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II–17 Investigations of Quadrupole Interaction on Excited Nuclei Recoiling through Matter

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Lindhard and Winther[1] pointed out that a nucleus recoiling through matter is subject to strong electric field gradients which arise from the scattering of the host electrons by the nucleus; the phenomenon is analogous to that which produces the transient magnetic field observed when nuclei recoil through ferromagnetic materials.[1,2] The magnitude of the transient EFG can be orders of magnitude larger than typical hyperfine EFGs observed in non-symmetric crystals. The interest in the transient EFG arises from the fact that it is in principle a calculable quantity whose magnitude can be varied by changing particle velocities and electron densities. Thus the quadrupole interaction with the transient EFG is attractive as the first spectroscopic method of reliably measuring the quadrupole moment of short lived nuclear states.

The theoretical description of transient fields is based on the well known fact that when electrons are scattered by an attractive Coulomb field, the electron density becomes very high in the scattering center.

In the model of Lindhard and Winther one first assumes that the recoiling nuclei meet a gas of electrons with a velocity $-\boldsymbol{v}$ parallel to the x-axis. In such a case the charge density distribution is parabolic, $\rho = \rho(r - z)$ with a maximum at $\rho(0) = \chi\rho(\infty)$ where

$$\chi = \frac{2\pi Z_1 e^2}{\hbar v}$$

describes the density increase for the unscreened Coulomb potential close to nucleus where Z_1 and v are the charge and velocity of the recoiling ion.

From the cylindrical symmetry of the scattering it follows that the field gradient has axial symmetry with respect to the recoil axis and that we are only left with the tensor component

$$V_0^2 = \frac{1}{4}\sqrt{\frac{5}{\pi}}\left(\frac{\partial^2}{\partial z^2} - \frac{1}{3}\Delta\right)\phi(0) ,$$

where $\phi(r)$ describes the electric potential. Because $\partial^2\phi(0)/\partial z^2 = 0$ we get from the Poisson equation that

$$V_0^2 = \frac{\sqrt{5\pi}}{3}\rho(0) = \frac{\sqrt{5\pi}}{3}\chi\rho(\infty)$$

or using the Lindhard-Winther notation the field gradient

$$Y = 4\sqrt{\frac{\pi}{5}}\,V_0^2 = \frac{8\pi^2 Z_1 v_0}{3v}\rho(\infty)\, f_1\!\left(\frac{v}{v_l}\right)$$

where $f_1(v/v_l)$ expresses an asymmetry correction due to the electronic velocity distribution.[1] Here v_l is the velocity of the electrons in the host. Averaging over all the electron velocities in the lattice, the total quadrupole field becomes

$$\bar{Y} = \frac{-8\pi e^3 Z_1 N Z_2}{3\hbar v}F(v);\; F(v) = \langle 1 - \frac{v_l^2}{v^2}\rangle \; .$$

The field gradient $\bar{Y}$ has been calculated using three different approaches for estimating the velocity distributions of the electrons in Sm metal and is shown in Fig. 1.

(i) The curve (a) is derived from the Thomas-Fermi model for neutral atoms for intermediate velocities ($1/70\; v_0 Z_2^{2/3} < v < 1/5\; v_0 Z_2^{2/3}$),

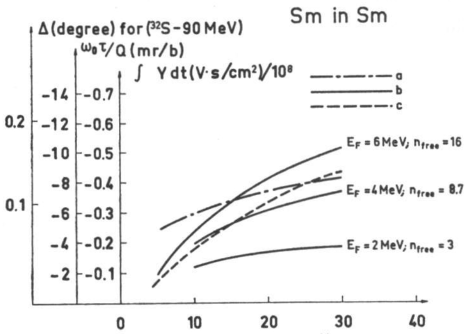

Fig. 1. Calculated transient EFG acting on Sm nuclei implanted into Sm as function of recoil energy (see text). The expected rotation of the angular correlation Δ is indicated for an experiment where 90 MeV ^{32}S is used to excite the first 2^+ state of ^{150}Sm through 90°.

$$F(v) = 1.04 Z_2^{-2/3}(v/v_0);\ v_0 = e^2/h\ ,$$

which also is consistent with the approximation given by Lindhard and Winther.[1)]

(ii) In the approximation, curves (*b*), we assume that there are two distinct groups of electrons, the inner tightly bound electrons with velocities high enough to make $F(v)=0$ and the slower more free electrons forming a Fermi gas

$$F_{\text{free}}(v) = \langle 1 - \frac{v_i^2}{v^2} \rangle$$

$$= \frac{n_{\text{free}}}{Z_2} \times \begin{cases} 1 - 3/5 \dfrac{v_F^2}{v^2};\ v_F < v \\ 2/5 \dfrac{v^3}{v_F^3};\ v_F > v \end{cases}$$

where the Fermi velocity $v_F = 3.6\ (n_{\text{free}} N)^{1/3}$ cm/sec and n_{free} is the number of free electrons.

The three curves (*b*) are calculated for Fermi energies 2, 4 and 6 MeV corresponding to 3, 8.7 and 16 free electrons per atom.

(iii) In the approximation, curve (*c*), also the bound electrons are taken into account. From the virial theorem it follows that the electron binding energy E_B is equal to the average kinetic energy, therefore we can try to approximate v_i^2 with $2E_b/m_e$ and get

$$F_b(v) = \sum_i \left(1 - \frac{2E_{bi}}{m_e v^2}\right).$$

In this calculation we take $n_{\text{free}} = 3$ because there are three conduction electrons in rare earth metals.

If in approximation (ii) one assumes that 10 electrons have low enough energy to be effective in the scattering process ($E_F = 4.8$ MeV) then the three approximations give comparable values in the 30 MeV region where we are primarily interested for experimental reasons discussed later.

Since approximation (iii) depends on known electrons energies we can try to estimate the influence from shell effects and possibly find the most suitable backing material. Calculations show that if the Sm host is replaced by Yb the field gradient increases a factor of 2.

It should be emphasized, however, that the above approximations are only meant to give an order of magnitude for the field gradient. In the approximation (iii) we have f.ex. not considered any velocity distribution for the individual atomic levels.

Also it should be stressed that there may be an appreciable correction due to relativistic effects. It is known that for precessions caused by magnetic transient fields on nuclei as heavy as Sm a correction of 30% due to relativistic effects must be added. So far there exist no estimates for relativistic corrections to transient quadrupole interactions but it may be as large as a factor of 2 in the Sm region.

Winther has pointed out[3)] that in Coulomb excitation in which the recoiling excited nucleus is polarized, the transient EFG may produce significant first order effects on the gamma-ray angular distributions in the Coulomb excitation reaction plane.

The effects are similar to those produced by the projectile-target interaction causing reorientation effects (see accompanying paper).[4)] In the reaction plane defined by the ingoing and outgoing projectile momenta, the gamma angular distribution is subject to both a precession and a breathing mode directly proportional to ω_Q (transient).

A detailed analysis of the angular correlation function for this geometry will be published elsewhere.[5)] For small precessions, $\int \omega(t) dt \ll 1$, the angular correlation function has a simple form

$$W(\theta) = N(x) + F(x) \cos 4(\theta + \Delta_1 + x\Delta_2)\ ,$$

where the interaction strength $x = \int \omega(t) dt$ and $N(x)$ and $F(x)$ are functions of the interaction strength and depend on the Coulomb excitation process. The Δ_1 and $x\Delta_2$ express the rotation of the angular correlation due to the reorientation effect and the transient effect discussed above, respectively.

The lines in Fig. 2 are calculated for a Coulomb

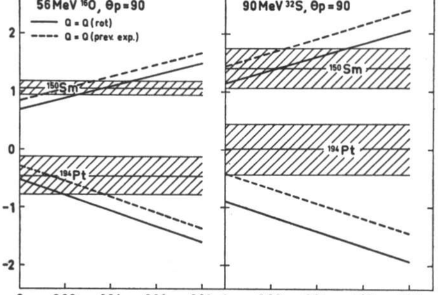

Fig. 2. Comparison between calculated and experimental values of Δ for the 2^+ states in ^{194}Pt and ^{150}Sm (see text). The full drawn lines correspond to $Q = -1.1$ barn for Sm and $Q = 1.3$ barn for Pt. The dashed lines correspond to $Q = -1.3$ barn for Sm and $Q = +0.7$ barn for Pt.

excitation experiment on the first 2^+ state of ^{150}Sm and ^{194}Pt when ^{16}O and ^{32}S ions are scattered through 90°. The angular shift $\Delta = \Delta_1 + x\Delta_2$ is plotted vs the interaction strength $\omega\tau = x$. The slope of the lines is determined by Δ_2 and depends on the degree of polarization. The intercept Δ_1, at $\omega\tau = 0$, represents the rotation due to the reorientation effect and depends on the parameters in the Coulomb excitation process and Q of the excited state. The full drawn lines are calculated for Q equal to its rotational value Q_{rot}. The dashed lines are calculated for Q equal to the best known experimental values.

Also our first preliminary data for the experiment are shown in the figure as shaded areas. It can be seen from Fig. 2 that the main part of the angular shift Δ is due to the reorientations effect Δ_1 and that the precession measurements are in overall agreement with earlier reorientation results extracted from cross-section measurements. The present accuracy does not allow us to extract any meaningful information about the transient electric fields. If one compares the experimental result to the calculations using rotational Q-values the data might indicate that there are anomalous precessions towards positive values.

One effect for such anomalous precession has been considered but not yet analyzed in detail. Quantum mechanical effects can influence the angular correlation and our data have only been corrected to first order according to a rough estimate based on a discussion given by Smilansky[6] (0.1° for ^{16}O and 0.5° for ^{32}S).

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