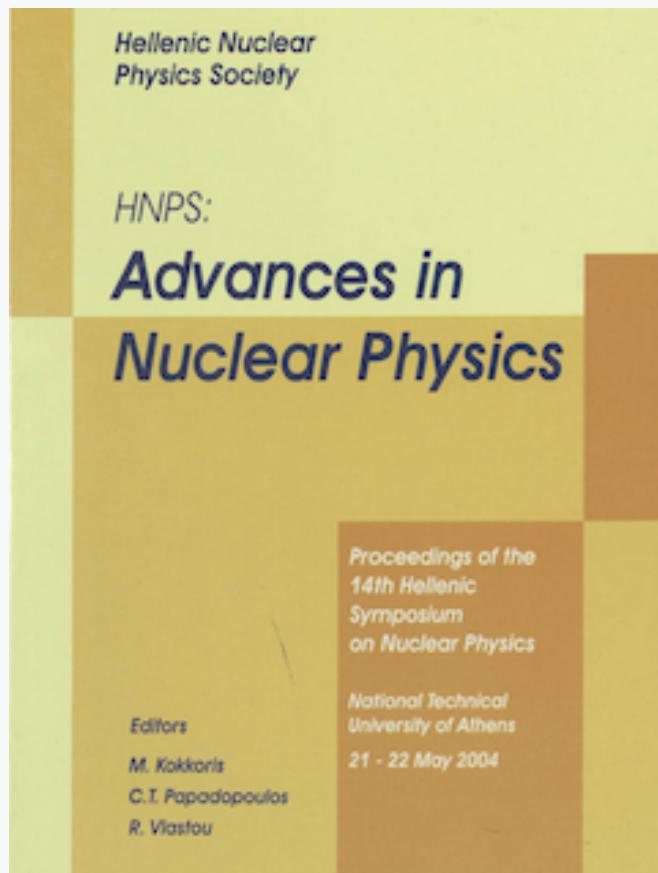


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# Study of Magnetic Rotation in $^{193}\text{Pb}$ : An Example of Collaboration Between Southeastern European Research Teams

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## Abstract

This paper summarizes the results of a series of experimental studies of magnetic rotation in mid-shell Pb nuclei. The focus is for the  $29/2^- \nu(1i_{13/2}^{-1}) \otimes \pi(3s_{1/2}^{-2} 1h_{9/2} 1i_{13/2})$  magnetic band in  $^{193}\text{Pb}$ , for which all experimental observables have been measured. This provides a stringent test of the theoretical models aiming at the description of such excitations. These studies have been carried out in collaboration with different research teams from the Balkans and are an example how to utilize most efficiently the huge scientific potential of the region.

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## 1 Introduction

The microscopic world imposes a severe restriction on rotational motion: the spherical symmetry must be broken for a quantal system. Thus, the rotation of an atomic nucleus is associated with the presence of a large electric quadrupole moment, *i.e.* with the breaking of the spherical symmetry of the charge distribution. As a result, sequences of enhanced electric quadrupole (E2) transitions connecting  $\Delta I = 2$  levels are observed in experiment;  $I$  denotes the nuclear spin.

Rotational-like sequences of enhanced magnetic dipole (M1) transitions between  $\Delta I = 1$  states have been observed for closed-shell nuclei; see Ref. [1,2] for reviews. For example, for the  $Z = 82$  Pb nuclei more than 60 sequences of this type have been discovered [3] and about half of them are connected to lower-lying states in the level schemes. These excitations arise from a spontaneous symmetry breaking by anisotropic currents of a few valence particles

and holes which occupy orbits with large angular momenta [4]. Angular momentum along the M1 bands is generated by the step-by-step alignment of the particle and hole spins into the direction of the total angular momentum, which resembles the closing of a pair of shears and is referred to as shears mechanism.

## 2 Magnetic dipole and electric quadrupole moments of magnetic excitations

For an understanding the phenomenon of magnetic rotation it is important to determine the configuration of the excited nucleons and to learn how they couple their angular momenta. As already stated, the coupling of high- $j$  particle and hole excitations creates states for which the rotational symmetry with respect to the angular momentum vector is broken. The associated total magnetic dipole moment is not oriented along the direction of the angular momentum. This specifies an orientation which is needed for the formation of rotational-like sequences. The observed large M1 transition strength is related to the large component of the magnetic moment perpendicular to the angular momentum. It is well known that the M1 transition probability depends on the perpendicular component of the magnetic moment vector with respect to the angular momentum direction, while the static magnetic moment depends on its parallel component [5]. A crucial proof of the suggested coupling scheme has been provided by the measurement of the static magnetic moment of the band head of such an excitation in  $^{193}\text{Pb}$  [6]. On the other hand, M1 transition strength within the bands, which is deduced from lifetime measurements, provides crucial test for the shears mechanism, because it demonstrates the expected decrease of the  $B(\text{M1})$  transition probabilities within the bands [1,2].

Another important aspect for the full understanding of the magnetic bands concerns deformation. The deformation should be small for bands that arise predominantly from the shears mechanism and not from a rotating deformed core. Both, static and transition quadrupole moments can provide information on the size of the deformation since they represent different components of the quadrupole tensor.

Here we report the results of a series of experiments of nuclear electromagnetic moments aiming at detailed studies of the nature of the shears states, the magnetic bands, and the shears mechanism.

### 3 Quadrupole moments of the “blades of the shears”

The closed-shell Pb nuclei are a well known example for shape coexistence; see Ref. [7,8] for reviews. As a result of the  $Z = 82$  shell closure they take spherical shapes close to their ground states, but at higher excitation energies a subtle interplay between spherical, prolate and oblate shapes has been observed experimentally in decay and in-beam studies [9,10]. We performed several experiments to measure the spectroscopic quadrupole moments of isomeric states in the Pb nuclei: the proton particle-hole ( $2p$ - $2h$ ) excitation across the  $Z = 82$  shell gap, which appear as  $11^-$  isomers across the Pb region, and the neutron-hole states in the  $1i_{13/2}$  sub-shell. The latter are either  $13/2^+$  or  $33/2^+$  isomers (one- or three-hole states in the odd- $A$  nuclei), or  $12^+$  isomers (two-hole states in even-mass Pb nuclei).

For the  $\nu(1i_{13/2}^{-n})$  states in the Pb small quadrupole moments were measured and these excitations are understood to polarize the core towards small prolate deformations; see Ref. [11] and references therein. The spectroscopic moments of the  $I^\pi = 11^-$  isomers in  $^{194,196}\text{Pb}$  have been measured applying the LEMS technique [12]. In the case of  $^{196}\text{Pb}$  the quadrupole interaction for the  $12^+$  and the  $11^-$  isomers was studied simultaneously. Since they experience the same electric-field gradient (EFG) and the quadrupole moment for the  $12^+$  isomer is known, it is straightforward to derive the quadrupole moment for the  $11^-$  isomer from the ratio of the quadrupole frequencies [13], having in mind that the magnetic moments of these states are also known. The magnetic moments of the  $11^-$  states were recently re-measured [14] and an evaluated value for the spectroscopic quadrupole moment has been suggested as  $Q_s(^{196}\text{Pb}; 11^-) = (-) 3.6(6) \text{ eb}$  [15]. Static quadrupole moments have been reported also for the  $11^-$  states in  $^{192}\text{Pb}$  [16], and  $^{194}\text{Pb}$  [15,17]. These results are summarized in Fig. 1, together with calculations within different theoretical models. The recent g-factor measurement of the Canberra group [14] confirms the oblate deformation of these states.

These results allow us to conclude that the  $2p$ - $2h$  proton “blade of the shears” has an oblate deformation  $\beta_2 \approx -0.13 \div -0.20$ .

### 4 Spectroscopic quadrupole moment of a “shears state” in $^{193}\text{Pb}$

We have measured the spectroscopic quadrupole moment of the  $29/2^-$  isomer in  $^{193}\text{Pb}$  ( $E_{ex} = 2584 \text{ keV}$ ,  $T_{1/2} = 9.4 \text{ ns}$ ) which is the band head of a magnetic band and has the  $\nu(1i_{13/2}^{-1}) \otimes \pi(3s_{1/2}^{-2} 1h_{9/2} 1i_{13/2})$  configuration. The spin and the configuration assignment for this state have been unambiguously fixed from spectroscopic studies [21,22] and a g-factor measurement [6], respectively.

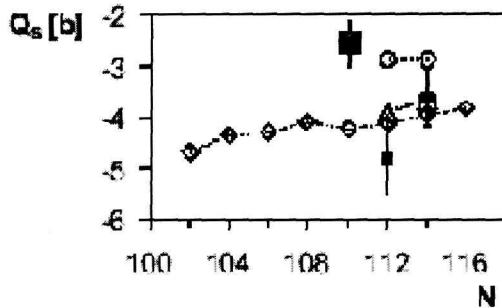


Fig. 1. Comparison between the experimental (filled symbols) and theoretical (empty symbols) spectroscopic quadrupole moments. The theoretical values include the results from Refs. [13,18-20].

The quadrupole interaction of the  $29/2^-$  isomer has been investigated in the EFG of solid Hg by applying the time-differential perturbed angular distribution (TDPAD) technique. The Hg host has been chosen because it provides a large EFG:  $V_{ZZ} = 17.4(9) \cdot 10^{21}$  V/m<sup>2</sup> at  $T = 170$  K, which results in a strong interaction on the short time scale given by the isomer lifetime. A quadrupole frequency of  $\nu_Q = 1.20(9)$  GHz was derived from the experimental TDPAD curves which are displayed in Fig. 2. It corresponds to a spectroscopic quadrupole moment of the isomer  $|Q_s| = 2.84(26)$  eb [23]. This is a rather large value which indicates that the deformation is defined by the 2p-2h proton “blade of the shears”.

It is not straightforward to determine the deformation of the  $29/2^-$  band head from the measured spectroscopic quadrupole moment. This state is not a high- $K$  isomer, hence  $K$ , the projection of the nuclear spin on the symmetry axis, is not a good quantum number, and, therefore, the strong-coupling formalism cannot be applied. One can overcome the problem by comparison to TAC-model [24] calculations. In this case the electric quadrupole moment is calculated as the expectation value of the proton system [25]. The quadrupole-quadrupole coupling constant, which controls the size of the deformation, was adjusted to reproduce the quadrupole moments of the  $\nu(1i_{13/2}^{-2})$  isomers in  $^{194,196}\text{Pb}$ . Using the same parameter set, the values of the quadrupole moments for the  $11^-$  isomers are somewhat underestimated and correspond to a quadrupole deformation of  $\beta_2 \approx -0.12$ . For the quadrupole moment of the  $29/2^-$  isomer the calculation yields a value  $Q_s^{TAC}(29/2^-) = -2.85$  eb, in a perfect agreement with the experimental result, and a value  $\beta_2 = -0.12$ , similar to that for the 2p-2h proton “blade of the shears”.

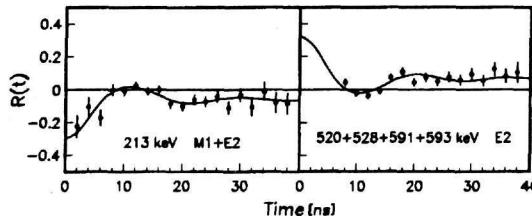


Fig. 2. TDPAD spectra for  $\gamma$  lines involved in the decay of the  $29/2^-$  isomer in  $^{193}\text{Pb}$  showing the quadrupole interaction in a solid Hg host at  $T = 170(1)$  K.

### 5 Lifetimes of excited states in $^{193}\text{Pb}$

As a next step in this experimental programme we have measured lifetimes of states in the  $\nu(1i_{13/2}^{-1}) \otimes \pi(3s_{1/2}^{-2}1h_{9/2}1i_{13/2})$  magnetic band in  $^{193}\text{Pb}$  [26], denoted as A11 band. Excited states in  $^{193}\text{Pb}$  were populated in the  $^{170}\text{Er}$  ( $^{28}\text{Si}$ , 5n) reaction at a beam energy of 149 MeV. The nuclear  $\gamma$ -decay was detected by the  $4\pi$   $\gamma$ -ray spectrometer GASP [27] which consists of 40 Compton-suppressed Ge detectors, grouped in 7 rings covering backward and forward angles. During the experiment two measurements were done: a recoil-distance method (RDDM) measurement (in order to approach the lifetimes at the bottom of the A11 band) and a Doppler-shift attenuation method (DSAM) measurement (in order to obtain information for short lifetimes). Here the results of the RDDM measurements are reported. For this part of the experiment, the Köln plunger device was used. Spectra were recorded for nine different distances, in the range from  $0.1 \mu\text{m}$  to  $257.1 \mu\text{m}$ . Triple  $\gamma\gamma\gamma$ -coincidence events have been collected during the experiment. For each distance the events were sorted off line into  $\gamma\gamma$ -coincidence matrices with  $\gamma$  rays detected in one given detector ring placed along one axis and  $\gamma$  rays detected elsewhere in the array along the second axis of the matrix. In order to extract the lifetimes of interest, the DDCM method [28] was used.

Prior our experiment lifetimes in the A11 band in  $^{197}\text{Pb}$  were measured [29], which can be used for comparison. These results together with our measurement are presented in Figure 3 and are in a fair agreement with each other. Note that due to arguments related to the systematics of the levels in the A11 bands in the Pb nuclei [26,30] we have shifted the spin of the levels in the  $^{197}\text{Pb}$  band by one unit upwards.

This measurement completes the experimental study of the A11 band in  $^{193}\text{Pb}$ . From the spectroscopic data [21,22] the in-band branching ratios are known which allows to deduce the E2 strength. It corresponds to an upper limit of the intrinsic quadrupole moment  $Q_0 \geq 1.69 \text{ b}$ , which in turn provides an upper limit for the deformation  $\beta_2 \geq 0.056$ .

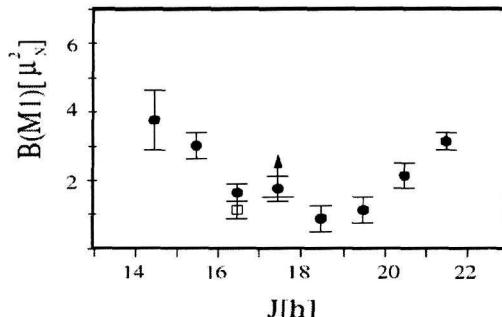


Fig. 3.  $B(M1)$  values for A11 bands in  $^{197}\text{Pb}$  (full circles) and  $^{193}\text{Pb}$  (empty square and arrow).

The measured  $B(M1)$  values have been compared to TAC-model calculations [25] and are a reasonable agreement have been observed.

## 6 Conclusions

We have done a series of experiments to study magnetic rotation in the Pb region. These experiments were focused around  $^{193}\text{Pb}$ , for which a complete set of experimental observables have been obtained for the A11 magnetic band. They have been compared to TAC-model calculations which describe the data reasonably well. Therefore, we conclude that the present parameterization of the model is fine-tuned to describe the properties of excited states in the Pb nuclei.

## Acknowledgements

It has to be noted that these experiments have been carried out in collaboration with different South-eastern European groups and present a nice example which demonstrates the research potential of the region. The quadrupole moment measurements have been done in collaboration with M. Ionescu-Bujor and A. Iordachescu from NIPNE, Bucharest. The lifetime measurements have been done in collaboration with S. Harrisopoulos and A. Spyrou from NSRC “Demokritos” in Athens. Fruitful collaboration with the Nuclear Moments group at the IKS, University of Leuven is also gratefully acknowledged. Experiments at the Laboratori Nazionali di Legnaro have been supported through the EC contract HPRI-1999-CT-00083. This work is supported through a NATO CLG no. 978799 and by the Bulgarian National Science Fund, contract VUF06/05.

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