plicable to larger values of $e^2qQ/h$ in asymmetric fields are now in progress.

A complete account of this work is being submitted to the *Canadian Journal of Physics.*

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† Holder of an Ontario Research Council Scholarship.
‡ Holder of a National Research Council Bursary. Now with the Dominion Gulf Company, Box 281, Larder Lake, Ontario.
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## Angular Correlation of the Gamma-Rays of $Cs^{134}$*

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A PROGRAM has been initiated for the study of the correlations of cascade radiations[1] in the decay of radioisotopes. We make use of the proportional properties of scintillation crystals and of the high efficiency of NaI(Tl) as a $\gamma$-ray detector. We reduce the accidental counting rates considerably by using fast amplifiers and a fast coincidence circuit for timing, and slower, linear amplifiers in parallel, pulse-height selection channels. There are no heavy metals in the vicinity of the detecting crystal and no collimation is used. We rely only upon pulse-height selection to eliminate false coincidences due to scattered radiation.

Each photomultiplier output goes to two parallel channels. One consists of a fast amplifier and leads to a "fast" coincidence circuit whose resolving time is 30 $\mu$sec. The other channel is a linear amplifier and single channel pulse-height selector and leads

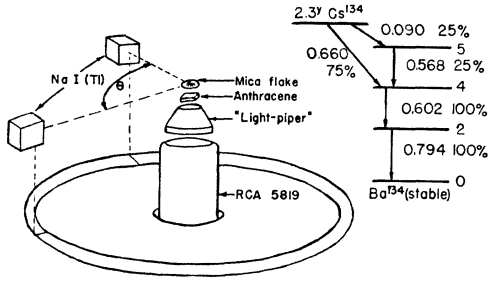


FIG. 1. Decay scheme of $Cs^{134}$ and schematic sketch of detector system ($\beta$-ray detector exploded).

to a "pulse-height" coincidence circuit, whose resolving time is $\frac{3}{4}$ $\mu$sec. The pulse-height selectors are set to accept pulses corresponding to $\gamma$-ray energies appropriate to the problem. For instance, in experiments on $Co^{60}$ and $Cs^{134}$, whose $\gamma$-rays are all of nearly the same energy, the pulse-height selectors are set to the peak of the Compton distribution. The "fast" and "pulse-height" coincidence signals are fed into still another coincidence circuit. An output signal in this last stage then indicates that there has been a coincidence of two signals of proper pulse height. All critical voltages are regulated, and the battery supplying the photomultipliers is monitored continuously.

The system was checked by measuring the angular correlation of the $\gamma$-rays of $Co^{60}$. The ratio $W(\pi)/W(\frac{1}{2}\pi)$ was found to be

TABLE I. Angular correlation of $\gamma$-rays coincident with 660-kev $\beta$-ray of $Cs^{134}$. Spins 4, 2, 0, and quadrupole radiations.

| | $W(\pi/2)$ | $W(3\pi/4)$ | $W(\pi)$ |
|---|---|---|---|
| Theoretical value | 1 | 1.073 | 1.167 |
| Theoretical value corrected for solid angle | 1 | 1.063 | 1.139 |
| Experimental value | 1 | 1.085±0.03 | 1.109±0.03 |

TABLE II. Theoretical and experimental "over-all" correlation ratios for $Cs^{134}$.

| Spin of 3rd state | Multipole character of 1st $\gamma$-ray | $W(\pi/2)$ | $W(3\pi/4)$ | $W(\pi)$ |
|---|---|---|---|---|
| 5 | Dipole | 1 | 1.036 | 1.074 |
| 5 | Quadrupole | 1 | 1.027 | 1.037 |
| 6 | Quadrupole | 1 | 1.063 | 1.139 |
| Experimental values | | 1 | 1.046±0.01 | 1.106±0.01 |

1.17±0.05, in good agreement with the results of other experiments.[2]

With a slight modification of this system we have investigated the $\gamma$-ray cascade following the $\beta$-decay of the 2.3-year isomer of $Cs^{134}$. The decay scheme is shown in Fig. 1.[3] The source was deposited on a mica flake mounted upon a chip of anthracene (about 1 cm×1 cm×1.5 mm) as shown in Fig. 1. The output of the $\beta$-detector photomultiplier was amplified by one of the fast amplifiers and fed into the "fast" coincidence circuit. The 90-kev $\beta$-ray was entirely suppressed since it gave pulses too small to actuate the fast coincidence circuit. The anthracene was quite insensitive to $\gamma$-rays and the overall efficiency for the 660-kev $\beta$-ray was about $\frac{1}{3}$. Thus we required a coincidence of two $\gamma$-rays with the further condition that one of them be in coincidence with a 660-kev $\beta$-ray.

Some 4000 events were counted at each of three positions, (90°, 135°, 180°). The angular correlation of the $\gamma$-rays coincident with the 660-kev $\beta$-ray is in good agreement with the theoretical correlation function for transitions involving spins 4, 2, 0, and quadrupole radiations. The results are shown in Table I.

At the same time we measured the "over-all" correlation of all the $\gamma$-rays; that is, accepting any of the three $\gamma$-rays. The results are shown in Table II and are in agreement with the other observations.[2]

Assuming the spins 4, 2, 0, and quadrupole radiations, theoretical correlation functions were calculated[4] on the assumptions that the third excited state of $Ba^{134}$ had spin 5 (dipole and quadrupole radiation) and spin 6 (quadrupole radiation.) Using the $\beta$-decay branching ratio of 3:1 and correcting for solid angle, we derive the results shown in Table II.

The spins of the excited states of $Ba^{134}$ may then be assigned as indicated in Fig. 1. This assignment is in agreement with the character of the radiations as deduced from interval conversion coefficients.[5]

Work is in progress on other triple correlations.

We are indebted to Dr. M. E. Rose of the Oak Ridge National Laboratory for the calculation of the angular correlations of the first and third $\gamma$-rays with the second unobserved one.

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## Anomalous Resistance of Noble Metals Containing Paramagnetic Ions

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EXPERIMENTS performed by Gerritsen and Linde[1] on diluted alloys of Mn in Cu, Ag, and Au reveal anomalies which are similar but more pronounced than those observed in

samples of "pure" noble metals.[2,3] Typical results are shown in Figs. I, 4 and II, 3–7 of reference 1.

A theoretical account can be given if we assume that it is possible to construct wave packets, formed from distorted Bloch waves with energy near the surface of the Fermi-sea only, which correspond to a state of one electron localized in a volume equal to the volume per Mn ion, and which, for low concentration $c$, do not contribute to the conductivity.

The interaction between a $Mn^{++}$ ion, which is in a $^6S$ state, and such an electron will remove the spin-degeneracy. The magnetic dipole interaction would give the energies $\pm E_1=\pm(8\pi/3)5\mu^2|\chi(0)|^2$ with respect to the Fermi level, $\chi(r)$ being the orbital part of the wave function of these packets. The exchange interaction is of opposite sign and probably larger. Such a splitting may very well be of the order of a few °K. As a result of overlap and finite lifetime these local states will form a band of width $\Delta E$. Both $\Delta E$ and $E_1$ will increase with increasing $c$.

The conduction electrons with energy in the intervals $\pm[E_1\pm\Delta E/2]$ give, due to resonance scattering, a negligible contribution to the current in an applied field. Therefore the conductivity is:

$$\sigma=\sigma_0[1+(\partial f_0/\partial E_1)\Delta E], \tag{1}$$

where $f_0$ is the Fermi function without field and $\sigma_0$ is the conductivity in the absence of this resonance effect. Equation (1) can reproduce the $R-T$ curves for low $c$ between $T=0$ and the minimum very well. Some experimental values of $E_1$ and $\Delta E$ as a function of $c$ are shown in Fig. 1.

There will be, apart from resonance scattering and coulomb scattering, another process which we will call nonresonance scattering. This occurs for all electrons and consists of a second order transition with a "local" state as a virtual intermediate state. We calculated it as if all conduction electrons were at the Fermi level.

The contribution of the nonresonance scattering and the coulomb scattering to the total resistance will be of the same order of magnitude. If $\psi_k$ is a Bloch wave normalized in the volume per Mn ion, the first is proportional to $|\int\psi_k^*V\chi d\tau|^4/E_1^2=V_{ke}^4/E_1^2$, the latter to $|\psi_k^*U\psi_{k'}d\tau|^2$, where $V$ is the effective field acting on the electron in the local state, and $U$ is the effective perturbation in the lattice potential.

Calculating separately the contribution from Mn ions with one or both local states unoccupied, gives Eq. (2) with $H=0$.

In a magnetic field $H$ the magnetic ions will be quantized according to $\cos\vartheta_m=m/j$, $m=-j,\cdots,j$ and distributed according to a Boltzmann law $\exp(-2m\mu H/kT)$. Moreover, the field will cause a perturbation of the local states:

$$E_m=\pm\lambda_m=\pm[\mu^2H^2+E_1^2+2\mu HE_1m/j]^{\frac{1}{2}}.$$

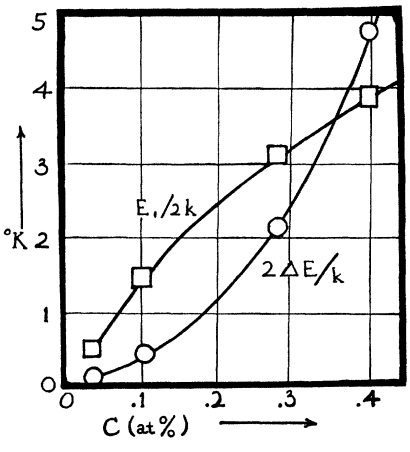


FIG. 1. Values of $E_1$ and $\Delta E$ as a function of $c$ deduced from the experiments with the use of formula (1).

A calculation of the spin part of the perturbed wave functions and of the transition probabilities for $\xi$ and $\eta$ electrons separately leads to:

$$\begin{aligned}
&-(\partial f_{\xi(\eta)}/\partial t)_{n.r.}=(f_{\xi(\eta)}-f_0)/\tau_{\xi(\eta)},\\
&1/\tau_{\xi(\eta)}=[N(\zeta_0)/4\pi^2\hbar]V_{ke}^4(P\pm Q);\\
&P=\Sigma_m(x^{2m}/\lambda_m^2)[1-f_0(-\lambda_m)f_0(\lambda_m)\\
&\quad-\tfrac{1}{2}\{f_0(-\lambda_m)-f_0(\lambda_m)\}\{f_0(-2\lambda_m)-f_0(2\lambda_m)\}]/\Sigma x^{2m},\\
&Q=\Sigma_m(x^{2m}/2\lambda_m^3)(\mu H+E_1m/j)\{f_0(-\lambda_m)-f_0(\lambda_m)\}\\
&\quad\times\{2-f_0(-2\lambda_m)-f_0(2\lambda_m)\}/\Sigma x^{2m}.
\end{aligned} \tag{2}$$

$N(\zeta_0)$ is the density of states at the Fermi level, $x=\exp(-\mu H/kT)$. For $H=0$, $Q=0$, $x=1$, and $\lambda_m=E_1$.

From (2) we find:

$$\begin{aligned}
&\sigma(H,T)=\tfrac{1}{2}(\sigma_\xi+\sigma_\eta)[1+\tfrac{1}{2}BH^2(\sigma_\xi^2+\sigma_\eta^2)]^{-1},\\
&\sigma_{\xi(\eta)}=(N_{\text{eff}}e^2/m_0)[1/\tau_{\xi(\eta)}+1/\tau_C+1/\tau_T]^{-1}.
\end{aligned} \tag{3}$$

$\tau_C$ and $\tau_T$ are the effective collision times for coulomb and temperature scattering ($\tau_\xi\approx\tau_C\ll\tau_T$ at low temperatures). $B$ is the coefficient determining the magnetoresistance of pure silver.

At low $H$ we find $\Delta R/R\approx a(T,c)H^2$, with $a<0$ for low $T$ and not too small $c$. At larger fieldstrength the $\Delta R/R$ *vs* $H$ curves show saturation. The sudden increase of $\Delta R/R$ at low $H$ for "large" $c$ (see Fig. II, 5 of reference 1, $c=0.61$ atomic percent) will be due to the conductivity of the local states. It can be shown that this becomes important for this magnitude of $c$; in a magnetic field the energy of the local states differs at different Mn ions, the electrons can no longer make transitions from one ion to another, and the corresponding term in the conductivity will decrease rapidly in a magnetic field.

A further consequence of this model is an anomalous specific heat:

$$\rho c_V=\tfrac{2}{3}\pi^2k^2TN(\zeta_0)-nE_1(d/dT)\tanh(E_1/2kT),$$

where $n$ is the number of Mn ions per unit volume. The local states could also lead to exchange interaction between the Mn ions; some of the irreproducible effects in the magnetoresistance, and the behavior of the susceptibility[4] seem to point to this direction.

A detailed account will be published in *Physica*.

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## Multiple Scattering of Electrons in Nuclear Emulsions*

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THE Fowler[1] method for deducing the momentum of a fast particle from its multiple coulomb scattering is highly useful in nuclear emulsion work and several preliminary calibration measurements have been reported.[2–4] Recently extensive calibration measurements have been reported,[5–8] among them an abstract[5] of the results recorded here.

The results are best presented in terms of multiple scattering theory, the Snyder and Scott[9] version being chosen as the most convenient here. Snyder and Scott give normalized distribution curves for the probability $W(\eta,z)$ that the particle will be scattered through an angle $\eta$ (projected on a plane) in traveling a distance $z$. $\eta$ is measured in terms of a unit angle $\eta_0$, which is a function of the atomic number of the scattering material and of the mass and energy of the particle. $z$ is measured in terms of the mean free path for scattering $\lambda$ which is a function of the atomic number of both the scatterer and the particle and of the particle's energy. Using Snyder and Scott's prescription for calculating these quantities, we find for singly-charged particles in Ilford G-5 emulsion that $\eta_0=1.39\,(m/\mu)(E^2-1)^{-\frac{1}{4}}$ degrees and $\lambda=0.160\,(E^2-1)/E^2$ mi-