QUADRUPOLE MOMENTS OF THE 12^+ STATES IN ^{206}Pb AND ^{200}Pb ☆

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The static quadrupole interaction of the 12^+ isomers in $^{206, 200}$Pb has been measured in solid Hg. The quadrupole moments of the 12^+ states indicate an increase in deformation with increasing number of neutron holes.

Near the ^{208}Pb doubly closed shell nucleus many isomeric states are known with spins from 4 to 30 which are, in most cases, associated with a unique quasiparticle structure. For most of these states the magnetic moments [1] could be determined yielding information on the magnetic moment operator as well as on the structure of these states. However, magnetic moments are rather insensitive to admixtures of collective modes. The theoretical analysis of the yrast states in ^{204}Pb and ^{212}Rn [2] indicates that a small core deformation has to be introduced to understand the energies of high-spin states in this mass region. In the present letter we report on the first in-beam observation of static quadrupole interactions of Pb isomers and on a substantial increase in the quadrupole moments of the 12^+ isomers between ^{206}Pb and ^{200}Pb.

Experimentally, the measurement of the quadrupole interaction of high-spin isomeric states is quite challenging since the basic interaction frequency (m-sublevel splitting) decreases quadratically with the nuclear spin. One therefore needs a host which provides an electric field gradient (efg) sufficiently high to induce a measurable sublevel splitting, such as for example solid Hg may play the same important role in determining quadrupole moments as did liquid Hg in determining magnetic moments especially in the Pb region [5]. We have therefore measured the quadrupole interaction of several isomers in different Pb isotopes, among them the 12^+ $(i_{13/2})^{-2}$ states in ^{200}Pb and ^{206}Pb using solid Hg as host.

The determination of nuclear moments, especially quadrupole moments, by "in-beam" techniques such as perturbed angular distributions (PAD) used in the experiments reported here can be hampered by damage of the lattice near the final site of the excited nucleus under study. Pb offered the advantage that the "in-beam" procedure could be checked easily by means of the well-known isomeric 4^+ state in ^{204}Pb. Consequently, we have studied the 4^+ state both „in-beam" and in the radioactive decay of the 1 h activity of ^{204}Pb^m.

The isomeric states were populated and aligned by the $^{A-2}$Hg$(\alpha, 2n)^{A}$Pb reaction using a pulsed 33 MeV α-particle beam from the tandem accelerator at the Chalk River Nuclear Laboratories. For the "in-beam" study of the 4^+ states in ^{204}Pb an energy of 22 MeV was chosen, while the radioactive source ^{204}Pb^m was produced at E_α = 28 MeV. The targets consisting of mercury enriched in the required Hg isotopes were prepared by placing a drop of liquid Hg into a small shallow hole cut in a copper plate which

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was then mounted onto a Joule–Thomson cryo-tip and cooled below the melting point of Hg.

The quadrupole modulation was measured by using the standar perturbed angular distribution method (PAD) [6]. Time spectra were derived for various γ-rays observed with Ge(Li) detectors placed at 0° and and 90° with respect to the beam direction. The background corrected ratio of the γ-ray intensities

$$R(t) = [I(0°, t) - I(90°, t)] / [I(0°, t) + I(90°, t)] ,$$

then yields the quadrupole modulation pattern which depends on the spin, the quadrupole coupling constant e^2Qq/h, the symmetry of the efg (axially symmetric for Hg) and the spatial orientation and distribution of the efg (e.g. oriented in a single crystal or randomly oriented in a polycrystal). For high-spin states especially, the proper orientation of the single-crystal axis can be very helpful in determining the quadrupole coupling constant unambiguously. As it turned out, our target preparation technique favoured the crystallization of Hg in large grains. Although possible in principle, we did not find it necessary to take special measures to ensure the growth of a single crystal or to orient it, but rather determined the crystal orientations by fitting the observed time spectra $I(\theta, t)$. In the case of ^{206}Pb three γ-ray transitions could be employed to observe the quadrupole modulation pattern, the $12^+ \rightarrow 9^-$ E3 transition (E_γ = 1369 keV), the $10^+ \rightarrow 9^-$ E1 transition (E_γ = 1299 keV) and the $9^- \rightarrow 7^-$ E2 transition (E_γ = 458 keV) [7] while in ^{200}Pb the only suitable transition was the $10^+ \rightarrow 9^-$ E1 transition (E_γ = 777 keV) [8]. Fig. 1 shows the modulation spectra observed for the 12^+ states in ^{206}Pb and ^{200}Pb, respectively. The patterns are basically different reflecting the fact that the ^{198}Hg target (^{200}Pb) solidified mainly in the form of a large grain with the c-axis perpendicular to the beam and γ-detection plane, while the ^{204}Hg target (^{206}Pb) formed a crystal with the c-axis in the plane perpendicular to the 90°-detector axis and with an angle of roughly 50° to the beam direction. The values for the quadrupole coupling constant e^2Qq/h, extracted from the modulation patterns are 201.6(8) MHz for the 12^+ state in ^{206}Pb and 322.8(16) for the 12^+ state in ^{200}Pb. Since the two coupling constants were measured at different temperatures the temperature dependence of the efg had to be determined. This was obtained from the measurement of the coupling constant of the 4^+ state in ^{204}Pb

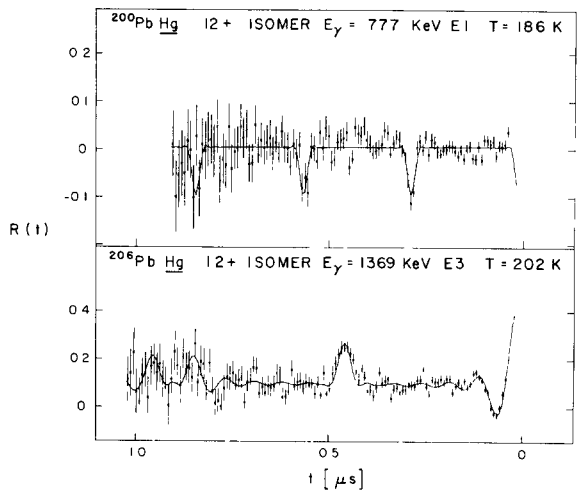

Fig. 1. Modulation patterns resulting from the quadrupole interaction of the 12^+ state of ^{200}Pb (top) and of ^{206}Pb (bottom) in solid Hg

between T = 82 and 202 K yielding $e^2Qq/h(T)$ = 224.5(10) $\{1 - 7.6(2) \times 10^{-5} T^{3/2}\}$ MHz. Applying the correction for temperature dependence, we then obtain for the ratio of the quadrupole moments of the two 12^+ isomers $|Q(^{200}\text{Pb}, 12^+)/Q(^{206}\text{Pb}, 12^+)|$ = 1.553(10).

Although the understanding of electric field gradients in metals, especially in sp-metals, has improved considerably, it is not yet good enough to deduce quadrupole moments from the measured coupling constant reliably. However, from the extensive studies, both experimentally and theoretically, on single-particle levels and effective charges in the lead region by the Stockholm group (e.g. ref. [9]) it can be concluded that the isomeric 12^+ and the 10^+ states in ^{206}Pb are rather pure members of the $(i_{13/2})^{-2}$ multiplet. Therefore, the qudrupole moment of this 12^+ state can be derived from the known B(E2) value of the $12^+ \rightarrow 10^+$ transition by using angular momentum algebra, $|eQ(12^+)| = 10.38[B(\text{E2}, 12^+ \rightarrow 10^+)]^{1/2}$, which yields $|Q(^{206}\text{Pb}, 12^+)| = 51(2)$ fm^2. (The error reflects only the experimental error of the B(E2) value.) This procedure is well justified for two-particle (hole) states in the Pb region, since the experimental transition moment B(E2, $8^+ \rightarrow 6^+$) in ^{210}Po agrees with the one calculated from the static moment $Q(^{209}\text{Bi}, h_{9/2}$ ground state) within an error of about 10%.

The derived quadrupole moment can now be used

Table 1
Summary of electromagnetic properties of the $12^+(i_{13/2})^{-2}$ states in ^{206}Pb and ^{200}Pb.

Nucleus	$T_{1/2}$ (ns)	μ (μ_N)	$B(E2, 12^+ \rightarrow 10^+)$ (e^2fm^4)	$\|Q\|$ (fm^2)
^{206}Pb	198(6) [a]	−1.860(48) [d]	24.1(14)	51(2) [b]
^{200}Pb	194(6) [a]	−1.884(72) [d]	57 (6) [c]	79(3)

a) From the present work.
b) Calculated from the $B(E2, 12^+ \rightarrow 10^+)$ value.
c) A transition energy of 40 keV was assumed (see text).
d) See ref. [1].

for calibrating the electric field gradient of Pb in Hg, resulting in a value of $eq = 16.3(7) \times 10^{17}$ V/cm^2 at $T = 202$ K. That the efg, at least in this temperature range, is not influenced by any kind of damage or other effects associated with the in-beam observation was proved by finding agreement within experimental errors for the coupling constant of the 4^+ state in ^{204}Pb obtained "in-beam" and in the radioactive source experiment. From the measured ratio and with the calibration of the efg from the 12^+ state in ^{206}Pb we derived for the moment of the 12^+ state in ^{200}Pb $|Q(^{200}\text{Pb}, 12^+)| = 79(3)$ fm^2. This rather large increase in the quadrupole moment indicates that ^{200}Pb can no longer be described by highly pure single-particle wavefunctions, but rather one has to consider additional collective effects. A similar increase is already observed in the $B(E2)$ value of the $12^+ \rightarrow 10^+$ transition in ^{200}Pb as compared to ^{206}Pb. Although the exact transition energy is not known (in the recent compilation of Schmorak [10] it is assumed to be below 50 keV) the $B(E2)$ value can be derived from the half-life within about 10% since the transition energy dependence is roughly balanced by the energy dependence of the conversion coefficient. In table 1 the $B(E2)$ values quoted for the $12^+ \rightarrow 10^+$ transition in ^{200,206}Pb are based on the more accurate data obtained for the half-lives in this experiment.

Assuming that the relationship between the quadrupole moment and the $B(E2)$ value still holds, one calculates from the transition rate a quadrupole moment for ^{200}Pb of $|Q_{cal}(^{200}\text{Pb}, 12^+)| = 78(4)$ fm^4, in close agreement with the value derived from the experimental ratio. This indicates that the 12^+ and the 10^+ state are influenced in a similar way. The increase in both the quadrupole moment and the $B(E2)$ value might be understood in terms of an increasing contribution from proton excitations. These excitations become more likely with increasing deformation which is suggested from the fact that the $i_{13/2}$ shell comes closer to the Fermi surface at slightly prolate deformation (see e.g. discussion on the lead region in ref. [2]). Using the simple relationship between in instrinsic moment and the deformation [11] one derives a deformation parameter for ^{200}Pb ($|\beta| \approx 0.03$) rather similar to the one Andersson et al. [2] had to use for states around $I = 12$ to calculate the yrast states of ^{204}Pb.

Since the 12^+ states in Pb isotopes are known to be isomeric over a wide range in mass numbers it will be interesting to determine their quadrupole moments to study the influence of the increasing number of neutron holes on the deformation.

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[1] Tables of Isotopes, eds. C.M. Lederer and V.S Shirley, Appendix VII (Wiley, New York, 1978).
[2] C.G. Andersson et al., Nucl. Phys A309 (1978) 141.
[3] H -E. Mahnke et al. Phys. Lett. 71A (1979) 112.
[4] H.-E. Mahnke, E Dafni, MIH. Rafailovich, G.D. Sprouse and E. Vapirev, to be published.
[5] K.H. Maier et al., Nucl. Phys. A186 (1972) 97, and other references in ref. [1].
[6] H. Frauenfelder and R.M. Steffen, In: Alpha-, beta- and gamma-ray spectroscopy, Vol. II, ed. K. Siegbahn (North-Holland, Amsterdam 1965).
[7] I. Bergström et al., Phys. Scripta 3 (1971) 11.
[8] M. Pautrat et al., Nucl. Phys. A201 (1973) 449.
[9] G Astner et al., Nucl. Phys. A182 (1972) 219.
[10] M.R. Schmorak, Nucl. Data Sheets 26 (1979) 81.
[11] A. Bohr and B.R. Mottelson, Nuclear structure Vol. II (Benjamin, Reading, 1975) 4.