Quadrupole moment of the 8^- isomer in ^{112}Sb

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The quadrupole interaction of the 8^- isomeric state ($T_{1/2}=536$ ns) in ^{112}Sb has been measured using the time differential perturbed angular distribution method. The linear momentum transfer from the ^{103}Rh(^{12}C, $3n$) reaction recoiled the isomeric nuclei into single crystals of Sb and Sn and a polycrystalline In foil. From the quadrupole coupling constant for the 8^- state of ^{112}Sb in Sb, the quadrupole moment was obtained relative to the moment of the stable ground state of ^{121}Sb: $|Q(^{112}\text{Sb},8^-)/Q(^{121}\text{Sb},\frac{5}{2}^+)|=1.958(10)$. The value is in accordance with the description of the isomer as an odd proton coupled to a neutron-excited Sn core. In addition, the measured coupling constants in Sn and In allow the determination of the quadrupole moments of isomers in ^{120,122}Sb and ^{115}Sb.

[NUCLEAR REACTIONS ^{103}Rh(^{12}C,$3n$)^{112}Sb, $E=50$ MeV, pulsed beam, recoil implantation into Sb single crystal, Sn single crystal, In; measured $I_\gamma(\theta,t)$ quadrupole modulation; deduced Q.]

INTRODUCTION

Over the whole mass range of known Sb isotopes[1] isomeric states are observed arising from the coupling of the odd proton outside the $Z=50$ closed shell to the neutron-excited cores of well-known isomers in corresponding Sn isotopes. A series of isomeric 8^- states with different lifetimes is observed from ^{112}Sb to ^{128}Sb and similar isomers have been observed in the odd mass Sb isotopes. Below the mass number $A=121$ the extra proton can be described as a $d_{5/2}$ quasiparticle; for nuclei with $A>121$ the $g_{7/2}$ orbital is favored, as is indicated by spin and magnetic moment measurements on the respective odd mass ground states.[2] The corresponding lower mass 8^- states can be described by $(\pi d_{5/2}\nu h_{11/2})$ configurations, in agreement with the magnetic moment measurements, while for ^{126,128}Sb the magnetic moments indicate a predominant $(\pi g_{7/2}\nu h_{11/2})$ configuration.[2]

While the magnetic moments of the Sb isomers are quite well explained within the simple single particle configurations, they are rather insensitive to collective features which have been observed in these nuclei, such as $\Delta I=1$ bands built on the $\frac{9}{2}^+$ states.[3] Therefore the determination of quadrupole moments of these states is rather interesting, especially since the quadrupole moments of many of the respective Sn states were determined in recent years.[4,5]

Unlike the magnetic moments, the determination of quadrupole moments is hampered by the fact that there are no large electric field gradients (EFG) available externally; instead one has to make use of either atomic or solid state properties. Therefore only ratios of quadrupole moments of different nuclear states belonging to the same element can be determined with high accuracy and the absolute value crucially depends on the calibration of the EFG.

The EFG at Sb nuclei in Sb metal, which has a rhombohedral lattice structure, is known from nuclear quadrupole resonance (NQR) measurements on both stable isotopes ^{121,123}Sb (Ref. 6) whose quadrupole moments have been determined by atomic beam and optical spectroscopy experiments. Thus the measurement of the quadrupole interaction of an isomeric Sb state in Sb metal directly yields the quadrupole moment relative to the ground state of ^{121}Sb.

The calibration procedure outlined above is rather simplified by the use of heavy ion nuclear reactions: The linear momentum transferred in such reactions allows implantation into the material of known EFG in a rather straightforward way.

In the following we report on experiments to determine the quadrupole moment of the 8^- state in ^{112}Sb. We then use the isomer to measure the EFG at Sb atoms in Sn and In metal to serve as calibration for other isomers for which the quadrupole interaction had been measured previously but whose moments could not yet be derived.

EXPERIMENTAL METHOD

The half-life of about 500 ns of the 8^- isomer in ^{112}Sb is rather convenient for a time differential perturbed angular distribution (PAD) experiment. A pulsed 50 MeV ^{12}C beam from the FN tandem at Stony Brook was used to populate the 8^- state in ^{112}Sb with the reaction ^{103}Rh(^{12}C,3n). The repetition time of the pulsed beam was 2 μs with a pulse width of typically 5 ns FWHM. The aligned and excited ^{112}Sb nuclei were implanted out of the 0.8 mg/cm^2 Rh foil into In, Sn, and Sb hosts.

The γ rays deexciting the isomer in ^{112}Sb were detected by two 5.1 cm$\times$5.1 cm NaI(Tl) detectors placed at 0° and 90° with respect to the beam direction. Time spectra were obtained using the conventional fast-slow coincidence method.

To reduce possible radiation damage effects, the Sb crystal was heated to about 473 K. The mobility of defects at room temperature should be much higher for the lower melting point metals, In and Sn. Therefore only little influence of damage was expected for these host materials at room temperature.

In a PAD experiment the interaction of the nuclear quadrupole moment Q with the electric field gradient (EFG) is observed as a modulation of the time spectra of the isomeric decay radiation. These modulation spectra can have quite complicated structure depending on the nuclear spin I of the isomer, the symmetry of the interaction, and the spatial orientation, i.e., the geometrical arrangement of the detectors. In the case of an axially symmetric EFG with the z component $V_{zz}=eq$, the modulation spectra are periodic with the basic repetition period T_0 given by

$$\frac{1}{T_0}=\frac{3e^2Qq/h}{4I(2I-1)}\times\begin{cases}1 & \text{for } I \text{ integer}\\ 2 & \text{for } I \text{ half-integer}\end{cases} \quad (1)$$

corresponding to the smallest spacing of the sublevel splitting

$$E_m=\frac{3m^2-I(I+1)}{4I(2I-1)}e^2Qq\ . \quad (2)$$

Because of the nonequidistant splitting, larger spins have more frequency components, all harmonics of $\omega_0=2\pi/T_0$; which of these harmonics contribute is determined by the highest rank k of the spherical harmonics in the angular distribution function and by the geometrical arrangement, *with* only frequencies corresponding to $|\Delta m|\leq k$ possible.

The general expression for the angular distribution[7,8] can be rewritten in the following form

$$W(\theta,t)=1+\sum_{\substack{k_1k_2\\N}} a^N_{k_1k_2}(\alpha,\beta,\theta)\,A_{k_1k_2}G^N_{k_1k_2}(t) \quad (3)$$

for an oriented EFG, as is realized in single crystals. Here the $a^N_{k_1k_2}$ are given by associated Legendre polynomials describing the geometrical arrangement, with α being the angle between the c axis and the beam-γ-ray plane, β the angle between the projection of the c axis onto the beam-γ-ray plane and the beam direction, and θ the angle between the beam and the γ ray. The coefficients $A_{k_1k_2}=B_{k_1}A_{k_2}$ are determined by the alignment parameter B_{k_1} and the angular distribution parameter A_{k_2} of the emitted radiation. The perturbation functions $G^N_{k_1k_2}(t)$

$$G^N_{k_1k_2}(t)=\sum_n s^{k_1k_2}_{nN}\cos(n\omega_0t) \quad (4)$$

contain the information on the quadrupole interaction; only those frequencies contribute which connect sublevels with $|\Delta m|=N$. The coefficients $s^{k_1k_2}_{nN}$ are tabulated for nuclear spins $I\leq 20$ and k_1, $k_2=2$, 4 in Ref. 9 in which values for the coefficients $a^N_{k_1k_2}$ are also given for some geometries. Typically, only terms with $k_1=k_2=2$ and the cross terms $k_1=2$, $k_2=4$ have to be taken into account. Rather distinct modulation patterns can thus be obtained by proper choice of the geometrical arrangement: (a) the symmetry axis of the EFG (i.e., the c axis of the crystal) is perpendicular to the detector plane ($\alpha=90°$). Then only even values of n (i.e., $N=2$) contribute. In a detector placed at $\theta=\pi$ (upper sign) and $\pi/2$ (lower sign) with respect to the aligning beam, the following expression

$$W(\theta=\tfrac{\pi}{\pi/2})=1+\tfrac{1}{4}A_{22}\pm\tfrac{3}{4}A_{22}G_{22}{}^2(t) \mp(\tfrac{15}{8})^{1/2}(A_{24}+A_{42})G_{24}{}^2(t)\ . \quad (5)$$

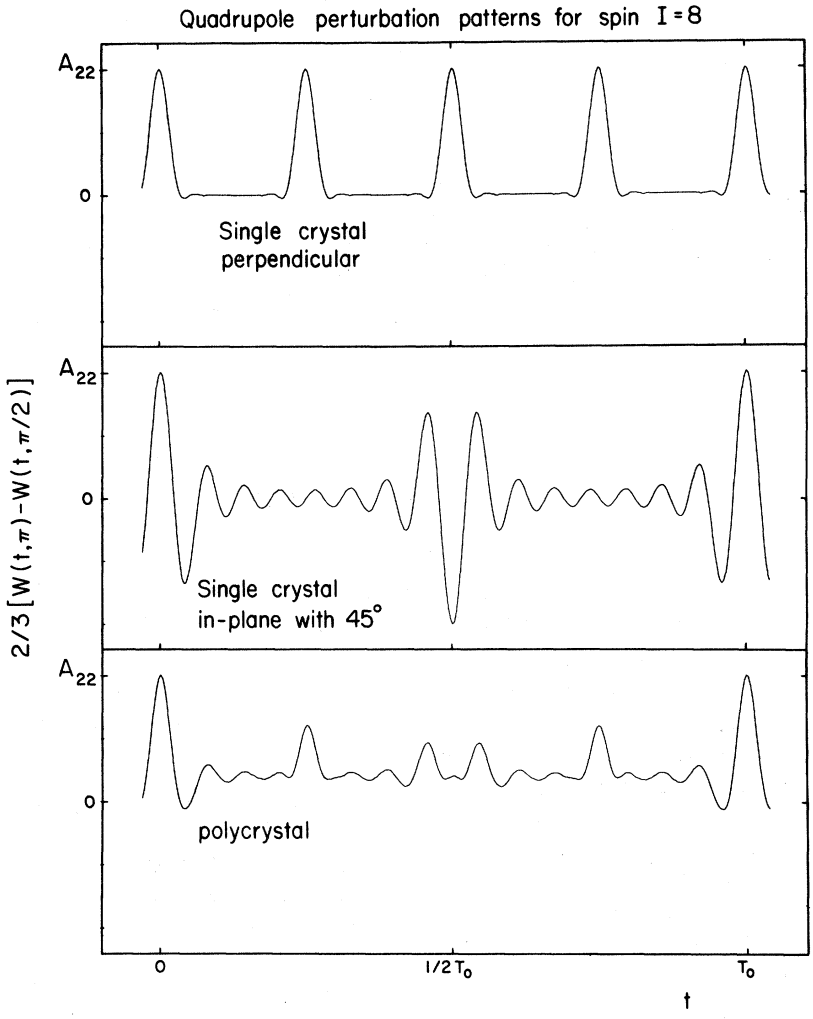

FIG. 1. Quadrupole modulation patterns for a spin $I=8$ and an axially symmetric electric field gradient with fixed orientation (top and center panel) or randomly oriented (bottom panel).

containing only odd harmonics (for half-integer spin I) or fourth harmonics (for integer spin I) is obtained. (b) The symmetry axis of the EFG lies in the detector plane ($\alpha=0°$) and makes an angle $\beta=45°$ with respect to the beam direction.[10] For this case the odd terms are enhanced, and a form of the correlation,

$$W(\theta=\tfrac{\pi}{\pi/2})=1+\tfrac{1}{16}A_{22}\pm\tfrac{3}{4}A_{22}G_{22}{}^{1}(t)+\tfrac{3}{16}A_{22}G_{22}{}^{2}(t)\pm\tfrac{3}{16}(\tfrac{5}{6})^{1/2}(A_{24}+A_{42})G_{24}{}^{1}(t)+\frac{5\sqrt{15}}{64}(A_{24}+A_{42})G_{24}{}^{2}(t)\,, \quad (6)$$

which contains only odd harmonics for integer spin I in the difference $W(\theta=\pi)-W(\theta=\pi/2)$, is obtained.

The different patterns that correspond to Eqs. (5) and (6) with a fraction of 10% for the G_{24}^{N} terms are illustrated in Fig. 1 for a nuclear spin $I=8$. They are compared to the pattern one obtains for a randomly oriented EFG as realized in polycrystalline samples with

$$W(\theta,t)=1+\sum_{k}A_{kk}G_{kk}(t)P_{k}(\cos\theta) \quad (7)$$

and

$$G_{kk}(t)=\sum_{n}s_{kn}\cos n\omega_{0}t\,.$$

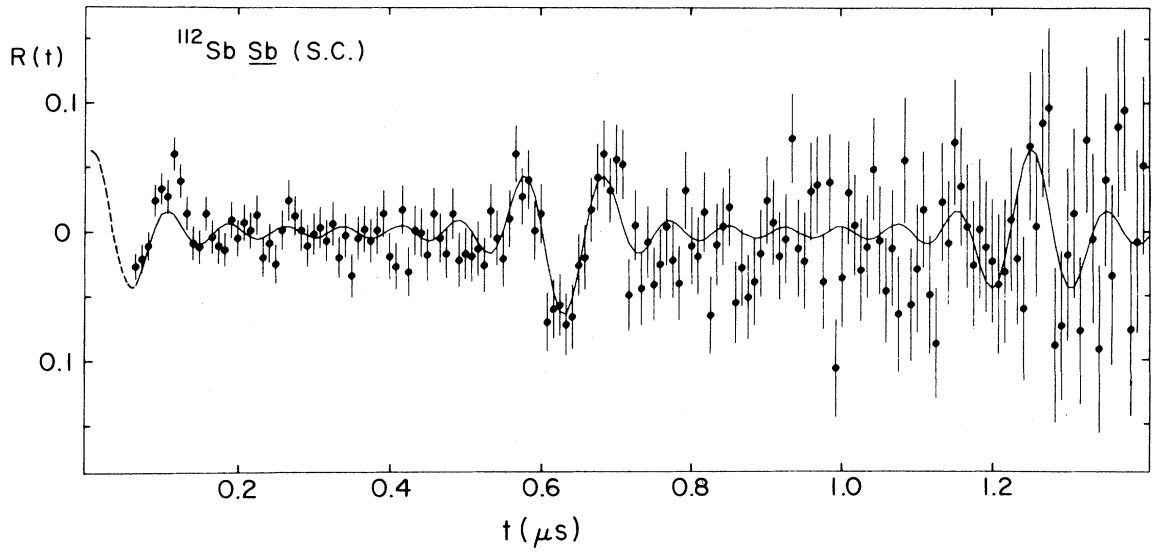

FIG. 2. Quadrupole modulation of the 8^- isomer of ^{112}Sb in Sb at a temperature of $T=504$ K. The single crystal was oriented with the c axis in the beam-γ-ray plane at 45° with respect to the beam direction.

The coefficients s_{kn} are also tabulated in Ref. 9. From the illustration one realizes that the proper choice of the geometry becomes quite important for high spin states when the basic period T_0 is larger than the nuclear lifetime.

In our experiments all three patterns have been observed by using a single crystal of Sb with the c axis in the 45° geometry (b), a single crystal of Sn with the c-axis perpendicular to the detector plane (a), and a polycrystalline In foil.

EXPERIMENTAL RESULTS

In the decay of the 8^- isomer at least three γ transitions are known with energies of 456, 237, and 103 keV.[11] Owing to the absorption in the targets, typically only the 456-keV γ ray was used. For the time spectra of the two detectors at 0° and 90°, modulation spectra are obtained by forming the ratio

$$R(t)=(I(0°)-I(90))/(I(0°)+I(90°)) \quad (8)$$

after proper background correction and normalization of the spectra. The quadrupole modulation spectra for Sb, Sn, and In hosts are shown in Figs. 2–4.

In the case of Sb an additional spectrum was taken at a lower host temperature. The frequency change we observed is in perfect agreement with the known temperature dependence of the EFG in Sb. This finding we take as support of the assumption that the excited ^{112}Sb nuclei find a substitutional lattice position in the Sb host at the end of the

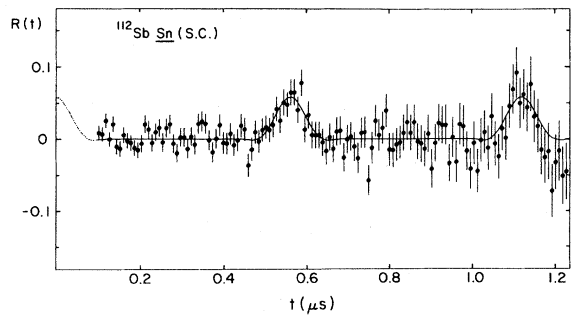

FIG. 3. Quadrupole modulation of the 8^- isomer of ^{112}Sb in Sn at $T=303$ K. The single crystal was oriented with the c axis perpendicular to the beam-γ-ray plane.

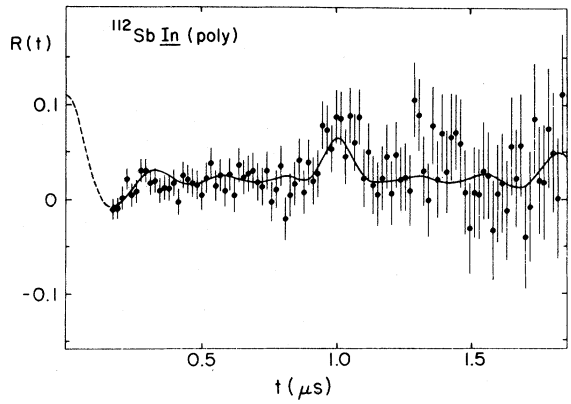

FIG. 4. Quadrupole modulation of the 8^- isomer of ^{112}Sb in polycrystalline In at $T=298$ K.

TABLE I. Observed quadrupole coupling constants e^2Qq/h for the 8^- state of ^{112}Sb.

Host	T (K)	e^2Qq/h (MHz)
Sb	504	128.1(6)
	311	139.1(15)
Sn	303	71.4(4)
In	298	40(1)

slowing-down process so that they experience the EFG known from NQR on stable ^{121}Sb. Table I summarizes the results for the quadrupole coupling constants obtained from the least squares fit of Eqs. (4), (5), or (6) to the respective modulation patterns. With the known coupling constant for ^{121}Sb in Sb at the same temperature we directly obtain the quadrupole moment ratio of

$$|Q(^{112}\text{Sb},8^-)/Q(^{121}\text{Sb},\tfrac{5}{2}^+)| = 1.958(10) .$$

A more precise value of the lifetime of the isomer could also be extracted from the time spectra, yielding $T_{1/2}=536(22)$ ns. The modulation amplitudes observed in these experiments (and also in magnetic interaction studies) indicated effective anisotropies of $A_{22}=+0.14(1)$ compatible with a stretched quadrupole transition for the 456-keV γ ray and $A_{22}=-0.10(1)$ for the 237-keV γ ray, indicating a dipole transition. These values imply that the decay sequence $8^-\rightarrow$456 keV$\rightarrow 6^+\rightarrow$237 keV$\rightarrow 4^+\rightarrow$103 keV$\rightarrow 3^+$ proposed by Ketel *et al.*[11] must be revised. The spin of the (4^+) state should be increased to $5^{\pm}$ in order to be consistent with the observed dipole character of the 237 keV transition.

The observed quadrupole interactions in Sn and In enables us to determine moment ratios of other Sb isomers: (a) 3^+ isomer in ^{120}Sb and ^{122}Sb: The quadrupole coupling constant and the temperature dependence of the EFG were determined in Sn.[12,13] Combined with our results we get

$$|Q(^{120,122}\text{Sb},3^+)/Q(^{121}\text{Sb},\tfrac{5}{2}^+)| = 1.151(7) .$$

(b) $\frac{19}{2}^-$ isomer in ^{115}Sb: The fact that we observe a unique quadrupole interaction for Sb*In* implies that a g-factor measurement by Faber *et al.*[14] of ^{115}Sb in solid In must be interpreted in terms of a combined interaction, i.e., a magnetic dipole interaction in the external magnetic field and an electric quadrupole interaction in the EFG of tetragonal In. The damping of their magnetic spin rotation spectrum can, therefore, be interpreted in terms of a static quadrupole interaction[15] and gives a coupling constant of

$$e^2Qq/h(^{115}\text{Sb}In, T=300\text{ K}) = 28(10)\text{ MHz} .$$

The moment ratio is determined as

$$|Q(^{115}\text{Sb},\tfrac{19}{2}^-)/Q(^{121}\text{Sb},\tfrac{5}{2}^+)| = 1.37(40) .$$

DISCUSSION

In addition to the quadrupole moment ratios determined in this experiment, ratios of quadrupole moments are known for ^{114}Sb, ^{118}Sb, ^{122}Sb (Ref. 16), and ^{117}Sb (Ref. 17) from nuclear quadrupole relaxation studies in liquid metals (In, Sn) and liquid metal alloys (In, Sb). All these values are summarized in Table II.

TABLE II. Quadrupole moments of Sb isomers in comparison with ^{121}Sb.

A	I^π	Configuration	$\lvert Q(^A\text{Sb})/Q(^{121}\text{Sb})\rvert$	$\lvert Q\rvert$ (fm^2) exp[a]	cal[b]
112	8^-	$\pi d\frac{5}{2}\nu h\frac{11}{2}$	1.958(10)[c]	71(7)	82
114	8^-	$\pi d\frac{5}{2}\nu h\frac{11}{2}$	1.87(30)[d]	66(11)	82
115	$\frac{19}{2}^-$	$\pi d\frac{5}{2}[\nu h\frac{11}{2}d\frac{3}{2}]_{7-}$	1.37(40)[c]	49(14)	70
117	$\frac{25}{2}^+$	$\pi d\frac{5}{2}[\nu h\frac{11}{2}]_{10+}{}^2$	2.1(1)[e]	75(9)	88
118	3^+	$\pi d\frac{5}{2}\nu s\frac{1}{2}$	1.6(4)[d]	57(14)	36
120	3^+	$\pi d\frac{5}{2}\nu s\frac{1}{2}$	1.151(7)[c]	41(4)	36
121	$\frac{5}{2}^+$	$\pi d\frac{5}{2}$	1	36(4)	36
122	3^+	$\pi d\frac{5}{2}\nu s\frac{1}{2}$	1.151(7)[c]	41(4)	36

[a]Quadrupole moment determined from the ratio (column 4) with $Q(^{121}\text{Sb})=-36$ fm^2.
[b]Calculated values as $Q(^A\text{Sb})=Q(^{121}\text{Sb})+Q(^{A-1}\text{Sn})$.
[c]This work.
[d]Reference 16.
[e]Reference 17.

To derive absolute values for the quadrupole moments one must rely on the determination of the moment of the ^{121}Sb ground state. The ^{121}Sb moment is obtained from the optical hyperfine structure data by calculating the EFG of the electronic configuration of the Sb atom. In the most recent analysis by Buchholz *et al.*[18] a value of $Q(^{121}\mathrm{Sb}, \frac{5}{2}^+) = -36(4)$ fm^2 is obtained. With this result we obtain the absolute values given in column 5 of Table II.

The magnetic moments of all the listed isomers are well described by the odd proton in the $d_{5/2}$ shell coupled to the respective excited Sn core, and their dominant configurations are given in column 3. We will, therefore, use simple additivity in trying to interpret the obtained quadrupole moments.

From atomic beam experiments the quadrupole moments of several $\frac{5}{2}^+$ ground states of the light odd-A Sb nuclei are known relative to ^{121}Sb, and they show little or no variation with A.[2] Therefore, the ^{121}Sb moment can be taken to estimate the $d_{5/2}$ proton part of the moment. For the neutron part we can take the quadrupole moments of the respective Sn cores which are known for the $\frac{11}{2}^-$ isomer in ^{113}Sn, the 7^- state in ^{114}Sn, and the 10^+ state in ^{116}Sn.[4,5] Here we take the average of the values given in Refs. 4 and 5, which differ only slightly due to different choices of the calibration. For ^{111}Sn, which is the core for ^{112}Sb, we use the moment of ^{113}Sn, since the investigation of Dimmling *et al.*[4] indicates very little variation of Q for the light isotopes. Using the additivity relation

$$Q(^A\mathrm{Sb}, I) = Q(^{121}\mathrm{Sb}, \pi d_{5/2}) + Q(^{A-1}\mathrm{Sn}, I - \tfrac{5}{2})$$

we then obtain the moments as listed in column 6 of Table II. All moments have been assumed negative because of the particlelike character of the states.

The overall agreement with the experimental values in column 5 shows the validity of the concept. However, there seems to be a tendency for the experimental values based on the ^{121}Sb moment to be consistently lower for the high spin isomers, especially for the most accurate cases of the 8^- isomer in ^{112}Sb and the $\frac{25}{2}^+$ isomer in ^{117}Sb. Taking additivity as strictly valid, a better agreement is obtained when the proton part is increased by about 30% as compared to the value given by Buchholz *et al.*[18] for ^{121}Sb. The data, however, are not conclusive enough at present to justify a readjustment of the proton part.

The effective charges of the $d_{5/2}$ proton in ^{121}Sb derived from the static quadrupole moments is $e_{\mathrm{eff}} \cong 2.5-3e$, depending on the values taken for the single particle moment. The enhanced charge implies a polarization charge for the proton of about $1.5-2e$ which is close to the polarization charge Dimmling *et al.*[4] derived for the $h_{11/2}$ neutrons in the Sn cores. According to Bohr and Mottelson[19] the polarization charge near $Z=50$ results from particle-vibration coupling. Within this picture the slight deviations from additivity observed in the quadrupole moments in Table II could be ascribed to small changes in the polarization charge for the coupled systems.

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