Static quadrupole moments of $^{106}Ag^m$ and $^{109}Ag^m$ and the electric field gradient of Ag in Zn and Cd

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Low temperature nuclear orientation of $^{106}Ag^m$ and $^{110}Ag^m$ in Zn and Fe and level mixing resonances on $^{109}Ag^m$ have been measured in order to deduce Q and V_{zz} values. A fourth-order resonance in $^{109}Ag^mZn$ has been found with a full width at half maximum of 1.9×10^{-9} eV, and $V_{zz}(AgCd)/V_{zz}(AgZn)=1.0064(34)$ was deduced. The electric quadrupole moments found in the literature, reevaluated for Sternheimer correction $Q(^{108}Ag^m)=+1.32(7)$ b and $Q(^{110}Ag^m)=+1.44(10)$ b, are used for the calibration of V_{zz} and yield $Q(^{106}Ag^m)=+1.11(11)$ b, $Q(^{109}Ag^m)=(+)0.97(11)$ b, and $V_{zz}(AgZn)=+4.2(5)\times10^{17}$ V/cm^2. Furthermore, $\mu(^{106}Ag^m)=(+)3.82(8)\,\mu_N$ and several $\delta(E2/M1)$ mixing ratios in ^{106}Pd are also determined. The quadrupole moments are in good agreement with Yukawa-plus-exponential macroscopic model and folded-Yukawa microscopic model calculations. The particle states can be described in terms of deformed Nilsson orbitals or three valence-proton holes coupled to a quadrupole vibrator.

I. INTRODUCTION

Silver isotopes are in a region of unstable equilibrium deformation, so the knowledge of their quadrupole moments is of particular interest. Nevertheless, only a few of their quadrupole moments are known; that is, those for $^{108}Ag^m$ and $^{110}Ag^m$, deduced from optical hyperfine spectra.[1] Level mixing resonance experiments on oriented nuclei (LMR-ON) were performed on $^{109}Ag^m$ in a Zn single crystal, which yielded $\nu_Q=eQV_{zz}/h=99.6(30)$ MHz (Put *et al.*[2]) Unfortunately, the only known electric field gradient of silver in zinc[3] would yield $Q(^{109}Ag^m)=2.4$ b, which seems to be too large for this nuclear region. Therefore, a thorough redetermination of this electric field gradient had to be undertaken. In this paper we present the determination of the electric field gradient for silver in zinc and also in cadmium, and of the quadrupole moment of $^{106}Ag^m$. Further developments of the LMR-ON method are also presented.

II. LEVEL MIXING RESONANCE ON $^{109}Ag^m$ IN Zn AND Cd

In our previous paper on LMR-ON, we have shown that higher order mixings produce narrow resonances.[2] For a third-order resonance we found a full width at half maximum FWHM$=4.5\times10^{-9}$ eV, which, defining the resolution R as the half width relative to the resonant field value, gave 0.023(4), but no attempt has been made to measure the fourth-order resonance. This has been done in Leuven on $^{109}Ag^m$ in Zn and Cd with a very homogeneous magnetic field produced by a solenoid, and by using field steps of 0.2 mT between two measured points. The experimental setup was similar to the one of Ref. 2. As the single crystal c axis direction cannot be established better than to about 2 deg from Laue-backscattering measurements, the tilting angle between the magnetic field direction and the c axis has been deduced from the FWHM of the third-order resonance as 7.9(5) deg for Zn and 10.5(5) deg for Cd single crystals. For the fourth-order resonance, the experiment yields FWHM$=1.5\times10^{-9}$ eV for Zn (Fig. 1) and 2.4×10^{-9} eV for Cd, representing resolutions of R(Zn)$=0.01$ and R(Cd)$=0.016$, respectively. The line widths, calculated from the level mixing theory,[2] are enhanced by the thermal relaxation;[4] taking into account the relaxation, the calculated line width fits the experimental one rather well. The ratio of the quadrupole frequencies is $\nu_Q(^{109}Ag^m Cd)/\nu_Q(^{109}Ag^m Zn)=1.0064(34)$, leading to $\nu_Q(^{109}Ag^m Cd)=100.2(30)$ MHz. The sign of this interaction frequency is contained only in the dispersion term of the resonance, which is not observable in the direction of the alignment axis.[5]

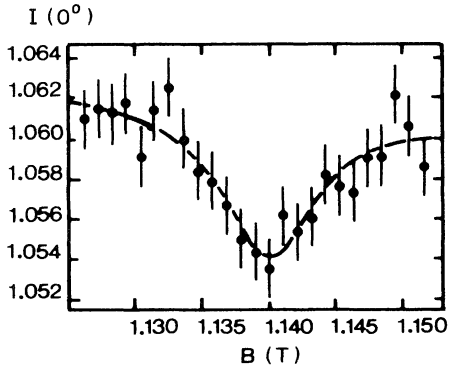

FIG. 1. Fourth-order level mixing resonance of $^{109}Ag^m$ in Zn.

III. QUADRUPOLE ALIGNMENT OF $^{106}Ag^m$ AND $^{110}Ag^m$ IN Zn

As we have mentioned in the Introduction, V_{zz} (AgZn), as established by van Walle *et al.*,[3] is too low, due probably to a bad substitutional fraction of the implants in the Zn single crystal. In order to have silver nuclei in good substitutional sites, the following source-preparation procedure has been applied in the present work:

(i) Radioactive $^{106}Ag^m$ and $^{110}Ag^m$ were produced through the Pd(d,xn) reactions;

(ii) before the isotopic implantation, silver was separated from palladium by thermal evaporation;

(iii) the Zn single crystal homogeneity and the c axis were checked by Laue-backscattering and α-particle channeling;

(iv) $^{106}Ag^m$ and $^{110}Ag^m$ were implanted with the isotopic separator of Lyon at 100 keV implantation energy with a very low total implantation dose (1.8×10^{13} atoms/cm^2) into the same single crystal;

(v) after implantation, the sample was annealed at 220 °C for 40 min.

The quadrupole alignment has been performed at temperatures down to 4.5 mK with the dilution refrigerator of Lyon. A 0.6 T magnetic field, applied in the c-axis direction, polarized the ^{60}Co*Fe* nuclear thermometer and broke the superconductivity of the Zn single crystal, which could cause heat contact loss. The $U_\lambda A_\lambda$ distribution coefficients of the angular distribution of the $^{110}Ag^m$ decay have been taken from the orientation of $^{110}Ag^m$ in iron; for $^{106}Ag^m$, we determined them (see Sec. IV) from a similar measurement.

The quadrupole interaction frequencies for $^{110}Ag^m$ in Zn, obtained from computer fits on the anisotropies of five gamma transitions, taking into account the precision of the thermometry and the small magnetic orientation as well, are given in Table I. Their weighted mean value is $\nu_Q(^{110}Ag^m Zn)=+146(14)$ MHz. This value is considerably higher than that of van Walle *et al.*[3] [67.1(19) MHz]. The low substitutional fraction in their measurement may be due to a higher implantation dose (5×10^{13} atoms/cm^2) and/or to the lack of annealing after implantation. We have no direct evidence that our implantation led to 100% substitutional sites, as the channeling experiment is not sensitive to such a low implantation dose. The consistency of the deduced quadrupole moments suggests, however, that the fraction of eventual bad hyperfine sites does not exceed ten percent.

TABLE I. Quadrupole interaction frequencies deduced from the gamma rays of oriented $^{110}Ag^m$ in Zn.

W_γ (keV)	$\nu_Q=eQV_{zz}/h$ (MHz)
658	145(22)
764	157(60)
884	145(30)
937	163(52)
1384	143(26)
Mean value	147(14)

The quadrupole frequency of $^{106}Ag^m Zn$ is derived directly from the comparison of the low-temperature anisotropies of the $^{110}Ag^m$ and $^{106}Ag^m$ decays. This method gives a better statistical accuracy for $Q(^{106}Ag^m)$, as it does not involve the error on the thermometry. Moreover, as $^{106}Ag^m$ and $^{110}Ag^m$ were implanted into the same single crystal under identical conditions and measured simultaneously, the ratios of the quadrupole interaction frequencies and of the quadrupole moments do not depend on the substitutional fraction. From the anisotropies of the 451, 512, 717, 1045, 1199, and 1527 keV gamma rays of the $^{106}Ag^m$ decay, we obtain

$$\nu_Q(^{106}Ag^m Zn)/\nu_Q(^{110}Ag^m Zn) = Q(^{106}Ag^m)/Q(^{110}Ag^m)=0.77(6)\ ,$$

and thus, with the previously established $\nu_Q(^{110}Ag^m Zn)$, we find

$$\nu_Q(^{106}Ag^m Zn)=+113(9)\ \text{MHz}\ .$$

The quadrupole moments of $^{110}Ag^m$ and $^{108}Ag^m$, uncorrected for the Sternheimer factor, are given by Fischer *et al.* as $+1.65(10)$ and $+1.52(8)$ b, respectively.[1] From a comparison of calculated free atom Sternheimer factors of Cs, Rb, and Cu, they suggest that the Sternheimer factor R defined as $Q=Q(\text{uncorrected})/(1-R)$ could be $R\approx-0.25$. A precise calculation of R, taking into account one and many electron shielding and antishielding mechanisms and Hartree-Fock values for $\langle r^{-3}\rangle$, is in progress by Das *et al.* A rather good estimation can be obtained meanwhile by estimating a correction to the Sternheimer factor of Fischer *et al.*,[1] namely the many-body effects which involve simultaneous excitations of valence and core electrons.[7] This effect, estimated from Figs. 2 and 3 of Ref. 7, gives a contribution of $\approx+0.1$ to the Sternheimer factor. The other correcting term to the usual Sternheimer factor discussed in the paper of Rodgers, Roy, and Das,[7] the perturbation by exchange interaction between $4p$ and $5p$ shells, is already included in the "uncorrected" quadrupole moment of Fischer *et al.*, as they used $\langle r^{-3}\rangle$ taken directly from magnetic hyperfine splitting instead of the Hartree-Fock value. So the Sternheimer factor becomes $R=-0.15$; the precision of this estimation can be about 20%, i.e., ±0.03, which will be considered in the quoted error. This Sternheimer factor is thus very close to the one of the very similar copper ($R=-0.175$), which is known to fit the experimental data.[8,9] Using the preceding Sternheimer factors, the spectroscopic quadrupole moments become $Q(^{110}Ag^m)=+1.44(10)$ b and $Q(^{108}Ag^m)=+1.32(7)$ b. Our quadrupole alignment measurement yields $Q(^{106}Ag^m)=+1.11(11)$ b, $V_{zz}(AgZn)=+4.2\times10^{17}$ V/cm^2, and from the LMR-ON measurement of Ref. 2, $Q(^{109}Ag^m)=0.97(11)$ b. The systematics in the isotopic chain $A=106$–109 suggests that $Q(^{109}Ag^m)$ is positive.

IV. MAGNETIC ALIGNMENT OF $^{109}Ag^m$ IN IRON

Low temperature nuclear orientation of $^{106}Ag^m$ in iron has been performed by Schoeters *et al.*[10] and Haroutunian

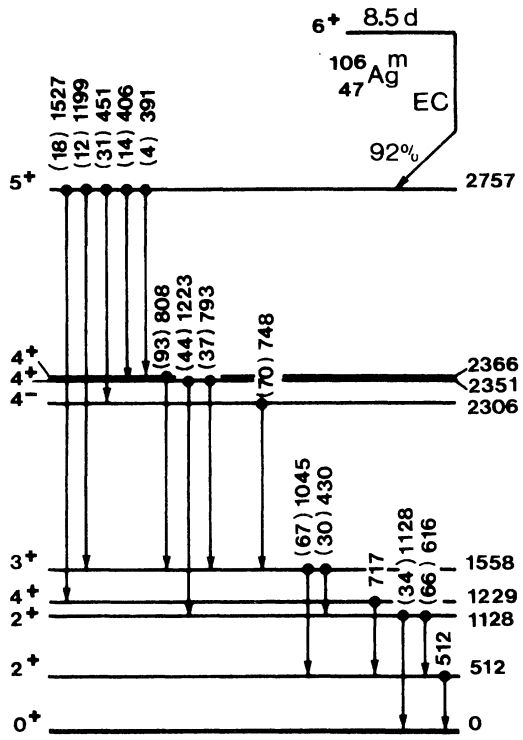

FIG. 2. Simplified decay scheme of $^{106}Ag^{m}$.

et al.,[11] but they do not give $U_\lambda A_\lambda$ coefficients, which are necessary to evaluate the quadrupole alignment of $^{106}Ag^{m}$ in zinc.

$^{106}Ag^{m}$, produced as described previously, has been evaporated onto an iron foil, melted together in an induction oven, and fused to form a 1.5 mm diam $\times 6$ mm long cylinder. The sample was cooled down in the dilution refrigerator of Lyon in a polarizing field of 2 T. The orientation pattern was measured at 0° and 90°, with respect to the magnetic field.

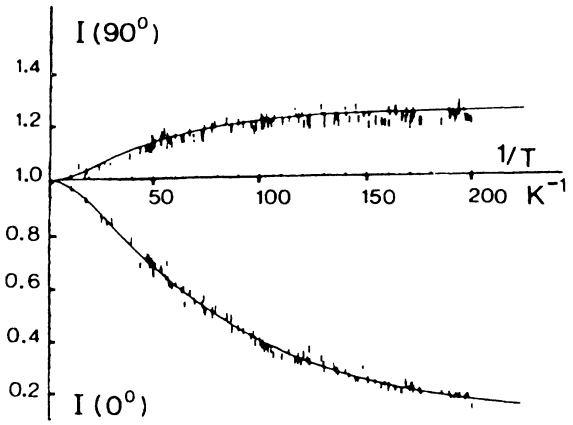

FIG. 3. The orientation patterns of the 1199 keV gamma ray of $^{106}Ag^{m}$ in an iron matrix.

The simplified decay scheme of $^{106}Ag^{m}$ is presented in Fig. 2. The orientation pattern of the pure $E2$ 1199 keV gamma rays (see Fig. 3) was fitted with two free parameters: $\mu(^{106}Ag^{m})$ and the substitutional fraction α. The latter has been established as $\alpha=0.99(1)$. The results of the angular distribution measurements are presented in Table II, which is discussed in the following.

2351 keV state. U_λ deorientation parameters are deduced from the angular distribution of the pure $E2$ 1223 keV transition and from the feeding of the state.

2306 keV state. The angular distribution of the 748 keV gamma rays is not in contradiction with a pure $E1$ character.

1558 keV state. The angular distributions of the 430 and 1045 keV gamma rays are analyzed to deduce $\delta(430)$, $\delta(1045)$, and $U_\lambda(1558)$ simultaneously. The U_λ was checked using the decay scheme presented in Fig. 2 and previous δ ($E2/M1$) values.

1128 and 512 keV states. U_λ is evaluated from the pure $E2$ 1128 keV and 512 keV $2^+ \rightarrow 0^+$ transitions. It can be remarked that all $E2/M1$ mixtures exhibit a near-

TABLE II. Distribution coefficients $A_\lambda U_\lambda$ and multipole mixing ratios for gamma rays of the decay of $^{106}Ag^{m}$.

Level (keV)	I^π	Gamma (keV)	A_2U_2	A_4U_4	U_2 deduced	U_4 deduced	$\delta(E2/M1)$ or multipolarity
2757	5^+	406	+0.485(6)	+0.437(15)			−3.6(2)
		451	+0.288(4)	+0.015(10)			$E1$
		1527	+0.658(4)	+0.413(43)			−2.5(4)
2351	4^+	793	+0.157(12)	+0.076(25)			−7(2)
		1223	−0.303(12)	−0.061(25)	0.700(26)	0.19(8)	$E2$
2306	4^-	748	+0.249(6)	−0.016(10)			$E1$
1558	3^+	430	+0.082(6)	+0.021(12)			−8.6(3)
					0.81(2)	0.43(4)	
		1045	+0.266(4)	+0.223(10)			−4.2(2)
1229	4^+	717	−0.274(4)	−0.068(10)	0.61(1)	0.22(3)	$E2$
1128	2^+	616	+0.096(4)	+0.013(10)			−7.2(13)
		1128	−0.203(10)	−0.044(22)	0.34(2)	0.04(2)	$E2$
512	2^+	512	−0.150(4)	−0.030(5)	0.259(7)	−0.028(5)	$E2$

ly pure $E2$ transition mode.

Fitting on the angular distributions of the 406, 451, 512, 748, 1045, 1199, and 1527 gamma rays and using for the hyperfine field $B_{hf}(AgFe)=44.72$ T, we find $|\mu(^{106}Ag^m)|=3.82(8)\ \mu_N$, which is in good agreement with that of Ref. 11, 3.71(15) μ_N.

V. DISCUSSION

The $^{106-110}$Ag nuclei have incompletely filled proton and neutron shells. The particle contribution to the total intrinsic quadrupole moment can be $Q_{0,p}\approx 0.05$—0.1 b. This contribution is negligible as compared to the core contribution, which is of the order of 2 b; therefore, the measured quadrupole moment is attributed to the core. Supposing that for these long-lived metastable states $I=K$, we can deduce the intrinsic quadrupole moments Q_0 with the well-known projection $Q_0=Q(I+1)(2I+3)/I(2I-1)$. These Q_0 values are presented in Table III, compared to the theoretical moments of Möller and Nix, and calculated with a Yukawa-plus-exponential macroscopic model and folded-Yukawa microscopic model.[12] The agreement between the experimental and theoretical values is excellent, and shows that the deformation increases slightly with increasing neutron number.

The calculations of Möller and Nix show that the hexadecapolar deformation is negligible in these nuclei. Using the Bohr-Mottelson expression for an axially symmetrical quadrupole deformation, and taking $r_0=1.16$ fm, the deformation parameter is $\beta=+0.16$ for $A=106$ and $+0.19$ for $A=110$. In the neutron configurations, the $\frac{5}{2}[413]$ Nilsson level crosses in this deformation region the $\frac{1}{2}[550]$, $\frac{1}{2}[420]$, and $\frac{5}{2}[532]$ orbitals in such a way that the level filling always yields a $\frac{5}{2}[413]$ neutron configuration. This filling is confirmed by the $I^\pi=\frac{5}{2}^+$ assignment for the surrounding odd Pd and Cd nuclei. For the above-mentioned deformations, the proton configuration can be $\frac{7}{2}[413]$ or $\frac{1}{2}[431]$, in agreement with experimental $\frac{7}{2}^+$ and $\frac{1}{2}^-$ levels. The proton-shell magnetic moment is almost constant: $\mu=4.27\ \mu_N$ for ^{103}Ag ($\frac{7}{2}^+$) and 4.47 μ_N for $^{109}Ag^m$ ($\frac{7}{2}^+$), yielding $g_p\simeq 1.249$ for $^{106-110}$Ag. The neutron shell magnetic moment varies for the $\frac{5}{2}$ states: for $N=59$ neutrons we can deduce from ^{105}Pd and ^{105}Cd, $g_n=-0.251$; for $N=61$ from ^{109}Cd, $g_n=-0.331$; and for $N=63$ from ^{111}Cd, $g_n=-0.314$. The addition of odd proton and neutron moments yields thus $\mu(^{106}Ag^m)=+3.74\ \mu_N$, $\mu(^{108}Ag^m)=+3.54\ \mu_N$, and $\mu(^{110}Ag^m)=+3.55\ \mu_N$. These values agree well with the experimental 3.82(8) μ_N, 3.58(2) μ_N, and 3.607(4) μ_N magnetic moments, respectively, when the experimental values are taken with positive signs, and suggest that the slight variations in the magnetic moments could be due to the neutron shell. It must be remarked, however, that for the proton configuration an alternative interpretation based on the Alaga model, coupling three valence holes to a quadrupole vibrator,[13] yields $Q(\frac{7}{2})=+(0.82-0.94)$ b, depending on the effective charge chosen, and $\mu(\frac{7}{2})=+(4.50-4.43)\ \mu_N$, both in agreement with the experimental data. The addition of the $(g_{9/2})^{-3}$ $I=j-1$ coupled odd-proton moment to the neutron moment yields the same result for odd-odd nuclei, as previously discussed.[11]

TABLE III. Experimental and theoretical quadrupole moments in silver. The theoretical values are those from Möller and Nix (Ref. 12).

Isotope	I^π	$Q_{(expt)}$ (b)	Q_0 (expt) (b)	Q_0 (th) (b)
106m	6^+	+1.11(11)	+1.76(17)	+1.8
108m	6^+	+1.32(7)	+2.10(11)	+1.9
109m	$\frac{7}{2}^+$	(+)0.97(11)	(+)2.08(24)	+1.9
110m	6^+	+1.44(10)	+2.29(16)	+2.1

The same method, as described in Ref. 3, can be used to derive the electronic enhancement factor of the field gradient $K=-V_{zz}$ (el)/V_{zz} (ion) for AgZn and AgCd, which is usually given at room temperature. For V_{zz}^{ion} (AgZn), the value of Ref. 3 with the γ_∞ antishielding factor of Schmidt *et al.* is used:[14] -6.4×10^{17} V/cm^2; for V_{zz}^{ion}(AgCd), a similar calculation gives -5.2×10^{17} V/cm^2. Our effective field gradients, corrected for room temperature, are $+4.0(5)\times10^{17}$ V/cm^2 in Zn and $+3.8(5)\times10^{17}$ V/cm^2 in Cd, giving $K(AgZn)\approx 1.6$ and $K(AgCd)\approx 1.7$, which are somewhat higher than those established by van Walle *et al.*[3]

Note added in proof. A recent more precise magnetic moment value for $^{109}Ag^m$, $|\mu|=4.402(8)\ \mu_N$ (R. Eder, E. Hagn, and E. Zech, Proceedings of the International Symposium on Nuclear Orientation and Nuclei far from Stability, Leuven, 1984, to be publishing in Hyperfine Interactions), allows one to deduce $\nu_Q(^{109}Ag^m Zn)=103.3(7)$ MHz and $Q(^{109}Ag^m)=(+)1.02(11)$ b.

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