# Circular Polarization of Muonic X Rays and Origin of Strange $\mu^-$ Depolarization in Pd Metal

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The circular polarization of muonic x rays has been measured in order to investigate the mechanism of the unexpectedly fast depolarization of the negative muon in Pd metal as observed by the negative-muon spin-rotation method. A large circular polarization consistent with the maximal theoretical value was observed in both Pd and Cd metals, showing that the polarization is preserved up to the time the muon reaches the 1$s$ atomic ground state.

It has been known from negative-muon spin-rotation experiments[1] that the $\mu^-$ is depolarized in some transition metals. During our recent studies of muon spin rotation,[2-4] it was found that the $\mu$-$e$ decay electrons from $\mu^-$Pd show no asymmetry even at a temperature of 4.2 K, indicating that the muon spin is completely depolarized.[2] If a muonic atom with nuclear charge $Ze$ behaves exactly like an impurity nucleus of apparent charge $(Z-1)e$, we can estimate the relaxation time $T_1$ for $\mu^-$Pd to be 16 $\mu$sec at $T=4$ K from the existing Rh NMR data $Pd$Rh,[5] but this $T_1$ is much longer than the muon lifetime in Pd (0.1 $\mu$sec). Insofar as this fast depolarization takes place in the ground state of $\mu^-$Pd, as is usually believed, the absence of muon spin rotation signal ($T_1<50$ nsec) would indicate the existence of a giant hyperfine anomaly between $\mu^-$Pd and its equivalent nucleus Rh, which may result from the difference in the charge distribution between $\mu^-$Pd and Rh, as discussed in Ref. 2. It can be expressed in terms of a dynamic hyperfine anomaly,

$$F_2 \equiv [(g^2T_1T)_{\mu^-\mathrm{Pd}}]^{-1}/[(g^2T_1T)_{\mathrm{Rh}}]^{-1} > 300, \qquad (1)$$

where $g$ is the Landé factor; $g(\mu^-\mathrm{Pd}) = -17.41\mu_N$ and $g(\mathrm{Rh}) = -0.177\mu_N$. In other words, the $\mu^-$Pd would feel more than 17 times as much enhanced contact field as nucleus Rh does. Such a large anomaly seems very unlikely based on the present understanding of the hyperfine field. Therefore, we asked the question whether the muon spin becomes depolarized during or even before the muonic cascade by the interaction of the muon magnetic moment with the huge perturbing field from the polarized electron clouds surrounding the capturing nucleus.

In order to distinguish between these two alternatives, the measurement of the circular polarization of the muonic $K$ x ray is essential. In the absence of the early-stage depolarization mechanisms, each muonic state of angular momentum $j$ has the following polarization with respect to the initial beam polarization $\sigma_\mu$:

$$P(j) \equiv \frac{\langle j_z\rangle}{j} \simeq \begin{cases} \frac{1}{3}\sigma_\mu & \text{for } j=l+\frac{1}{2}, \\ -\frac{1}{3}\sigma_\mu & \text{for } j=l-\frac{1}{2}, \end{cases} \qquad (2)$$

provided that the direction of the muon momentum is completely randomized at the formation of the muonic atom and that the 2$p$ states are fed by a series of stretched $(j\to j-1)$ $E1$ transitions.[6] Thus, the muonic x rays emitted at 0° with respect to the muon beam polarization of 100% should have large circular polarization as shown in Table I, while the circular polarization would be missing if $\mu^-$ is depolarized during the cascade. The values in Table I provide a theoretical upper limit of the circular polarization.

The experiment was performed at the stopped-muon channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The experimental arrangement is shown in Fig. 1. A thin Pd wire with impurity concentration below 5 ppm was cut and stacked to form a 5 cm×5 cm×4 g/cm² target. This sample is the same as used in the pre-

TABLE I. Theoretical estimate of circular polarization $P_x$ of muonic x rays at zero degrees with respect to the initial beam polarization.

| Transition | | | $P_x$ at $\theta = 0$ | |
|---|---|---|---|---|
| | $j_i$ | $j_f$ | General | Maximum |
| Stretch | $l + 1/2$ | $l - 1 + 1/2$ | $1.5P(j_i)$ | $+0.50\sigma_\mu$ |
| | $l - 1/2$ | $l - 1 - 1/2$ | $1.5P(j_i)$ | $-0.50\sigma_\mu$ |
| Nonstretch | $l - 1/2$ | $l - 1 + 1/2$ | $1.5P(j_i)/(j_i + 1)$ | $-[0.50/(j_i + 1)]\sigma_\mu$ |
| | $p_{1/2}$ | $s_{1/2}$ | $P(p_{1/2})$ | $-0.33\sigma_\mu$ |

$[P_x(K\alpha_1) - P_x(K\alpha_2)]^{\max}/\sigma_\mu = 0.50 - (-0.33) = 0.83$

vious muon spin-rotation experiment.[3] A metallic Cd target (5 cm×5 cm×5 g/cm$^2$) was used as a reference. Since a clear muon spin-rotation precession had been observed in Cd,[7] the muonic x rays from Cd should show an unperturbed circular polarization. Both targets were placed at room temperature. The negative muon beam of 85 MeV/$c$ was collimated by an iron collimator with 3.8 cm aperature and stopped in the target.

A conventional transmission-type magnetic analyzer, using Compton scattering by polarized electrons, was placed at 0° to the beam direction. The center piece of the analyzer was made of Permendur (50% Fe and 50% Co). The length of the analyzer (7 cm) was optimized for 3-MeV photons, the $K$ x-ray energy of the Pd-Cd region. A 56-cm$^3$ intrinsic Ge detector was used to detect the x rays, looking at the target through the analyzer. A plastic counter was placed between the Ge detector and the polarization analyzer in order to reject the straight-through electrons. A set of plastic counters was used to obtain the logic signal "$\mu_{\text{stop}}$," which was used to gate the Ge

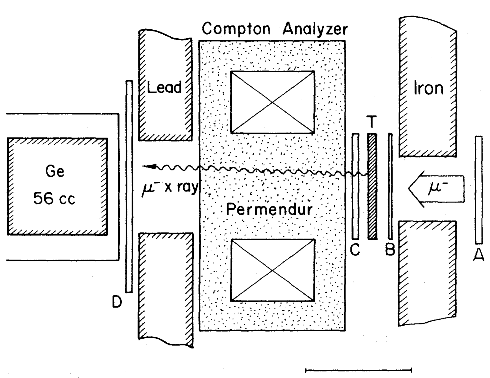


FIG. 1. Experimental arrangement for the measurement of the circular polarization of muonic x rays. $A$, $B$, $C$, and $D$ are the plastic scintillation counters which establish a $\mu^-$ stop signal ($=A\cdot B\cdot \overline{C}\cdot \overline{D}$). The counters $C$ and $D$ are used also to veto the Ge signal.

detector signal. Typically the muon stopping rate was $2\times10^5$ sec$^{-1}$ at the primary proton beam current of 150 $\mu$A, and the singles rate of the Ge detector was 850 sec$^{-1}$. The use of the counter logic helped us to reduce the background significantly. The use of a pileup rejector was also effective.

For each target, two energy spectra were accumulated; one [$\uparrow\uparrow$] with the muon spin ($\vec{\sigma}_\mu$) parallel to the electron spin ($\vec{\sigma}_e$) in the magnet, and the other [$\uparrow\downarrow$] with $\vec{\sigma}_\mu$ antiparallel to $\vec{\sigma}_e$. The polarity of the magnet was flipped every 100 seconds and the energy signal of the Ge detector was routed into two halves of the memory of a pulse-height analyzer. No absolute normalization between those two spectra was attempted. Rather, we made use of the fact that $K\alpha_1$ and $K\alpha_2$ have opposite circular polarization, and formed the double ratio

$$R = \frac{[N(K\alpha_1)/N(K\alpha_2)]_{\uparrow\uparrow}}{[N(K\alpha_1)/N(K\alpha_2)]_{\uparrow\downarrow}}, \tag{3}$$

where $N(K\alpha_1)/N(K\alpha_2)$ is the intensity ratio of the $K\alpha_1$ and the $K\alpha_2$ lines. This double ratio is related to the circular polarization $P_x$ as

$$R \simeq 1 + 2A[P_x(K\alpha_1) - P_x(K\alpha_2)], \tag{4}$$

where $A$ is the analyzing power of the magnet. When analyzed in this manner, the result is almost free from systematic errors arising from uncertainties in the normalization.

The beam polarization and the analyzing power of the magnet were determined by separate experiments. The beam polarization was determined from the precession amplitude of positive muons in a carbon target and was found to be (90 ± 5)%, which is consistent with the channel beam optics. The negative-muon precession in a carbon target was also performed to obtain a further confirmation on the result.

The analyzing power of the magnet was determined by use of an intense $^{60}$Co $\gamma$ source and another identical magnet as used by Chesler.[8] The analyzing power at the muonic x-ray energy was then calculated by scaling the $^{60}$Co result by the energy dependence of the spin-dependent Compton scattering cross section.[9] The analyzing power was determined to be $-0.020\pm 0.003$ at 3 MeV.

In each spectrum, about $10^5$ $K\alpha$ events were accumulated. The spectra, shown in Fig. 2, were fitted by a composite Gaussian-plus-background function and the areas of the $K\alpha_1$ and $K\alpha_2$ peaks were obtained. Since both Cd and Pd targets are of natural isotope composition, the lines due to the individual isotopes had to be taken into account. In the case of Pd, the quadrupole splitting of $^{105}$Pd was also considered. The observed spectra and fitted curves are presented in Fig. 2. Single-escape peaks and double-escape peaks were analyzed in the same way and results were combined with those of the full-energy peaks to derive the following final values:

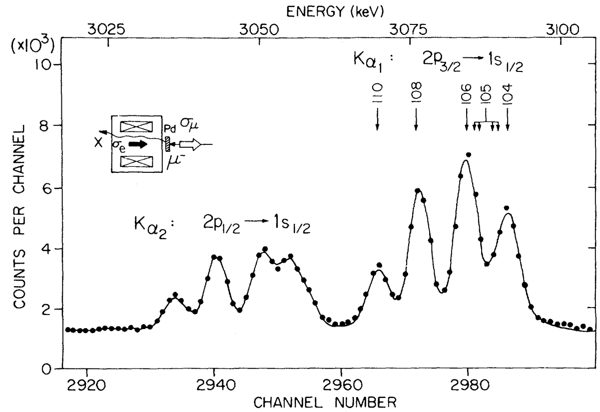


FIG. 2. Full-energy peaks of $K\alpha_1$ and $K\alpha_2$ lines from muonic Pd detected with a 56-cm$^3$ intrinsic Ge detector through a polarization analyzer placed at zero degree to the muon beam. The smooth curves reproduce the experimental points by best fitting with free isotope shifts (indicated by arrows).

$$\text{Cd: } R=1.029\pm 0.009,\quad [P_x(K\alpha_1)-P_x(K\alpha_2)]/\sigma_\mu=0.82\pm 0.30;$$
$$\text{Pd: } R=1.028\pm 0.010,\quad [P_x(K\alpha_1)-P_x(K\alpha_2)]/\sigma_\mu=0.79\pm 0.31. \quad (5)$$

These are to be compared with the maximum value predicted by the theory, 0.83.

From these results, we conclude that there is no anomaly in the capture or the cascade process of muonic Pd. The experiment provides a clear-cut evidence that the depolarization of $\mu^-$ takes place in the ground state of $\mu^-$Pd.

Does this lead to the conclusion that the $\mu^-$Pd feels more than 20 times larger contact field than the Rh does? Before jumping to such a surprising conclusion let us examine possible differences between the $\mu^-$Pd muon spin-rotation and Rh*Pd* NMR experiments.

(i) In the muon-spin rotation the Rh-like $\mu^-$Pd atom is perfectly dilute, while the Rh*Pd* sample in the NMR experiment[5] includes 2 at.% of Rh. In the latter the observed $T_1$ seems to decrease with the decrease of the Rh concentration down to 2%. A question is then raised as to whether $T_1$ decreases further toward lower concentration while keeping the Knight shift unchanged ($K=-0.15$ both in the Rh*Pd* NMR experiment and in the $^{100}$Rh*Pd* $\gamma$-$\gamma$ angular correlation[10]).

(ii) In the Rh*Pd* NMR experiment a longitudinal field of 60 kOe was applied, while in the $\mu^-$Pd experiment[3] the $\mu^-$Pd spin precesses in the transverse field of 6.8 kOe, and is subject to transverse relaxation ($T_2$). If the Rh atom has a local moment, $T_1T$ may have a complicated dependence on the temperature and magnetic field.[11]

These questions can be answered by further experiments in both muon-spin rotation and NMR. If it turns out that the depolarization of $\mu^-$Pd is ascribed to a large hyperfine anomaly,[12] what would this mean? We can consider the following effects. (i) The charge distribution of $\mu^-$Pd, which has a positive charge surrounded by a negative charge, changes the electron density. (ii) If the electron spin density has a considerable spatial distribution (namely, not of $s$ character but of $d$ character), the $\mu^-$Pd may feel an enhanced field because of its extended magnetization. (iii) The local density of states, which is known to have a peak at the Fermi surface in Pd, might be affected by the unusual charge distribution of $\mu^-$Pd. If so, it will affect the Knight shift and $T_1T$. This possibility has not been considered so far.

A similar strange depolarization of $\mu^-$ is observed also in another strong paramagnetic metal, namely in Ni.[4] In this case, the $T_1$ of Co*Ni* in the paramagnetic phase is not known and we cannot compare $\mu^-$Ni with Co*Ni*. However, it was shown that the muon spin-rotation signal becomes visible as Cr is added to Ni to reduce the susceptibility. A small magnetic moment ($\sim 0.1\mu_B$) is sufficient to depolarize $\mu^-$Ni. Further systematic studies of muon-spin rotation in paramagnetic metals are required.

From the view point of atomic physics, the measurement of circular polarization is an interesting new method to understand the capture and cascade process. It may be possible to distinguish between different initial $l$ distributions by this technique. Recent theoretical work by Akylas and Vogel[13] indicated that the circular polarization may be used for this purpose. The study of circular polarization of muonic x rays from odd-$Z$ targets is also interesting. Depending on which level of the muonic cascade the hyperfine splitting becomes dominant over the natural linewidth (see discussions by Nagamine and Yamazaki[14]), the circular polarization of muonic $K$ x ray will be very much affected. Such measurements are also planned.

It should be noted that the circular polarization measurement serves as a straightforward way of the determination of the helicity of $\bar{\nu}_\mu$. The present experiment is consistent with the known fact that the helicity of $\bar{\nu}_\mu$ is $+1$.

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# Measurement of Molecular-Alignment Relaxation Rate in $NH_3$ Using Non-Lorentzian Laser-Induced Saturation Resonances

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A general technique is presented in which narrow non-Lorentzian laser-induced resonances are used to study molecular reorientation. The experiments, which study the $\nu_2 as Q(8, 7)$ $NH_3$ transition, yield a value of $6 \pm 1$ MHz/Torr for the excited-state alignment relaxation rate, 50% larger than the corresponding population relaxation rate.

The technique of laser-induced line narrowing in coupled three-level systems has been the subject of much recent work.[1,2] Theoretical studies[3,4] have shown that the shape of the narrow resonance is a sensitive function of the relaxation processes, and non-Lorentzian line shapes[5] have been observed in neon.[6] This Letter reports the first application of this technique to study $M$-changing collisions in an infrared molecular transition.[7-9] The non-Lorentzian line shapes thus observed are used to extract Zeeman-coherence (alignment) relaxation rates. Thus, the present technique complements the well-established technique of level crossing (Hanle effect) in optical