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Transient Magnetic Field Effects on Pd and Ru Ions Recoiling in Fe at Low Velocities

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There have been a large number of experiments during the last few years which show the presence of transient magnetic field effects on ions recoiling in polarized ferromagnetic lattices. The theory of transient magnetic field has been formulated by Lindhard and Winther[1] and it explains the gross features of the experimental observations. The observed effects at high recoil velocities[2] are about a factor of two larger than that predicted by this theory (for $V_p = V_0$). Very few experiments are, however, performed at low recoil velocities ($V < V_0$ the Bohr velocity). With a view to make a quantitative comparison of observed effects with the theory, we have made measurements on Pd and Ru ions recoiling with energies ~330 keV in polarized iron lattice.

Measurements

The experimental set up and procedure have been described earlier.[3] 20 at.% Pd–Fe and 5 at.% Ru-Fe alloys were used as targets for Pd and Ru measurements respectively. The targets of about 10 mg/cm^2 thickness were placed between the pole tips of an electromagnet capable of giving field of about 1 kG. The magnet itself was attached to a cold-finger and was cooled down to liquid nitrogen temperature. A 5 MeV α-beam from the Van de Graaff accelerator at Bhabha Atomic Research Centre, Bombay, was used to Coulomb excite the first 2^+ states in Pd and Ru isotopes. The beam current was about 0.6 μA on the target. The deexciting γ-rays were detected by two Ge(Li) detectors, one of 20 cc. and the other of 30 cc. active volume.

The intensities of the γ-rays obtained from Coulomb excitation of Pd and Ru isotopes were determined by adding counts in each peak and substracting background under it. A computer fit was used for gamma peaks which were not well resolved. The angular distribution coefficients, A_2 and A_4, for the 434 keV and the 374 keV γ-ray from ^{108}Pd and ^{110}Pd respectively, were measured with a Pd-metal target using the 20 cc. Ge(Li) detector. The measurements were made at an interval of 15° between 90° and 270° with respect to the beam direction. The measured values were found to agree with the theoretically calculated values within the experimental errors. These angular distributions were also checked with the 20 at.% Pd-Fe targets. The theoretical values were used for angular distributions in the case of Ru isotopes.

Since A_4 terms are small in all the cases, the detectors were placed at ±45°. The quantity $R(\pm 45°)$, defined as the fractional change in counting rate on reversal of magnetic field, was measured by recording spectra for field up and field down positions alternately for fixed number of charge counts collected in the current integrator. Each run took about 40 minutes. The angle of spin rotation, $\omega\tau$, for each γ-ray, was calculated from the measured values of 'R' and the angular distribution coefficients in each case. A Pd-metal target was used to measure the beam bending effect which was found to be (-1 ± 2) mr. Instrumental check was also provided by the measured value of $R = -(3.2 \pm 0.7)\%$ for 127 keV $3/2^+$ state in ^{101}Ru, which agrees with the expected value of $-(2.8 \pm 0.6)\%$ obtained by using a value of (-442 ± 31)kG for the static hyperfine field at Ru in Fe.[4] The experimentally observed rotations for first 2^+ states in ^{108}Pd, ^{110}Pd, ^{102}Ru and ^{104}Ru are given in Table I.

H_{st} at Pd nuclei in 20 at.% Pd-Fe sample was measured experimentally. For this purpose a small amount of ^{106}Ru activity was electroplated on the sample and diffused at about 800°C for 100 hrs. The residual activity on the surface was removed by scrapping the surface with an emery paper and then washing it with dilute HCl and water. A PAC experiment was performed on 512 keV 2^+ state in ^{106}Pd populated in the decay of ^{106}Ru. Using the value $g = 0.40 \pm 0.03$,[4,5] the H_{st} on Pd nuclei in 20 at.% Pd-Fe alloy was measured to be $H_{st} = (-412 \pm 37)$ kOe.

Table I.

Nucleus	Level energy (keV)	τ (ps)	$\omega\tau_{obs.}$ (mr)	$\omega\tau_{st}$ (mr)	$-\omega\tau_{trans.}$ (mr)	$-\omega\tau_{trans.}$ Theory[1] (mr)
^{108}Pd	434	34.4	13.2 ± 2.8	21.7 ± 4.3	8.5 ± 5.1	3.9
^{110}Pd	374	66.0	23.2 ± 3.0	33.8 ± 6.0	10.6 ± 6.7	3.0
^{102}Ru	474	25.4	7.4 ± 8.2	20.9 ± 4.2	13.5 ± 9.2	4.8
^{104}Ru	358	83.5	45.5 ± 4.3	56.6 ± 8.5	11.1 ± 9.5	3.8

Discussion

The spin rotation angles, $\omega\tau_{st}$, due to the static hyperfine magnetic fields can now be calculated if g-factors of the nuclear states under consideration are known. The g-factors of the first 2^+ states in Ge, Se, Mo, Ru, Pd and Te isotopes have been measured by the Wisconsin and the MIT[6] groups using IMPAC technique at high recoil velocities. The IMPAC data has been analysed by the Wisconsin and the MIT groups under the assumption that the g-factors of the lowest 2^+ states in all doubly even isotopes of an element are constant. We have not used this assumption in our reanalysis of the data[6] for Pd and Ru isotopes. In the first place, the room temperature values for H_{st} obtained by radioactivity method[4,7] were used instead of the values obtained at low temperature by NMR technique to extract the $(\omega\tau)_{st}$, the static rotation in each case. In addition the g-factors obtained by radioactivity method were used to extract the transient field correction factor from the observed rotation in IMPAC measurements by using the equation

$$\omega\tau_{IMPAC} = g\left[4.8\ H_{st}\tau + \frac{(\omega_1 t_1)_{tr}}{g}\right],$$

where H_{st} is in MOe, τ in ps and the rotation $\omega\tau$ is given in milliradians. The correction factor $(\omega_1 t_1)_{tr}/g$ obtained from here is then applied to the observed rotation $\omega\tau_{IMPAC}$ for other isotopes of the same element and the g-factors are obtained from the corrected values of the rotation. The g-factors for Pd and Ru isotopes so obtained along with those measured by radioactivity method are given in column 3 of Table II.

It is seen from Table II that although the apparent discrepancy between g-factors obtained by radioactivity method and IMPAC method is removed by the constraint introduced in our reanalysis, the g-factors for other isotopes (^{108}Pd, ^{110}Pd and ^{104}Ru) have not

Table II.

Isotope	E(keV)	g-factor	g_{IMPAC}[c]
^{104}Pd	554	0.26 ± 0.46	—
^{106}Pd	512	0.40 ± 0.03[a]	0.29 ± 0.17
^{108}Pd	434	0.32 ± 0.06	0.30 ± 0.04
^{110}Pd	374	0.26 ± 0.03	0.25 ± 0.03
^{100}Ru	540	0.51 ± 0.07[b]	—
^{102}Ru	473	0.40 ± 0.09[b]	—
^{104}Ru	358	0.32 ± 0.05	0.29 ± 0.04

a) refs. 4, 5.
b) ref. 4. g-factors corrected for mean-lives listed in ref. 6.
c) ref. 6.

changed significantly. These g-factors were used to calculate the static rotations for ^{108}Pd, ^{110}Pd, ^{102}Ru and ^{104}Ru, which are given in Table I. The difference between the static and the observed rotations gives the contribution due to transient rotation. These are also given in Table I.

In evaluation of the theoretical estimates, the average recoil energy was obtained by averaging it over all recoil directions, *i.e.*

$$\overline{E_R} = \frac{\int_0^\pi E_R \frac{df(\theta,\xi)}{d\Omega} \sin\theta\, d\theta}{\int_0^\pi \frac{df(\theta,\xi)}{d\Omega} \sin\theta\, d\theta},$$

where θ is the recoil angle of the projectile and $df(\theta, \xi)$ is the differential Coulomb excitation cross section. It may be pointed out that the probability of recoil of target atoms in backward direction is almost negligible, *i.e.* more than 99% recoils will be in forward direction. The transient rotation is now given by

$$(\omega_1 t_1)_{tr} = -\frac{g\mu_N}{\hbar}\int_0^{V_R} \frac{M_1}{dE/dR} B(V)dV,$$

where M_1 is the mass of recoiling ion, dE/dR is the energy loss at velocity V and $B(V)$ is the transient magnetic field given by

$$B(V)=\frac{8\pi}{3}N\mu\rho C2\pi Z_1\cdot\begin{cases}\frac{V_0}{V}\text{ for }V>\frac{1}{2}V_0\\ 2\text{ for }V<\frac{1}{2}V_0\ ,\end{cases}$$

where N is the number of atoms per unit volume, μ is the Bohr magneton, ρ is the number of polarized electrons per atom and Z is the atomic number of the ion. The constant C is given by

$$C=1+(Z_1/84)^{5/2}\ .$$

The theoretical estimates for transient rotation are given in last column in Table I. It is seen that on an average the experimentally observed values are about a factor of 2 larger than the theoretical estimates for $V_p=\frac{1}{2}V_0$. The disagreement between theory and experiment may be due to following reasons.

(1) The static hyperfine field in an IMPAC experiment may be smaller compared to the field measured by radioactivity method because of the finite radiation damage around the lattice site where the ion finally stops.

(2) The H_{st} can also decrease due to rise in temperature of target due to local heating.

(3) Some oscillations in transient field effect, at high recoil velocity, have been observed[2] as a function of Z of recoiling atom. The maximum appears in a region with Z between 40 and 50. If such oscillations exist they will be more pronounced at low recoil velocity. The larger effect observed in our experiment may possibly be due to this oscillatory behaviour.

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