Communications

The Communications section is for brief reports on completed research. A Communication may be no longer than the equivalent of 2800 words, i.e., the length to which a **Physical Review Letter** *is limited. (See the editorial in the 21 December 1970 issue of* **Physical Review Letters.**) *Manuscripts intended for this section must be accompanied by a brief abstract for information retrieval purposes and, if they report on properties of particular nuclides, a keyword abstract.*

Nuclear orientation of $^{106}Ag^m$

E. Schoeters, R. Geerts, R. E. Silverans,* and L. Vanneste†
Instituut voor Kern- en Stralingsfysika, Leuven University, 3030 Heverlee, Belgium
(Received 8 July 1975)

Nuclei of $^{106}Ag^m$ embedded in an iron matrix have been oriented at low temperatures. The decay to ^{106}Pd allowed determination of the spin values for the levels at 2366 keV ($J = 4$), 2351 keV ($J = 4$), 2283 keV ($J = 4$), 2077 keV ($J = 4$), and 1932 keV ($J = 4$). The $E2$ fractions $Q = \delta^2/(1+\delta^2)$ could be deduced for 12 mixed $M1$-$E2$ transitions (energies in keV): $Q(222) = 0.017 \pm 0.005$, $\delta < 0$; $Q(391) = 0.996^{+0.004}_{-0.006}$, $\delta < 0$; $Q(406) = 0.91 \pm 0.01$, $\delta < 0$; $Q(430) = 0.982 \pm 0.003$, $\delta < 0$; $Q(474) = 0.01 \pm 0.01$ or $Q(474) = 0.94 \pm 0.02$, $\delta < 0$; $Q(601) = 0.03 \pm 0.03$ or $Q(601) = 0.90^{+0.03}_{-0.06}$, $\delta < 0$; $Q(616) = 0.990 \pm 0.005$, $\delta < 0$; $Q(703) = 0.54 \pm 0.14$, $\delta < 0$ or $Q(703) = 1.00 - 0.04$, $\delta > 0$ or $\delta < 0$; $Q(793) = 0.00 + 0.01$, $\delta > 0$ or $Q(793) = 0.980^{+0.005}_{-0.020}$, $\delta < 0$; $Q(825) = 0.002 \pm 0.002$ or $Q(825) = 0.97 \pm 0.01$, $\delta < 0$; $Q(1046) = 0.005 \pm 0.003$, $\delta < 0$; $Q(1528) = 0.07 \pm 0.01$ or $Q(1528) = 0.84 \pm 0.02$, $\delta < 0$. In addition, the magnetic moment of 6^+ isomeric state of ^{106}Ag was determined to be $|\mu| = (2.8 \pm 0.2)\mu_N$.

[RADIOACTIVITY $^{106}Ag^m$; measured $I_\gamma(\theta)$ polarized nuclei, deduced μH. ^{106}Pd deduced J, π, δ. ^3He-^4He refrigerator, Ge(Li) detectors.]

The structure of the ^{106}Pd levels populated in the decay of $^{106}Ag^m$ has been studied extensively in recent years.[1,2] Most spins and energies of the excited levels have been determined; ambiguities remained, however, for five spin values, and only a few mixing ratios of lower-energy γ rays could be derived from the conversion data.[1,3-5] In the vibrational ^{106}Pd nucleus this information is very important for the interpretation of the level structure. We have performed a nuclear orientation experiment on $^{106}Ag^m$ in iron to determine the unknown spin values and the mixing ratios of 12 $M1$-$E2$ transitions. A second purpose of our investigation was to measure the hyperfine interaction of the 6^+ isomeric state of ^{106}Ag in iron.

The $^{106}Ag^m$ (8.3 day) activity was produced by bombarding natural Pd power with 20 MeV deuterons for 9 μA h. The only important contamination was ^{105}Ag (40 day). A $^{106}Ag^m$(Fe) nuclear orientation sample was prepared by vacuum melting 1 mg Pd and 100 mg of high purity iron and rolling it to a thickness of 0.1 mm. To produce a substitutional alloy, the sample was quenched from 1200°C in about 30 seconds.[6] As a test a second identical sample was vacuum annealed at 1200°C for 8 h and cooled over a long period.

In two separate experiments, the two samples were soldered to the cold finger of a ^3He-^4He refrigerator, which has been described previously.[7] Spectra were taken with two 30 cm^3 Ge(Li) detectors and recorded with a PDP 11/20 computer-based multichannel analyser system. The detectors were positioned at 0° and 90° with respect to the orientation axis, established by a polarizing field of 3 kOe of a superconducting coil.

The decay scheme of $^{106}Ag^m$ is given in Fig. 1. To determine the hyperfine interaction μB of $^{106}Ag^m$ in iron, the anisotropies of the $E1$ radiation of 451 keV and the $E2$ radiation of 1199 keV were used. They were fitted to the usual expression[8]:

$$W(\theta) = 1 + \sum_k Q_k U_k F_k B_k P_k(\cos\theta) \quad \text{with} \quad k = 2, 4 . \tag{1}$$

$W(\theta)$ denotes the normalized probability of emission in the direction defined by the angle θ with respect to the quantization axis. The Q_k factors take into account the finite solid angle of the detectors. The U_k and F_k factors characterize the angular distribution of the radiation and have been tabulated by Yamazaki.[9] For a mixed transition

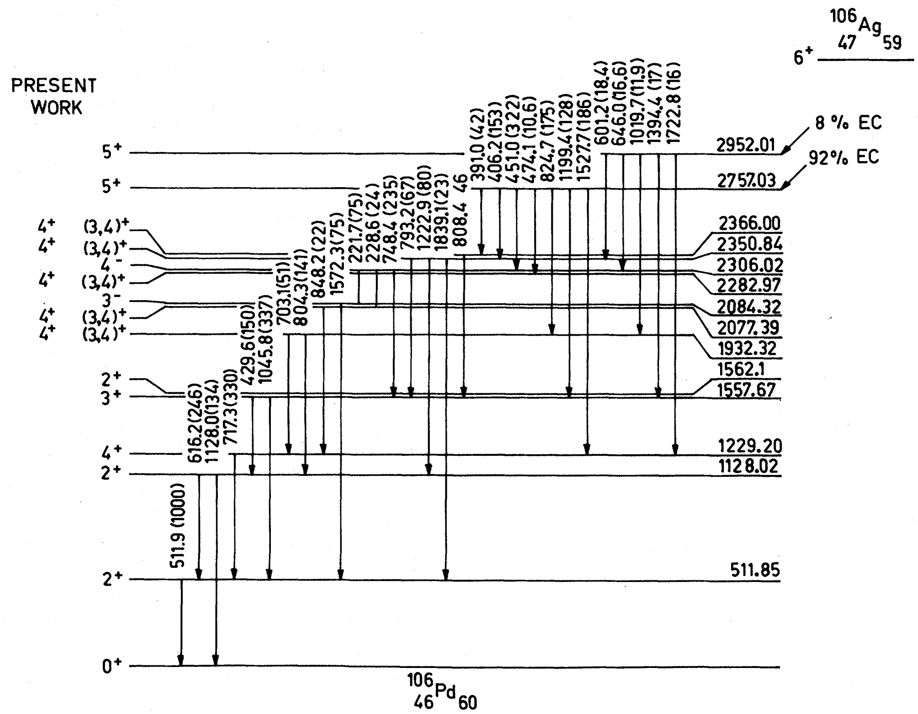

FIG. 1. Decay scheme of $^{106}Ag^m$ as given in Ref. 1, including our spin assignments.

F_k must be replaced by $[F_k(LL)+2\delta F_k(LL')+\delta^2 F_k(L'L')]/(1+\delta^2)$. The B_k functions contain the temperature dependence of the radiation pattern and depend on the magnetic hyperfine splitting of the parent nuclei. The P_k functions are the well-known Legendre polynomials of order k. In the least-squares fitting the ratio $\epsilon = W(0°)/W(90°)$ was used to correct for the 8.3 day half life. An example of the temperature dependence of the emitted radiation is given in Fig. 2. The mean value derived for the hyperfine interaction of the quenched sample was $|\mu B| = (1235 \pm 80)\ \mu_N$ kG. With a field value of $B = -447.2(2)$ kG,[10] it yields $|\mu| = (2.8 \pm 0.2)\mu_N$ for the magnetic moment of the $J^\pi = 6^+$ isomeric state. The annealed sample yielded a $|\mu B|$ value which was 25% smaller, confirming the preparation technique of Johnston and Stone.[6] If one takes the shell model structure

$$\pi[(g_{9/2})^7]_{9/2}\nu[(1g_{7/2})^4(2d_{5/2})^5]_{5/2}$$

and empirical g factors from neighboring nuclei,[11,12] one calculates a theoretical value of $4.5\mu_N$. However, there is some evidence that the 6^+ isomeric state might be a three quasiparticle state in the proton side.[13] If one accounts for this in the calculation of the g factor according to the jj-coupling model,[14] one obtains a value of $3.6\mu_N$. None of these values agrees with the experimental result, although the three quasiparticle description is clearly favored. Even for the latter configuration the discrepancy is large and calls for more detailed calculations. The field value used in deriving μ may also be questioned although the preparation of the sample was analogous to a well-measured case.[6] A nuclear mag-

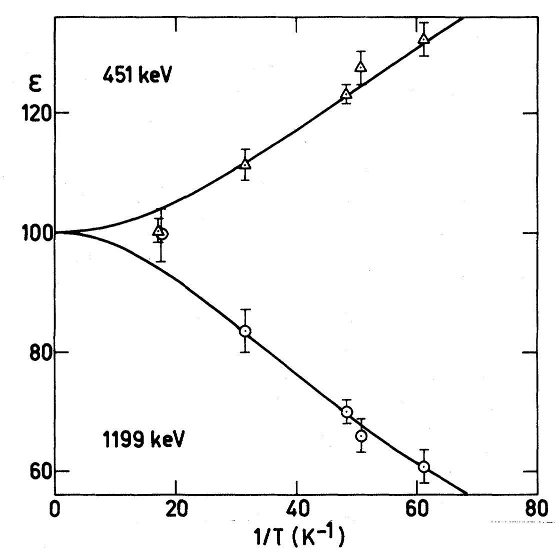

FIG. 2. Temperature dependence of the anisotropies of the 451 and 1199 keV transitions.

TABLE I. The $E2$ fractions $Q=\delta^2/(1+\delta^2)$ of mixed $M1$-$E2$ transitions. The sign after the Q value is the sign of δ.

Transition energy (keV)	Present work		Previous work
222	0.017 ± 0.005 [a]	$-$ [b]	$0.10^{+0.12}_{-0.10}$ [c]
391	$0.996^{+0.004}_{-0.006}$ [a]	$-$	$1.0^{+0.0}_{-0.4}$ [c]
406	0.91 ± 0.01 [a]	$-$	$0.9^{+0.1}_{-0.4}$ [c]
430	0.982 ± 0.003 [a]	$-$	$1.0^{+0.0}_{-0.2}$ [c]
474	0.01 ± 0.01	$-$	
	or		
	0.94 ± 0.02	$-$	
601	0.03 ± 0.03	$-$	
	or		
	$0.90^{+0.03}_{-0.06}$	$-$	
616	0.990 ± 0.005 [a]	$-$	≥ 0.985 [d]
703	0.54 ± 0.14	$-$	
	or		
	$1.00\ -0.04$	$\pm$	
793	$0.00\ +0.01$	$+$	
	or		
	$0.980^{+0.005}_{-0.020}$	$-$	
825	0.002 ± 0.002	$-$	
	or		
	0.97 ± 0.01	$-$	
1046	0.005 ± 0.003 [a]	$-$	≥ 0.035 [d]
1528	0.07 ± 0.01	$-$	
	or		
	0.84 ± 0.02	$-$	

[a] The alternate root is disallowed by conversion-coefficient measurements (Refs. 1 and 2).
[b] Sign convention of Ref. 15.
[c] From Ref. 1.
[d] From Ref. 2.

netic resonance (with oriented nuclei) experiment would be a solution to this problem but is hampered by the small activities we have yet managed to obtain. An eventual error in the field cannot, however, alter the conclusions about the decay scheme which follow. The uncertain spin values of the levels at 2366, 2351, 2283, 2077, and 1932 keV have been fixed unambiguously by analyzing the anisotropies of the γ rays reaching or deexciting these levels. The only possible values were restricted to $J=3$ or $J=4$, all with positive parities.[1]

2366 keV level. A value $J^\pi=3^+$ for this level would establish the 391 keV transition as $E2$ and hence involve a negative anisotropy $[F_2(I_f, L_1, L_2, I_i)=F_2(3,2,2,5)=-0.42]$. The other possibility $J^\pi=4^+$ would involve $M1$-$E2$ character and allows both positive and negative anisotropies, depending on the mixing ratio. The observed positive anisotropy at 24 mK, $\epsilon(391\text{ keV})=W(0°)/W(90°)=1.07\pm 0.04$, points uniquely to a $J^\pi=4^+$ assignment.

2351 keV level. Again, a spin value of 3^+ would require the 406 and 601 keV γ rays to be $E2$ and have large negative anisotropies in contradiction with the measured anisotropies $\epsilon(406\text{ keV})=1.34\pm 0.02$ and $\epsilon(601\text{ keV})=1.31\pm 0.10$ at 24 mK. As a check we note that the 4^+ spin-parity involves an $E2$ character for the 1223 and 1839 keV transitions deexciting this level in agreement with their large negative ϵ values.

2283 keV level. If this level would have $J=3$, the weak 474 keV transition should have $E2$ character. Our experimental result $\epsilon(474\text{ keV})=1.27\pm 0.03$ at 24 mK clearly excludes this possibility.

2077 keV level. The 229 keV transition reaching this level starts from a 4^- level. A transition $4^-\to 3^+$ has $F_2(11)=0.31$ and a transition $4^-\to 4^+$ has $F_2(11)=-0.44$. At 24 mK we measured an anisotropy $\epsilon(229\text{ keV})=0.75\pm 0.02$. As the 229 keV transition is known to have $E1$ character[1] this value is only compatible with a 4^+ spin-parity assignment.

1932 keV level. A 3^+ spin-parity would require the 825 keV radiation to be $E2$. As we measured $\epsilon(825\text{ keV})=1.20\pm 0.02$ at 24 mK, the tentatively assigned 4^+ value[1] is confirmed.

The $E2$ fraction $Q=\delta^2/(1+\delta^2)$ and the sign of δ of 12 mixed $M1$-$E2$ transitions have been determined. The results are summarized in Table I. For comparison, results of other measurements are also included.

The spins and parities of particularly the lower-lying excited levels in ^{106}Pd are typical of quadrupole vibration in a spherical nucleus and have therefore been well studied. Extension of these studies to the higher-energy states was made difficult by the lack of information on spins and multipolarities. Theoretical calculation of the vibrational character of these states and especially of their possible anharmonicity may become more attractive now.

The appearance of three quasiparticle states too has been found in different models[16,17]; calculation of their moments has been restricted mostly to comparing the g factors of the single quasiparticle and the three quasiparticle state. Only in few cases[13] more detailed calculations have been published. According to our results they may turn out to be interesting for $^{106}Ag^m$.

The authors wish to thank the Belgian Universitair Instituut voor Kernwetenschappen for financial support. They are indebted to the cyclotron staff of the Université Catholique de Louvain for the irradiation facilities. The calculations have been executed on the IBM 370/158 computer of the Universitair Rekencentrum of the Katholieke Universiteit Leuven.

*Aangesteld navorser Nationaal Funds voor Wetenschappelÿ b Onderzoek.

†Bevoegdverklaard navorser Nationaal Funds voor Wetenschappelÿ b Onderzoek.

[1]H. Inoue, J. Phys. Soc. Jpn. 35, 957 (1973), and references quoted therein.

[2]P. Weigt, P. Herzog, B. Richter, H. Hübel, H. Toschinski, and J. Fechner, Nucl. Phys. A A122, 577 (1968), and references quoted therein.

[3]W. Scheuer, T. Suter, P. Reyes-Suter, and E. Aasa, Nucl. Phys. 54, 221 (1964).

[4]W. G. Smith, Phys. Rev. 122, 1600 (1961); *ibid.* 131, 351 (1963).

[5]D. E. Alburger and B. J. Toppel, Phys. Rev. 100, 1357 (1955).

[6]P. D. Johnston and N. J. Stone, Nucl. Phys. A A206, 273 (1973).

[7]R. E. Silverans, R. Coussement, G. Dumont, H. Pattyn, and L. Vanneste, Nucl. Phys. A A193, 367 (1972).

[8]R. J. Blin-Stoyle and M. A. Grace, Handb. Phys. 42, 555 (1957).

[9]T. Yamazaki, Nucl. Data A A3, 1 (1967).

[10]R. A. Fox, P. D. Johnston, and N. J. Stone, Phys. Lett. A 34A, 211 (1971).

[11]G. Kaindl, F. Bacon, H.-E. Mahnke, and D. A. Shirley, Phys. Rev. 8, 1074 (1973).

[12]A. C. Gossard and V. Jaccarino, Bull. Am. Phys. Soc. 7, 556 (1962).

[13]A. Kuriyama, T. Marumori, and K. Matsuyanagi, J. Phys. Soc. Jpn. Suppl. 34, 407 (1973).

[14]J. P. Elliott and A. M. Lane, Handb. Phys. 39, 241 (1957).

[15]L. C. Biedenharn and M. E. Rose, Rev. Mod. Phys. 25, 729 (1953).

[16]L. S. Kisslinger, Nucl. Phys. 78, 341 (1966).

[17]A. Kuriyama, T. Marumori, and K. Matsuyanagi, Prog. Theor. Phys. 47, 498 (1972).