in the beam so that the study of the most forward angles can be completed.

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Measurement of the Circular Polarization of Resonance-Scattered Gamma Rays Following the Electron Capture of Se^{75}†

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The circular polarization of the 265-kev γ rays following the mixed Gamow-Teller and Fermi electron-capture decay of Se^{75} into As^{75} has been measured. The neutrino momentum was fixed with the help of a resonance scattering process. From the experimentally determined degree of right-hand circular polarization of -0.21 ± 0.15 it was concluded that the sign of the Gamow-Teller to Fermi matrix-element ratio in this beta decay is negative.

I. INTRODUCTION

It is well known that the distribution of beta particles emitted with respect to the nuclear spin is of the form $(1+a\cos\theta)$ in an allowed nuclear beta decay. In a beta-decay process which preserves the nuclear spin, I, two types of beta transitions can occur, Fermi transitions (nonspin-flipping) and Gamow-Teller transitions (spin-flipping). In a mixed Gamow-Teller and Fermi transition the asymmetry coefficient a is strongly dependent on the interference between the two types of interaction. A large interference due to approximately equal contributions of both parts gives rise, in general, to a large asymmetry.

For this type of allowed transition the relative size of the Gamow-Teller and Fermi matrix elements can be estimated theoretically, with the help of nuclear models, and selection rules and wave functions based on them. For example, the isotopic spin selection rule $\Delta T=0$ for Fermi transitions will strongly suppress any Fermi contribution to a $\Delta T\geq1$ transition. However, more refined arguments taking into account isotopic-spin mixing of the (model dependent) nuclear wave functions due to Coulomb interactions show that Gamow-Teller and Fermi matrix elements may be present simultaneously. Theoretical estimates of these admixtures have been made for several cases.[1-3] In order to help achieve a better understanding of the details of nuclear coupling it seems worthwhile to obtain more experimental information on the relative signs and relative magnitudes of the Gamow-Teller and Fermi matrix elements in such transitions.

In the beta decay of initially unpolarized nuclei, a measurement of the degree of nuclear polarization (with respect to the electron momentum) *after* beta decay determines the asymmetry coefficient a. Experimentally, the polarization in the nuclear state produced by beta decay can be determined from a measurement of the degree of circular polarization of a subsequently emitted gamma ray, the polarization axis being fixed by counting the beta particles in a given direction. Experimental studies of such β-γ circular-polarization correlations have, in some cases, provided data on the Gamow-Teller to Fermi matrix-element ratio.[4-6]

An alternative experimental approach is also possible: instead of counting the electrons directly one can make use of the recoil momentum transferred to the nucleus as a consequence of beta decay. If certain momentum conditions are fulfilled a fluorescent scattering process can be produced. The direction in which the gamma ray capable of producing resonant excitation is emitted is then used as the polarization axis to determine the mean angle of emission of the lepton pair in beta decay, or the direction of the neutrino in an electron-capture process. If the circular polarization of the fluorescent-scattered gamma ray is also measured, the nuclear polarization can then be inferred. An experiment of this

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type was first successfully performed by Goldhaber et al.[7] with a different goal in mind.

We describe here an experiment of the recoil type on the As^{75} nucleus. The Se^{75} to As^{75} electron-capture decay is an allowed transition with no spin change. Our aim in this experiment is to find if the transition proceeds by a mixture of Fermi and Gamow-Teller matrix elements, and if so, to determine the relative sign and magnitude of this admixture.

II. DESCRIPTION OF THE EXPERIMENT

Data on the electron capture decay of Se^{75}, which has been extensively studied by many investigators, are summarized in the Nuclear Data Sheets.[8] For the following discussion we have adopted the decay scheme shown in Fig. 1 which is based on reference 8 and on other more recent work.[9–12]

Experimental data on the fluorescent scattering of $\mathrm{As}^{\cdot 5}$ γ rays are available owing to the excellent studies of Metzger[13] and Langevin-Joliot and Langevin.[14] These authors have studied the resonant excitation of As^{75} levels under various experimental conditions. For a gaseous source of SeH_2 at a pressure of about 0.1 atm—the source condition which we employ in the present experiment—Metzger and Langevin-Joliot and Langevin have observed a strong resonant scattering of the 265-kev γ ray and no detectable scattering of the 280- and 401-kev γ rays.

Consequently the experimental data indicate that only the following decay branch leads to resonant scattering:

$$5/2^{+}(\mathrm{E.C.},E_0)5/2^{+}(\gamma_1,E_1)3/2^{-}(\gamma_2,E_2)3/2^{-},$$

with $E_1=136$ kev, $E_2=265$ kev. A possible contribution of the 121 kev–280 kev cascade is discussed in Sec. IV.

We propose to measure the circular polarization of the second gamma ray, γ_2, in this branch after it has been resonant scattered at an As scatterer.

Let us consider first the recoil-momentum conditions necessary for a scattering process. The decay energy is known from studies of the reaction $\mathrm{As}^{75}(p,n)\mathrm{Se}^{75}$ [15] to be 864 kev, which corresponds to a neutrino energy, E_0, of 452 kev for K capture to the 401-kev state. Clearly the fluorescent scattering condition for γ_2, $E_0+E_1>E_2$, is fulfilled and resonance scattering can occur.

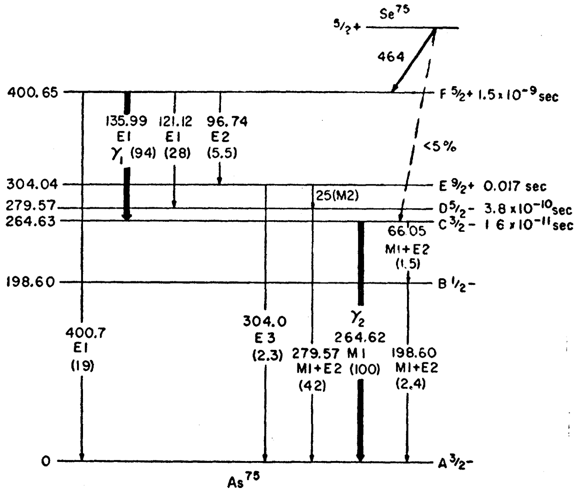

FIG. 1. Scheme of the electron-capture decay of Se^{75} into As^{75}. The gamma rays labelled γ_1 and γ_2 measured in the present experiment are indicated by heavy lines. Energies are in kev. The numbers in parentheses represent relative gamma intensities.

If we had only one gamma ray, γ, with an energy E_1 of 401 kev following the electron-capture, then the resonance condition would be simply $\cos\vartheta=-E_1/E_0$, where ϑ is the angle between the neutrino and the γ quantum. However, in the presence of two gamma rays, γ_1, and γ_2, the resonance condition becomes

$$E_0\cos\vartheta+E_1\cos\varphi+E_2=0, \tag{1}$$

where ϑ is the angle between neutrino and γ_2 and φ is the angle between γ_1 and γ_2. For each value of ϑ there is a value of φ in accordance with the resonance condition (1). We can express the resonance condition as a function of φ alone by writing

$$\mathrm{Max}\left[-1,\,-\frac{E_0+E_2}{E_1}\right]\leq\cos\varphi\leq\mathrm{Min}\left[+1,\,\frac{E_0-E_2}{E_1}\right]. \tag{2}$$

In the case of our experiment we have $(E_0-E_2)>E_1$ and the condition becomes extremely simple because $\cos\varphi$ can assume all values between $+1$ and -1.

We now have to calculate what the circular polarization of those γ_2 quanta capable of producing a resonant excitation should be. General formulae for the degree of circular polarization of the second gamma ray in a triple cascade through states with spins consecutively I_0, I_1, I_2, and I_3 have been derived by Morita[16]

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and Krüger.[17] For the present case, assuming pure multipoles L_2, L_3, Krüger's result is

$$W(\vartheta,\varphi)=[1+A_2P_2(\cos\varphi)]+[B_0+B_2P_2(\cos\varphi)]A\cos\vartheta, \quad (3)$$

where

$$A_2=F_2(L_1,L_1,J_1,J_2)F_2(L_2,L_2,J_3,J_2),$$

$$B_k=(-1)^{L_1}3(2L_1+1)[(2J_1+1)(2J_2+1)]^{\frac{1}{2}}\langle 1,0;\,1,0|k,0\rangle \times\langle L_1,1;L_1,-1|k,0\rangle\begin{Bmatrix}1 & J_1 & J_1\\ k & L_1 & L_1\\ 1 & J_2 & J_2\end{Bmatrix} \quad (k=0,2).$$

A is the coefficient for (β^-,γ)-circular polarization correlation such as quoted in reference 18

$$A=\tfrac{2}{3}F_1(L_2,L_2,J_3,J_2)\{F_1(1,1,J_0,J_1)x^2-F_1(0,1,J_0,J_1)x\}/(1+x^2), \quad (4)$$

where $x=|C_A/C_V|M_{\mathrm{GT}}/M_F=1.25M_{\mathrm{GT}}/M_{\mathrm{F}}$ is the ratio of Gamow-Teller to Fermi matrix elements.

Expression (3) becomes, after ϑ has been replaced by φ by virtue of (1) and the resulting expression has been averaged over-all values of φ,

$$\bar{W}=\langle W(\varphi)\rangle_{\mathrm{av}}=1-A(E_2/E_0)\times\frac{I_1(I_1+1)+I_2(I_2+1)-L_1(L_1+1)}{2[I_1(I_1+1)I_2(I_2+1)]^{\frac{1}{2}}}. \quad (5)$$

When this expression has been evaluated for the (E.C.,γ_1,γ_2)-cascade in As^{75}, the circular polarization of those γ_2 quanta capable of exciting resonance fluorescence is finally $\bar{W}=1-0.536A$.

It is interesting to notice that the averaging over the neutrino and γ_1 momenta reduces the corresponding result for a $(\beta^-,\gamma_{\mathrm{circ}})$ correlation only by a factor of about two.

III. EXPERIMENTAL TECHNIQUE

Source Preparation

The experimental conditions for fluorescent excitation of the 265-kev level have been investigated by Metzger[13] and Langevin-Joliot and Langevin.[14] Due to the relatively long lifetime of the 401-kev state ($\tau_{\frac{1}{2}}\cong 1.5\times 10^{-9}$ sec) it is imperative to use a gaseous source. Both authors have found that in order to preserve full recoil momentum the gas pressure should not exceed a few cm Hg. The gaseous compound of selenium chosen was SeH$_2$. SeH$_2$ has a boiling point of -42°C and has a molecular weight only a few percent higher than that of atomic selenium. In our experiment we used a pressure of 0.11 atm of SeH$_2$, which was an empirically determined compromise between source strength and signal-to-noise ratio in the resonance peak.

Se^{75} was prepared by irradiating selenium metal enriched (12.3%) in Se^{74} in the MTR reactor in Arco, Idaho. The source was prepared in the following way: 4.5 mg of irradiated selenium metal corresponding to about 170 millicuries radioactive Se^{75} was placed in a quartz capsule of $\sim$15 cc volume and attached to a vacuum system. The capsule was evacuated to $\sim 10^{-3}$ mm Hg, thereafter filled with hydrogen to a pressure of 0.11 atm and finally sealed. The reaction $\mathrm{Se}+\mathrm{H}_2\rightarrow\mathrm{SeH}_2$ was produced by heating the capsule in an oven at $\sim$800°C for two hours, after which time no evidence for unreacted Se was observed. The capsule was allowed to cool off slowly. The heating of the source was repeated every five days during the experiment because SeH$_2$ has a tendency to decompose slowly.

Experimental Setup

Figure 2 illustrates the experimental setup. The As scatterer consists of a hollow aluminum cylinder (0.5-mm aluminum), 1-inch thickness, 6-inches high, filled with powdered As metal. A Se scatterer with identical dimensions was made.

A comparison of the nonresonant Se^{75} spectra from the As and the Se scatterer was made using a nongaseous Se^{75} source. The spectra appeared to differ by about 6% in intensity. An appropriate correction was applied, therefore, to the resonant- to nonresonant scattering ratio in the actual experiment.

In order to minimize background it was important to eliminate as much as possible all mass surrounding the source and scatterer. The experiment was set up well above the floor in the center of a large room.

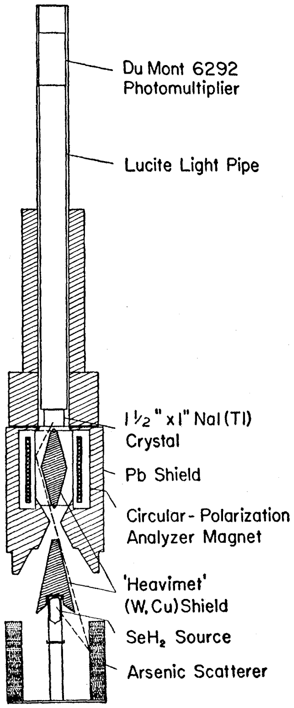

FIG. 2. Experimental arrangement for measuring the circular polarization of resonant scattered 265-kev γ rays in As^{75}.

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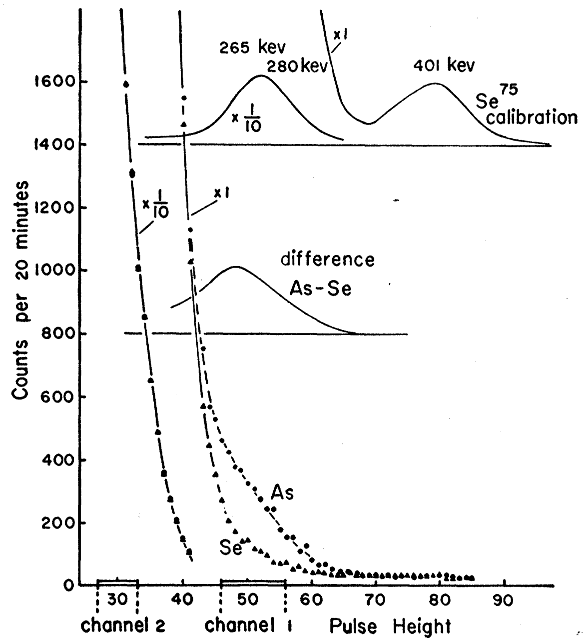

FIG. 3. Pulse distribution from the $Se^{75}H_2$ source. Curves labeled As and Se represent the pulse-height distribution after scattering from As and Se scatterer, respectively, followed by a scattering from the iron of the polarization analyzer. The difference between the As and Se curves is also shown. The setting of channel 1 and channel 2 during the experiment is indicated on the abscissa.

A cylindrically symmetric geometry was employed for the polarization analyzer. The analyzer magnet was similar to, though somewhat smaller than, the one used in reference.[4,18] The pulses from the NaI detector were fed into two single-channel analyzers, one accepting the Compton quanta due to the scattered 265-kev radiation, the other set to accept quanta below that energy. The position of these settings is shown in Fig. 3. The spectrum of the radiation Compton-scattered from the analyzer magnet for both the As scatterer and Se scatterer using a freshly prepared SeH_2 source is shown in Fig. 3. The resonant-to-nonresonant ratio in channel 1, $(N_{As}-N_{Se})/N_{As}$, which is the number of quanta due to the resonance scattering, divided by the total number of quanta, varied between 0.3 and 0.55 depending on the source condition. An unscattered Se^{75} gamma-ray spectrum is shown at the top of Fig. 3. The shift in energy of the 265-kev peak shown is in good agreement with the shift expected from the mean angle for Compton-scattering in the apparatus.

Data Taking

The magnetic field of the analyzer was changed every ten minutes during a run. At the end of each interval the counts in channel 1 and 2 were recorded automatically with a camera. The counting rates were such that from 2000 to 5000 and about 100 000 counts per 10 minutes were collected in channels 1 and 2, respectively. Averages were taken for the relative difference of counting rate with the As scatterer for field "up" and field "down," $(N\uparrow_{As}-N\downarrow_{As})/N_{As}$, for both channels. In the control channel 2 this difference was always zero within the error limits, indicating that no noticeable instrumental asymmetry such as might arise from the influence of the magnetic field on the counter was present. The relative difference obtained in channel 1, corrected for the nonresonant background, is a measure for the degree of circular polarization.

Three SeH_2 sources were prepared, each being used for a two-week run with the As scatterer. Every other day the nonresonant background was determined using the Se scatterer.

Efficiency of the Analyzer

In order to derive the degree of circular polarization from the measured asymmetry we have to know the "efficiency" of the analyzer defined as the percent counting rate difference for opposite magnetic fields for a 100% circularly polarized gamma ray. We have obtained a calibration curve for our magnet by using the bremsstrahlung of P^{32}. The degree of circular polarization as a function of the photon energy of the P^{32} bremsstrahlung can be computed readily from the formulas of McVoy.[19] We have calibrated the analyzer with 1300-kev and 800-kev bremsstrahlung quanta and extrapolated the efficiency curve with the help of the energy dependence from an equation similar to Eq. (1) in reference 18. For the 265-kev γ ray an efficiency $\epsilon=1.1\%$ with an estimated error of 0.1% is found.

IV. RESULTS AND CONCLUSION

The counting rate asymmetries in channel 1 and in channel 2 are summarized for the three experiments in Table I. With the help of the known magnet analyzer efficiency this asymmetry can be expressed in terms of the circular polarization of the γ_2 quanta after resonant scattering. We obtain an average value of $+0.175 \pm 0.125$ for this circular polarization from the three experiments. Taking into account that we have detected backward-scattered fluorescent quanta $(\cos\bar{\theta}=-0.82)$ we find for the circular polarization of γ_2

$$P_{\gamma 2}=\bar{W}-1=-0.21\pm 0.15.$$

This experimental result can be compared with the predictions from Eqs. (4) and (5).

TABLE I. $(N\uparrow_{As}-N\downarrow_{As})N_{As}$ corrected for nonresonant background.

	Channel 1	Channel 2
Experiment *A*	$+(0.182\pm 0.175)\%$	...
Experiment *B*	$+(0.142\pm 0.32)\%$	$+(0.032\pm 0.050)\%$
Experiment *C*	$+(0.287\pm 0.26)\%$	$+(0.016\pm 0.048)\%$

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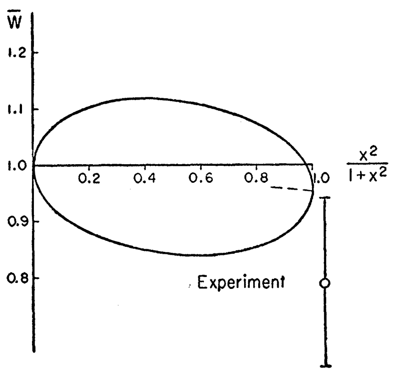

FIG. 4. Comparison of experimental and theoretical values of the circular polarization of the resonant scattered gamma rays. The ordinate represents the averaged angular distribution, $\overline{W}$, according to Eq. (5) and the abscissa is the relative contribution of Gamow-Teller interaction. The curve gives the theoretical values assuming a positive Gamow-Teller to Fermi matrix-element ratio (upper branch) and a negative ratio (lower branch).

Equation (5) gives the following explicit answer:

$$\overline{W}=1-0.536[0.0873(x^2+5.91x)/(1+x^2)].$$

If we plot $\overline{W}$ as a function of $x^2/(1+x^2)$, the fractional contribution of Gamow-Teller interaction, we obtain the curve reproduced in Fig. 4. The upper branch corresponds to positive values of x and the lower branch to negative values of x. The experimental point is also shown in this figure. We conclude from the experiment that x is negative and, therefore, $M_{\mathrm{GT}}/M_{\mathrm{F}}$ is negative, although we are aware of the relatively large experimental uncertainty.

Metzger[13] puts an upper limit of 4% to the fluorescent scattering contribution of the 280-kev line (see Fig. 1) with respect to the 265-kev line. For the 121 kev–280 kev cascade one finds $\overline{W}=1-0.554A'$. A' differs from A only by the F_1-coefficient of the second γ ray the ratio $F_1(1,1,\frac{3}{2},\frac{5}{2})/F_1(1,1,\frac{3}{2},\frac{3}{2})$ being 2.3. A 4% contribution of the 280-kev γ line would therefore result in an increase of the absolute value of the anisotropy curve of Fig. 4 of 10%, not affecting our conclusion.

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Radioactive Decay of Tm^{166}

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Erbium oxide enriched to 72.9% in the 166 mass number was irradiated with 6-Mev protons. An activity decaying by electron capture and positron emission with a half-life of 7.69±0.05 hours was produced by a (p,n) reaction and its assignment to Tm^{166} confirmed. The observed activity consists of the K x ray of erbium, gamma rays with energies of 81, 184, 289, 405, 460, 598, 674, 694, 707, 759, 782, 788, 878, 1052, 1179, 1276, 1351, 1589, 1874, and 2058 kev, annihilation radiation, and particle radiation with an end-point energy of 2090±40 kev. Gamma-gamma coincidence measurements and consideration of the energies and relative numbers of the observed radiations have led to the assignment or confirmation of energy levels at 81 (2+), 265 (4+), 554 (6+), 788 (2+), 863 (3+), 959 (4+), 1248 (2), 1317 (5), 1462 (0+), 1547 (3+), 1701 (4+), 1894 (5+), 2139 (3), and 2168 (0) kev in Er^{166}. The 2139-kev level is highly populated by electron capture and the positron transitions occur to the 265 (4+)-kev level. The positions of the observed radiations and the branching ratios of electron capture are shown in a proposed energy level scheme.

INTRODUCTION

An activity decaying 99+% by electron capture and <1% by positron emission with a half-life of 7.7 hours has been assigned to Tm^{166}.[1] Gamma radiation of approximately 1.7 Mev was detected in this activity and the positron end-point energy was found to be 2.1 Mev. Conversion electron measurements following the proton irradiation of natural ytterbium oxide have led to the assignment of transitions with energies of 80.7, 154.6, 184.7, 194.8, and 215.4-kev and to the postulation of energy levels of 81 (2+) and 265 (4+) kev in Er^{166}.[2] One group of workers has reported gamma rays in this activity with energies of 80, 180, 670, 800, and possibly 1320 kev.[3] Another group has reported gamma rays with energies of 80, 180, 690, and 780 kev in this activity and have postulated an energy level of 780 kev (2+) in addition to the 265 (4+)- and 81 (2+)-kev levels.[4] The assignment of an 80.6-kev level resulted

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