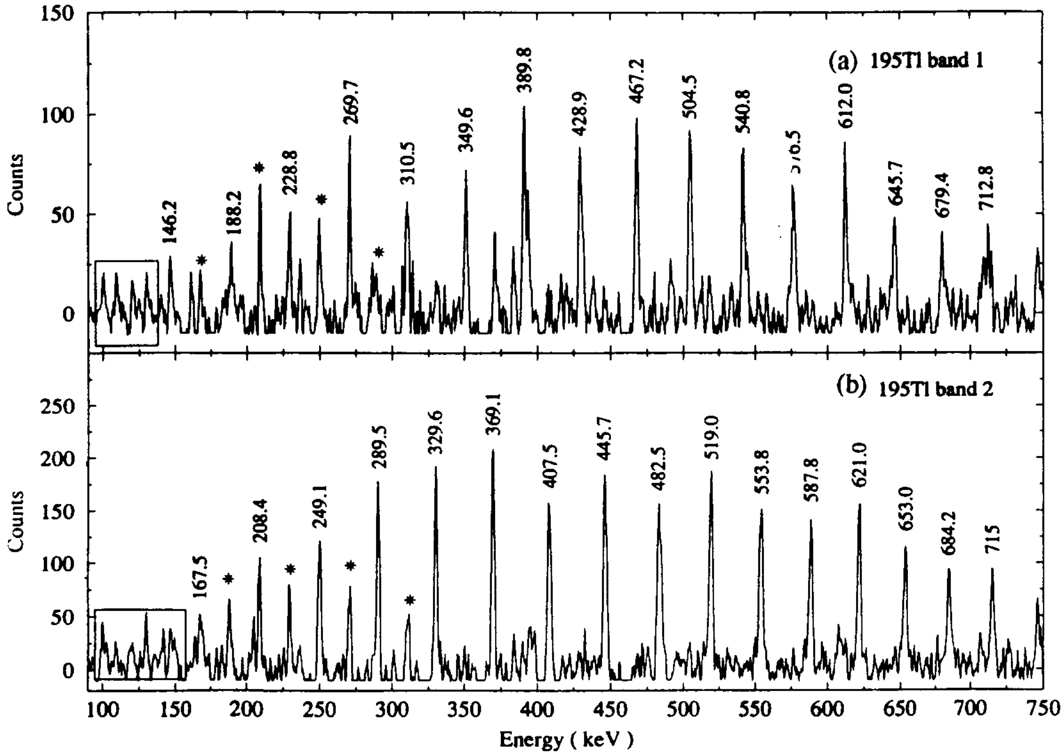

Fig. 5 - Spectra of SD bands 1 and 2 in ^{195}Tl. The spectra are from quadrupole coincidences showing γ rays in coincidence with three γ rays that are in the band of interest.
(a) Band 1 with members of band 2 denoted * and candidates of interband dipoles (box).
(b) Band 2 with members of band 1 denoted * and candidates of interband dipoles (box).

The triple-gated spectra of the two SD bands in ^{195}Tl, obtained from the EUROGAM experiment, are displayed in fig. 5. The higher selectivity of EUROGAM enable us to extend the bands to higher and lower transition energies (transition energies as low as 146 keV and 167 keV were observed in band 1 and band 2 respectively). In the spectrum of band 1 (fig. 5a), γ-transitions of band 2 can clearly be seen, up to 300 keV. The corresponding cross-talk transitions are very weakly seen at energies ranging from 100 keV to 180 keV, as shown in the box of fig.5a. In the spectrum of band 2 (fig. 6b), the situation is reversed and transitions in band 1 are seen, as well as very weak cross-talk transitions (in the box of fig.5b). The interband transitions together with the transitions in band 1

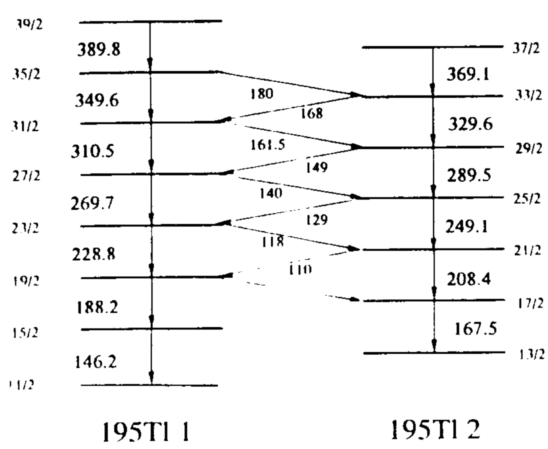

Fig. 6 - Level scheme for the pair of signature partner bands in ^{195}Tl. The energies of the dipoles are assigned with 0.5 keV errors.

and band 2 can be organised in a unique way as shown in fig. 6. This suggests that the cross-talk transitions are probably dipoles. Having in mind the fact that band 1 and band 2 are the expected signature partner of the $i_{13/2}$ (Ω=5/2) proton configuration, it is therefore suggested that in this case (^{195}Tl), the two-way cross talk would most likely indicate the presence of M1 decays.

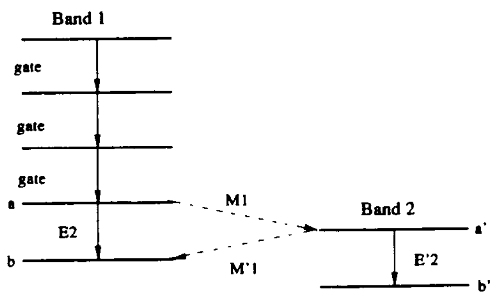

Fig. 7 - Scenario where transitions above the level : a are used as gates, and where the intensities I_γ(E2) and I_γ(E'2) are used to extract the $\frac{B(M1)}{B(E2)}$ value.

Because of the lack of statistics, and the weakness of the SD bands in ^{195}Tl, we were not able to measure directly the intensities of the M1 transitions. Therefore an alternative method has been used in order to extract the $R_\gamma = \frac{I_\gamma(M1)}{I_\gamma(E2)}$ branching ratios, and subsequently the M1 strengths within a band. If we consider the decay sequence illustrated in fig. 7, where multiple gates above the transition : a → b of band 1 were required and where the cross-transitions : a → a' and a' → b are unobserved, the branching ratios of the decay of level a to b and a' and of the decay of a' to b and b', can be respectively expressed as :

$$\text{i)} \qquad \frac{I_\gamma(M1)}{I_\gamma(E2)} = 14556.0 \times \frac{E_\gamma^3\,(M1)}{E_\gamma^5\,(E2)} \times \frac{B(M1)}{B(E2)}$$

$$\text{ii)} \qquad \frac{I_\gamma(M'1)}{I_\gamma(E'2)} = 14556.0 \times \frac{E_\gamma^3\,(M'1)}{E_\gamma^5\,(E'2)} \times \frac{B(M'1)}{B(E'2)}$$

In addition, if we assume no signature dependance of the B(M1)'s, and no feeding and no decay out of the level a' of band 2, the total intensity conservation gives a third equation:

$$\text{iii)}\ [1+\alpha(M1)]\, I_\gamma(M1) = [1+\alpha(M'1)]\, I_\gamma(M'1) + [1+\alpha(E'2)]\, I_\gamma(E2)$$

(where the α's are the total internal conversion coefficients , taken from ref. 15)

Using the equations i), ii) and iii), one obtains :

$$\frac{B(M1)}{B(E2} = 6.87\ 10^{-5} \frac{[1+\alpha\ (E'2)]\, I_\gamma(E'2)}{[1+\alpha\ (M1)] I_\gamma(E2) \frac{E_\gamma^3(M1)}{E_\gamma^5(E2)} - [1+\alpha\ (M'1)]\, I_\gamma(E'2) \times \frac{E_\gamma^3 M'1}{E_\gamma^5 E'2}}$$

which involves only the intensities of the observed E2 transitions.

This procedure has been applied , and B(M1) values has been extracted for several SD states in both bands. The quadrupole moment Q_0 = 17.5 ± 2 eb is assumed to be the same as the measured for Yrast SD band in ^{194}Hg nucleus [19] (^{195}Tl could be considered as a core of ^{194}Hg with a single proton outside the core). Fig. 8 shows the measured B(M1) values for different levels of the two signature partner bands as function of their spins. The spins of the SD states are suggested using the methods of Draper et al. [20] and Becker et al. [21]. We have indicated by the dashed lines, in the same figure, the theoretical B(M1) values [12] for the configurations where the single proton is occupying the orbitals [642]5/2 and [514]9/2, which are the two lowest available configurations [22,23]. The data are in agreement with the assignement of the intruder configuration [642]5/2 to the two SD bands in ^{195}Tl. The corresponding measured g_K value is 1.6 ± 0.3 which is very close to g_K = 1.45 given by the strong coupling model for the proposed proton orbital.

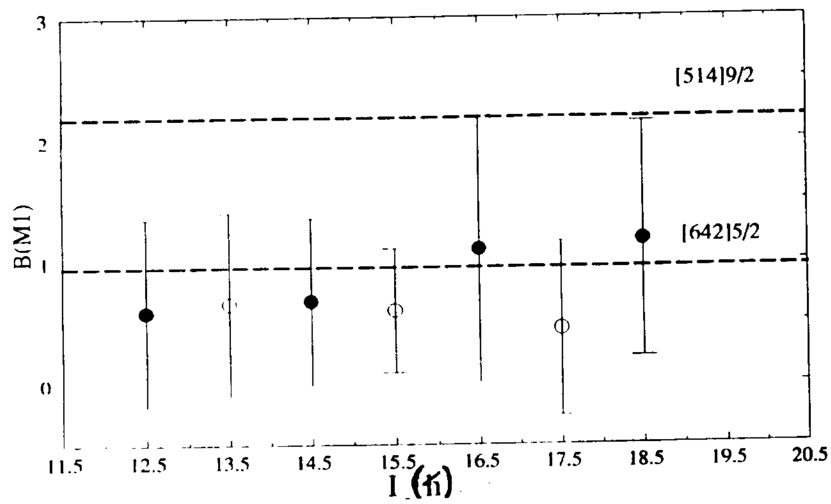

Fig. 8 - The extracted B(M1) values for the pair of signature partner bands in ^{195}Tl, assuming Q_0 = 17.5 ± 2 eb. The B(M1) are in units of μ_N^2 and the indicated spins are those of the considered states (the equivalent to a in fig. 7) in band 1 (•) and in band 2 (o). The theoretical values for the [514]9/2 and [642]5/2 proton configuration are from ref. 12.

Conclusion

We have observed dipole transitions between SD signature partner bands in ^{193}Hg and ^{195}Tl nuclei. This enable us to measure M1 strengths and to extract g-factors for the SD bands. A very good agreement was found with the g-factors predicted by the strong coupling model for the proposed single-particle configurations. This represents an evidence that spectroscopic informations could be obtained on SD nuclei in the mass-190 region, despite the lack of informations on spins and excitation energies of the bands. In other cases of nuclei which are not discussed here, the same method could be applied in order to establish configuration assignement for the SD bands. Indeed, the EUROGAM data revealed competition between M1 and E2 transitions in the SD bands of ^{193}Tl and ^{194}Tl nuclei [24]. Finally , the first experimental evidence of two identical SD bands in ^{193}Hg was presented.

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