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FERROMAGNETIC EFFECT AND SPIN ASSIGNMENT FOR THE 390 keV STATE IN ^{62}Cu

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Résumé. — Nous avons attribué à l'état isomérique à 390 keV du ^{62}Cu les caractéristiques $J^{\pi} = 4^{+}$. L'interaction hyperfine est observée dans la réaction ^{60}Ni(α, pnγ) ^{62}Cu. La période de Larmor déduite est compatible avec les valeurs connues du facteur g et du champ hyperfin du cuivre dans le nickel.

Abstract. — The 390 keV isomeric state of ^{62}Cu is assigned as $J^{\pi} = 4^{+}$. The magnetic hyperfine interaction has been observed in the ^{60}Ni(α, pnγ) ^{62}Cu reaction and the deduced Larmor period is consistent with known values of g and the hyperfine field of Cu in Ni.

1. **Introduction.** — The magnetic hyperfine interaction is often used to measure the g-factor through application of an external field. However this effect can be observed in the ordinary experimental set-up when the studied nucleus recoils in a ferromagnetic lattice. This interaction can severely perturb the γ-angular distribution and cause difficulties in the deduction of the multipolarity of the transition under study. A striking illustration for the 349 keV γ-ray decaying from the isomeric 390 keV state

$$(T_{1/2} = 11 \text{ ns})$$

has been observed in the ^{60}Ni(α, pnγ) ^{62}Cu reaction.

2. **Angular distribution and magnetic hyperfine interaction.** — The angular distribution of the 349 keV γ-ray has been measured in the ^{60}Ni(α, pnγ) reaction at $E_{\alpha} = 32$ MeV. It is almost isotropic as observed by Sunyar *et al.* [1] in the same reaction at

$$E_{\alpha} = 39 \text{ MeV}.$$

This is due to the fact that the time integrated angular distribution of this γ-ray is severely perturbed by the Larmor precession of the magnetic moment of the recoil nuclei around the magnetic field randomly oriented in the plane of a thin target (~ 2 mg/cm^2). This interaction tends to destroy the alignment produced by the reaction. If this explanation is correct, we must observe an anisotropy when we suppress this interaction by heating the target above the Curie point (358 °C) using the Joule effect (~ 2.5 A through the target). The angular distribution obtained under these conditions is shown in figure 1. It is now ani-

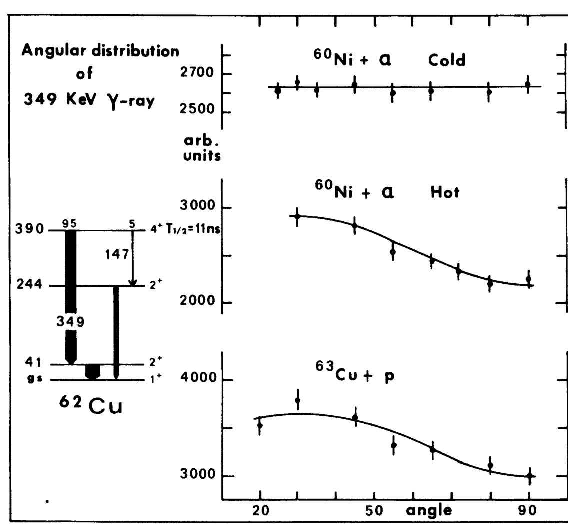

FIG. 1. — Angular distribution of the 349 keV γ-ray of ^{62}Cu.

sotropic as in the case of the angular distribution observed in the ^{63}Cu(p, pnγ) reaction at $E_{p} = 26$ MeV where the ferromagnetism does not exist.

3. **Observation of the Larmor frequency and lifetime measurement.** — We can also observe the Larmor precession in the ^{60}Ni(α, pnγ) reaction by a time differential measurement. The target is in the plane perpendicular to the beam axis and there is no external magnetic field. We observe oscillations when the target is at room temperature and these oscillations disappear when the target is heated above the Curie point. The magnetic field is randomly oriented in

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the target plane, so we can calculate the time distribution $W(\theta, t)$ by considerations analogous to those of ref. [2] (where the magnetic field is randomly oriented throughout the target volume). We find when the A_4 term is neglected :

$$W(\theta, t)=\frac{1}{\tau}\,e^{-t/\tau}(1+A_2\,P_2(\cos\theta)\,P_2(\cos\omega t)) \quad (1)$$

where τ is the lifetime of the level.

However, a convolution is necessary due to the width of the cyclotron pulse and the electronic timing resolution $b(t')$ (FWHM = 5 ns), that leads to :

$$N(\theta, t) = \int_0^t W(\theta, t - t')\,b(t')\,dt' . \quad (2)$$

By fitting the experimental curve, we can deduce the values of the Larmor period T_L and A_2. We find $T_L = 37 \pm 8$ ns and $A_2 = 0.20 \pm 0.08$. These results are consistent with the values of A_2 (0.22) deduced from angular distributions from a heated target and of T_L (45 ns) deduced from known values of $g = 0.667$ [3] and the magnetic hyperfine field of Cu in Ni (− 45 kG) [4].

The quasi-isotropy of time integrated angular distribution at room temperature can be understood by integrating the formula (1). Performing this integration, we find A_2 int./A_2 diff. = 0.275.

We emphasize that this result is obtained without any external magnetic field. If unknown, either g or the hyperfine field could be deduced from such measurements as is done in the case of an external field but now with very simple experimental set-up.

The lifetime of the 349 keV γ-ray has been measured in the ^{63}Cu(p, pnγ) and ^{60}Ni(α, pnγ) reactions. The result is $T_{1/2} = 11 \pm 1$ ns consistent with those of Bleck *et al.* [4] and Sunyar *et al.* [1]. Several measurements under different conditions (reactions, energy of incident particle, different detectors at different angles...) were each done with relative error of 3 %.

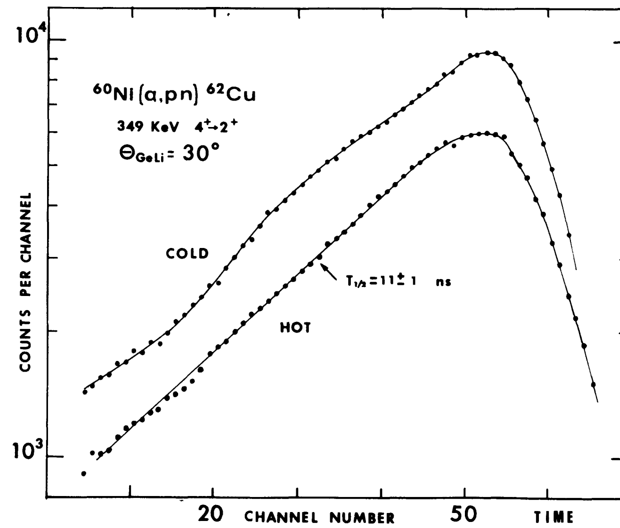

FIG. 2. — Time decay of 349 keV γ-ray of ^{62}Cu observed in the ^{60}Ni(α, pnγ) reaction. Observation of Larmor oscillations with the cold target.

However owing to the difficulty of giving absolute time calibrations better than 5 % in this time range, we give an absolute error of 1 ns. It should be noted that the lifetime measurement may be perturbed when the Larmor period is greater than the time measurement range. (In our case less than 70 ns, the time between two cyclotron beam bursts.) The deduced value may, in this case, contain a systematic error.

4. **Spin assignment of the 390 keV state in ^{62}Cu.** — Verheul in a recent compilation [5] has adopted a 4^+ assignment for the 390 keV state of ^{62}Cu although 3^+ has been assigned by Sunyar *et al.* [1] and Bleck *et al.* [3]. (We point out that the γ-cascade observed in the ^{60}Ni(α, pnγ) reaction [1] is 41, 349, 981, 925, 597 keV and not 41, 597, 925, 981 keV as reported in ref. [5].) We assign 4^+ to this state for the following reasons :

TABLE I

Angular distribution analysis of the 349 keV *γ-ray in* ^{62}Cu

Reactions	A_2 (^{a})	A_4 (^{a})	Transition	α_2 (^{b})	δ (^{b})	χ^2 (^{b})
^{60}Ni(α, pnγ) heated target	0.22 ± 0.03	-0.09 ± 0.04	$4^+ \to 2^+$	0.55	$-0.10\,^{+0.15}_{-0.10}$	1.4
			$3^+ \to 2^+$	0.6 − 0.28 (^{c})	0.4 −1.7 (^{c})	5
^{63}Cu(p, pnγ)	0.14 ± 0.03	-0.08 ± 0.04	$4^+ \to 2^+$	0.45	$-0.15\,^{+0.2}_{-0.1}$	0.9
			$3^+ \to 2^+$	0.6 − 0.15 (^{c})	0.4 −1.7 (^{c})	1.8

(^{a}) $W(\theta) = 1 + A_2\,P_2(\cos\theta) + A_4\,P_4(\cos\theta)$.

(^{b}) Fit parameters (alignment α_2, mixing ratio δ) using a Gaussian distribution of magnetic substate population as defined by Yamazaki [5].

(^{c}) Constant value of χ^2 in this range of δ.

5. **Angular distributions.** — Table I shows the values of A_2, A_4, δ and the alignment parameters of the 349 keV γ-ray deduced from the angular distribution analysis using the formalism of Yamasaki [5]. These values agree well with the $J^\pi = 4^+$ assignment to the 390 keV state. The hypothesis of $J^\pi = 3^+$ cannot be ruled out but we must admit a large value of the mixing parameter ($\delta = 0.8$) and the obtained χ^2 value is three times greater than the one obtained in the case of $J^\pi = 4^+$ in the angular distribution analysis. The angular distribution of the 147 keV γ-ray decaying from the same 390 keV state to the 2^+ state at 243 keV has a similar behaviour. If we had done our analysis with data obtained with cold target, the 4^+ assignment would give a value of mixing of E2 and M3 of $\delta = -2$, a value difficult to accept.

6. **Lifetime.** — As mentionned by Bleck *et al.* [3], the Weisskopf estimate for the transition probability of the 349 keV γ-ray agrees with the observed value for E2 (0.3 W.U.). Under the 3^+ assumption for the 390 keV state with the obtained value of mixing ($\delta \simeq 0.8$) we find for the M1 transition about 3×10^{-5} W.U., whereas 10^{-3} W.U. is the usual experimental lower limit for a M1 transition with large mixing of E2 [7]. This favours 4^+.

7. **Magnetic moments.** — Magnetic moments of odd nuclei (Mass number A spin J) can be interpreted in terms of moments μ_p, μ_n of both odd particles coupled to an even core nucleus of mass number A-2 and spin zero. The total magnetic moment μ can than be calculated from the angular momenta j_p j_n and the g factor g_p and g_n of single particles [8]

$$\langle j_p j_n J \mid \mu \mid j_p j_n J \rangle = gJ = = \left[\frac{g_p + g_n}{2} + \frac{g_p - g_n}{2} \frac{j_p(j_p + 1) - j_n(j_n + 1)}{J(J + 1)} \right] J .$$

The 390 keV state is excited in the (d, t) reaction by $l_n = 3$ [9] so that the most probable configuration of this state is $\pi\ 2p_{3/2}\ \nu\ 1f_{5/2}$. Taking the g_p and g_n from the known values of moments of neighbouring odd mass nuclei

$$(\mu\ ^{61}\text{Cu}_{3/2^-} = 2.13 ; \mu\ ^{61}\text{Ni}_{5/2^-} = 0.479)\ [10] ,$$

we find for the 4^+ state at 390 keV in ^{62}Cu the value $g = 0.65$ that agrees well with the experimental value $g = 0.667 \pm 0.04$ measured by Bleck [3]. The deduced g factor value in the case of $J^\pi = 3^+$ is $g = 0.55$ ($\pi\ 2p_{3/2}\ \nu\ 1f_{5/2}$ configuration) and $g = 0.46$ ($\pi\ 2p_{3/2}\ \nu\ 2p_{3/2}$ configuration).

We remark finally that the knowledge of the exact J^π of the 390 keV state in ^{62}Cu is important for the determination of the J^π of high spin levels deduced from the ^{60}Ni(α, pnγ) and ^{63}Cu(p, pnγ) reactions, the main γ-rays observed in these reactions being in coincidence with the 349 keV γ-ray. A detailed level scheme of ^{62}Cu will be published later.

8. **Conclusion.** — Angular distribution and lifetime measurement may be perturbed by the magnetic hyperfine interaction when the target is ferromagnetic even without any external field. Thus, analysis of, and conclusions concerning these measurements must be made carefully when the target is ferromagnetic.

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