Isospin Conservation and β-γ Circular-Polarization Correlation in Mixed Transitions*

STEWART D. BLOOM, LLOYD G. MANN, AND JOHN A. MISKEL
Lawrence Radiation Laboratory, University of California, Livermore, California
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Measurements have been made of the β-γ circular-polarization correlation parameter A in the β decays of Na^{22}, Co^{60}, Na^{24}, Ar^{41}, Sc^{44}, Sc^{46}, and Mn^{52}. Of these seven radioisotopes the first two are pure Gamow-Teller ($\Delta J=1$) transitions and therefore are expected to have values of $A=+\frac{1}{3}$ and $-\frac{1}{3}$, respectively. This expectation is well verified in the present work (in conformity with previous findings), and hence the use of these sources as standards to compare with the remaining five cases is justified. The other five nuclides involve mixed transitions ($\Delta J=0$, $J\neq 0$) and may therefore exhibit Fermi contributions to the extent that isospin conservation, which requires $\Delta T=1$, is violated. The experimental technique used here was the now standard one of scattering the γ rays from a cylinder of magnetized iron and then measuring the coincidence rate between β rays and γ rays as a function of the direction of magnetization. An added feature of the present method was the data sampling technique (*rapid alternation*) wherein the magnetic field direction was reversed every 8 sec in order to obviate the effects of instrumental instabilities. Such effects are of paramount importance in this experiment because the quantities measured differ by less than 1%.

The results obtained for the asymmetry parameter A were 0.085 ± 0.027 for Na^{24}, 0.061 ± 0.070 for Ar^{41}, -0.151 ± 0.030 for Sc^{44}, 0.075 ± 0.018 for Sc^{46}, and -0.089 ± 0.028 for Mn^{52}. The results on Na^{22} and Co^{60} are equal in magnitude within 5%. These results are consistent in all cases with a zero or near-zero Fermi matrix element, the value for the ratio $|C_V M_V/C_A M_A|$ being always less than ≈ 0.04. This finding is in strong disagreement with most previous experimental results, particularly in the cases of Ar^{41}, Sc^{44}, and Sc^{46}. However, the tenor of the present results is quite consistent with the conserved vector-current theory of Feynman and Gell-Mann. Thus support is lent to the idea of a universal weak-interaction form constructed from general charge and current conservation laws, at least in the cases of the electromagnetic and β-decay Hamiltonians.

The spins of some of these nuclides receive additional support from the present results. A spin of $\frac{5}{2}$ or $\frac{9}{2}$ for the state at 1.29 Mev in K^{41} would imply $A=-0.33$ or $+0.38$, respectively, and is definitely ruled out. Similarly all spins except 4 may be ruled out for Sc^{46} and all spins except 2 for Sc^{44} and the state in Ca^{44} at 1.16 Mev. (The spin of Sc^{44} has previously been measured directly by Harris and McCullen.)

I. INTRODUCTION

FOR the past two years a series of measurements of the angular correlation between β rays and circularly polarized γ rays in various radiosotopes has been in progress at this laboratory. Some report of this work has already been made.[1,2] The method used is essentially the same as described by Schopper[3] in his review article and consists, in brief, of the measurement of the change in coincidence rate between electrons and γ rays in a β-γ cascade for two orientations of a γ-polarimeter. The polarimeter in this case is a magnetized iron scatterer and its two orientations are simply opposite directions of magnetization (see Fig. 1). A detailed description of the present method is given in the next section. This description will include a discussion of our data sampling technique (*rapid alternation*) which constitutes an important part of our approach to this kind of measurement.

Theoretical expressions for the β-γ circular-polarization angular correlation are given in several references for various special assumptions.[4–7] However, a complete formula for allowed transitions where *no* limiting conditions are imposed, such as time-reversal invariance or particular spin sequences, has never been published. Therefore we present here a more general formula than has appeared hitherto for the asymmetry parameter A in

$$W(\theta_{\beta-\gamma})=1+\tau(v/c)A\cos\theta, \tag{1}$$

the expression for the angular correlation between the electron and the photon in an allowed β-γ cascade. In Eq. (1), τ represents the sense of circular polarization of the detected γ ray, being (as is now customary[1,4]) $+1$ for photons of positive helicity; v/c is the ratio of the velocity of the detected β particle to the velocity of

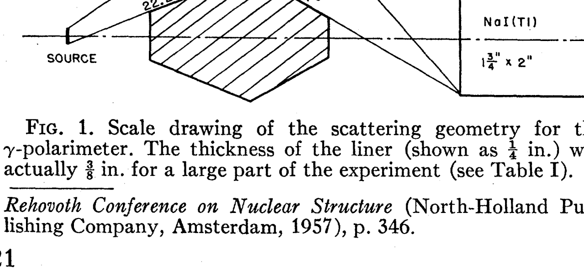

FIG. 1. Scale drawing of the scattering geometry for the γ-polarimeter. The thickness of the liner (shown as $\frac{1}{4}$ in.) was actually $\frac{3}{8}$ in. for a large part of the experiment (see Table I).

* Work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] S. D. Bloom, L. G. Mann, and J. A. Miskel, Phys. Rev. Letters **5**, 326 (1960).
[2] S. D. Bloom, L. G. Mann, and R. J. Nagle, Bull. Am. Phys. Soc. **6**, 334 (1961); see also L. G. Mann, S. D. Bloom, and R. J. Nagle, Nuclear Phys. (to be published).
[3] H. Schopper, Nuclear Instr. **2**, 158 (1958).
[4] K. Alder, B. Stech, and A. Winther, Phys. Rev. **107**, 728 (1957).
[5] Y. V. Gaponov and V. S. Popov, Nuclear Phys. **4**, 453 (1957).
[6] J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Phys. Rev. **106**, 517 (1957).
[7] Other references may be found in C. S. Wu, *Proceedings of the Rehovoth Conference on Nuclear Structure* (North-Holland Publishing Company, Amsterdam, 1957), p. 346.

light; $\theta_{\beta\text{-}\gamma}$ is the angle between the β and γ particles; A is the asymmetry parameter for which we give the following general expression (for electrons),

$$A=\frac{\sqrt{3}}{6}\sum_{\lambda\lambda'}\delta_\lambda\delta_{\lambda'}F_1(\lambda,\lambda',I_{ff},I_f)\left[\frac{I_f(I_f+1)-I_i(I_i+1)+2}{[I_f(I_f+1)]^{\frac{1}{2}}}\left|\int\beta\boldsymbol{\sigma}\right|^2(C_TC_T'^*+C_T^*C_T'-C_A^*C_A'-C_AC_A'^*)\right.$$
$$\left.-4\left|\int\beta\right|\times\left|\int\beta\boldsymbol{\sigma}\right|\mathrm{Re}(C_SC_T'^*+C_S'C_T^*-C_VC_A'^*-C_V'C_A^*)\right]\left\{\sum_\lambda|\delta_\lambda|^2\left[\left|\int\beta\right|^2(C_S^2+C_S'^2+C_V^2+C_V'^2)\right.\right.$$
$$\left.\left.+\left|\int\beta\boldsymbol{\sigma}\right|^2(C_T^2+C_T'^2+C_A^2+C_A'^2)\right]\right\}^{-1}. \quad (2)$$

The notation used in Eq. (2) is identical with that of Alder, Stech, and Winther.[4] In fact, Eq. (2) is simply a generalization of their Eq. (7) to include the possibilities of A (axial-vector) and V (polar-vector) couplings. Equation (1) with Eq. (2) now describes the angular correlation in an allowed β-γ sequence where the β decay can be due to all four couplings, S, V, T, and A, and the γ is also an arbitrary mixture of many multipoles (λ) of radiation. However, it is important to note that Eq. (2) is still not the most general form possible since only 20 coupling constants (if we include the noncontributing pseudoscalar terms in our count) are apparently required to specify A. Actually, if lepton conservation, implicitly assumed in (2), is dropped, 40 coupling constants are required. However, as far as is known no serious attempt at data analysis has yet been made with this completely unrestricted formulation of β decay.

Equation (2) applies only to electrons; the following changes are required for positron decay:

$$\begin{aligned} &C_S\to -C_S^*, && C_P'\to +C_P'^*,\\ &C_S'\to +C_S'^*, && C_V\to -C_V^*,\\ &C_T\to +C_T^*, && C_V'\to +C_V'^*, \qquad (3)\\ &C_T'\to -C_T'^*, && C_A\to +C_A^*,\\ &C_P\to -C_P^*, && C_A'\to -C_A'^*. \end{aligned}$$

The use of the whole system of Eqs. (1)–(3) in a complete analysis of all available data presents a tedious prospect, to say the least. However, the Feynman—Gell-Mann[8] theory of a universal Fermi interaction in β decay eliminates all S and T contributions, equates C_A to C_A' and C_V to C_V', and requires all four of these to be equal in absolute magnitude. The results of the various measurements on helicity and angular distribution of electrons and neutrinos,[7,9] in addition, require that C_A equal $-C_V$. Equation (2) then reduces to,

$$A=\mp\frac{\sqrt{3}}{6}\sum_{\lambda\lambda'}\delta_\lambda\delta_{\lambda'}F_1(\lambda,\lambda',I_{ff},I_f)\left\{\frac{I_f(I_f+1)-I_i(I_i+1)+2}{I_f^{\frac{1}{2}}(I_f+1)^{\frac{1}{2}}}\right.$$
$$\left.\times|M_{\mathrm{GT}}C_A|^2\pm4|M_{\mathrm{GT}}|\,|M_{\mathrm{F}}|\,\mathrm{Re}(C_VC_A)\right\}$$
$$\times\{\sum_\lambda|\delta_\lambda|^2[|M_{\mathrm{F}}C_V|^2+|M_{\mathrm{GT}}C_A|^2]\}^{-1}, \quad (2')$$

where the upper signs refer to β^- decay and the lower to β^+ decay. In Eq. (2′) we have replaced $\int\beta$ and $\int\beta\boldsymbol{\sigma}$, the expressions used in (2) for the Fermi and Gamow-Teller nuclear matrix elements, respectively, with the symbols M_{GT} and M_{F}. As is the habit nowadays, it is Eq. (2′) to which we refer throughout this work since the bulk of all experimental evidence[9] heavily supports the (A-V) description for the β-decay interaction Hamiltonian. We have left C_A and C_V explicitly indicated in Eq. (2′) because of certain effects (discussed below) which might destroy the relationship predicted for them in the Feynman-Gell-Mann theory. Also time-reversal invariance[9] will be assumed henceforth, making all the coupling constants real.

The principal incentive for the work to be described here has been the investigation of the validity of the isospin conservation law in β decay. The form of this law, which distinguishes Gamow-Teller and Fermi transitions, is exactly the same in isospin space as the analogous law in angular momentum space:

Gamow-Teller transitions, $\Delta T=0$ or 1;

Fermi transitions, $\Delta T=0$.

In the case of J space (J=angular momentum) the selection rules are rigorous for allowed transitions, but the effect of neutron-proton charge and mass differences makes the selection rule in T space (T=total isospin) only approximate. However, under certain assumptions the degree of their breakdown should be calculable. The nature of these assumptions has been described in a few

[8] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[9] M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. **120**, 1829 (1960).

recent theoretical treatments.[10–12] In brief, the considerations involved are as follows: All β decays, except for superallowed mirror transitions ($\Delta T=0$, $T=\frac{1}{2}$), generally involve a $\Delta T=1$. In this case Fermi contributions to the β decay can arise from two possible sources in general: (I) The differences in mass and charge between neutron and proton already mentioned above, and (II) β-decay events connected with the virtual meson states of the nucleons involved. In the conserved vector-current theory[8] these effects can be expressed completely[10,11,13] in terms of the isospin impurities introduced by (I) into the nuclear wave functions, the contribution of (II) being then identically zero. It is therefore clear that there exists here a possibility of testing at least partly the very interesting concept of a universal Fermi interaction if one can calculate the effects due to (I) with sufficient accuracy. Until now the detailed comparison of theory and experiment, certainly as far as actual values for A are concerned, has not been particularly encouraging.[10–12] However, size limits on the magnitude of interference terms due to effect (I) alone make it extremely difficult to explain the existence of Fermi matrix elements $|M_{\mathrm{F}}|\gtrsim 0.01$, that is, $\gtrsim 0.1 M_{\mathrm{GT}}$. Thus some of the published findings[14–20] in the cases of Sc^{46}, Mn^{52}, Sc^{44}, and Ar^{41}, where these limits are apparently exceeded, imply the necessity of invoking effect (II), which would invalidate the idea of a conserved vector current in β decay.[8,11–13] The importance of checking these adverse findings hardly needs comment because of the attractive simplicity of the Feynman-Gell-Mann theory and its apparent success in other respects. Accordingly we have conducted a reinvestigation of the three nuclides mentioned above as well as several others (see below) by using the technique of rapid alternation plus calibration interlacing of "standard" sources, Co^{60} and Na^{22}. Our first published results,[1] on Sc^{46} and Ar^{41}, were in sharp disagreement with all other measurements up to that time[14–17,20] in that our findings indicated $M_{\mathrm{F}}\approx 0$. The previous measurements had indicated $M_{\mathrm{F}}\gtrsim 0.2$. In the case of Ar^{41}, theoretical considerations again[21] make it difficult to explain as large an interference term as indicated by the work of Mayer-Kuckuk, *et al.*[20] if one is confined to mass and charge differences between the proton and neutron. The present work extends the original scope[1] by three more nuclides as well as incorporating a considerable number of technical improvements discussed below. As will be seen, in no case is evidence found (at this laboratory) for a Fermi matrix element exceeding a few percent, at most, of the Gamow-Teller matrix element.

II. EXPERIMENTAL TECHNIQUES

In our experiment the circular polarization of γ rays is detected by means of the dependence of the Compton scattering cross section on the polarizations of the γ ray and the electron.[22,23] This was done by using magnetized iron in a cylindrical design (Fig. 1) similar to that used by several other investigators[22,3] as a source of partially polarized electrons. The change in the theoretical scattering cross section for 100% polarized γ rays is approximately 7% when the magnetic field is reversed. The magnetized scattering cylinder was made rather thin in an attempt to minimize multiple scattering effects. Gamma rays which penetrate the iron cylinder are prevented from scattering off the copper coil and reaching the γ-ray detector by means of an air gap between the cylinder and the coil and by placing lead shielding between the coil and the γ-ray detector. The magnet design is as small as possible in order to maximize the γ-ray solid angle. This small size demands correspondingly small sources ($\frac{3}{16}$-in. diameter) and careful positioning to assure optimum shielding of the γ-ray detector from direct radiation. It turns out that a somewhat larger design utilizing a thick scattering cylinder[3] (or a larger air gap) would be desirable from the point of view of reducing the γ rays which reach the detector by paths that do not involve scattering from polarized electrons. However, our magnet is ideal from the standpoint of power requirements and the demands of the rapid alternation system to be described.

The technique used for obtaining data is indicated by the block diagram shown in Fig. 2. The objective is to

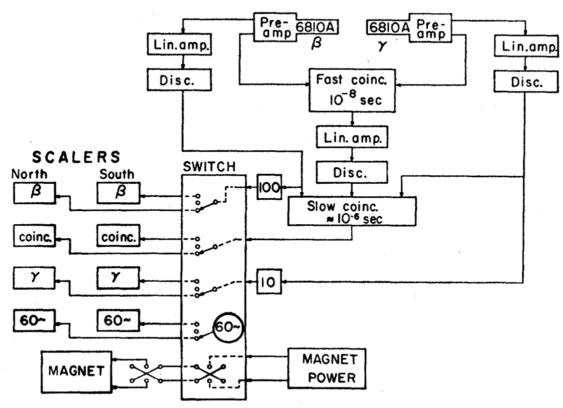

FIG. 2. Electronic schematic for the rapid alternation technique. The "switch" shown was actually a transistorized circuit (see text).

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[11] C. C. Bouchiat, Phys. Rev. **118**, 540 (1960).
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[17] R. M. Steffen, Phys. Rev. **115**, 980 (1959).
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[22] L. W. Fagg and S. S. Hanna, Revs. Modern Phys. **31**, 711 (1959).
[23] H. A. Tolhoek, Revs. Modern Phys. **28**, 277 (1956).

measure the difference in β-γ coincidence rates for opposite directions of the magnetic field, assuming this difference is all due to a change in the Compton scattering cross section. (In general, instrumental effects may also affect the coincidence rates.) Due to background effects this difference is only of the order of $\frac{1}{2}\%$ or less in our equipment. Therefore it is necessary to reduce instrumental drifts to the absolute minimum.

Early in our experiment attempts were made to record data and reverse the magnetic field periodically at intervals of 2 to 4 min. However, it was not possible to obtain consistent results with this method, which was tried with Co^{60} and Ar^{41}. The results were especially bad with Ar^{41}, possibly because of the short half-life of this radioisotope. In this method of operation, which has been the standard approach heretofore, the data from each 4-min period were transferred (in our case) to IBM cards. Then the coincidence rate, corrected by division by the product of the singles rates, was calculated for each card. These rates were finally combined to give the percentage difference between the north- and south-field coincidence rates.

This method will give the correct answer provided the following two conditions are fulfilled: The coincidence rate must be linearly proportional to the singles rates for small changes in the singles, and the explicit time dependence of the coincidence rates (due to drifts in the coincidence circuit itself, for example) must be negligible compared to the true effect expected for times of the order of the switching period. We suspect that the second condition at least was not satisfied for our apparatus. We therefore attempted to develop a technique in which it is virtually impossible for any difference whatever to exist in the equipment between the "north" field data and the "south" field data (except for the field direction), by drastically reducing the cycling period. Thus successive north- and south-field datum points are brought so close together in time that there is no chance for slow drifts in either the gains or the (common) coincidence efficiencies to cause a significant change in the rates. Occasional large discontinuous changes are also rendered harmless (if they occur) because the transition affects only one or a few datum points, and in this method one datum point has a completely negligible effect on the results. (There are approximately 6000 cycles during a 24-hr period, so that one cycle contributes $\approx 0.015\%$ of the data obtained each day.) The assumption that significant drifts between successive datum points are eliminated also greatly simplifies the data reduction. Since there is then no reason to calculate the rates during each cycle, it is only necessary to total all the north-field coincidences and all the south-field coincidences, correct by the total singles counts, and compute the fractional difference in the totals. Only a few minutes of hand calculations are required at the conclusion of each run.

The advantages of this type of operation, which we have called *rapid alternation*, can be clarified by the following argument. To avoid *both* statistical and instrumental drift errors two criteria must be satisfied: (1) The total number of *counts* must be large enough to achieve the desired statistical accuracy. (2) The total number of *cycles* must be large enough so that drift effects which occur in each single cycle will average statistically to an acceptably small value. (We assume there is no systematic relation between the drift effects and the field direction.) In our data the number of coincidences per cycle ranges from ≈ 10 to ≈ 100, giving statistical errors of 10 to 30%. Since the error occurring during a period of 8 sec due to all other effects will obviously be small compared with this, both of the above conditions are automatically satisfied by the time sufficient statistical accuracy has been achieved.

The block diagram of Fig. 2 shows a fast-slow coincidence circuit,[24] a transistorized multicircuit switch to control the storage of pulses and the direction of the magnetic field, and scalers which store the data. Data associated with opposite field directions are stored in separate banks of scalers. The switching period is controlled by a free-running relaxation oscillator. This avoids any possible synchronization between the switching period and the 60-cps pulses used to monitor time.

Approximately 0.7 sec is required for the field to reverse direction and build up to saturation. During this period pulses are not admitted to either set of scalers. As a compromise between rapid alternation and a high duty cycle we have used a half-cycle period of 8 sec which includes 1.2-sec dead time during the magnet reversal.

Our first switch, which was used for the data on Ar^{41} and Sc^{46}, consisted of relays. Because of occasional breakdown of the relay contacts this switch was replaced by a transistor circuit. The magnet current of 0.9 amp is easily controlled with transistors, and greater speed of the switching action (10 μsec) insures simultaneity of operation of each circuit.

Because of the importance of avoiding any systematic differences between the north-field equipment and the south-field equipment it is desirable in this work to use the same equipment for both sets of data. Our use of two separate banks of scalers violated this principle and introduced special problems. It was found by paralleling the inputs of each north-south pair of scalers and running the switch normally that the numbers obtained were not identical and frequently differed by more than the permissible 0.01%. This is due to the fact that the dead times associated with each scaler input differ somewhat; the effect is far worse at high counting rates. This difficulty was completely removed by introducing a common scale of 100 before the beta switch and a common scale of 10 before the gamma switch. The use of these prescalers cannot prejudice the results of the experiment, because it can be proved

[24] Designed by H. I. West. See H. I. West, L. G. Mann, and R. J. Nagle, Phys. Rev. 24, 527 (1961).

that their average output rates during one half-cycle are always proportional to the input rate during that half-cycle. The possibility of systematic errors is further reduced by the external reversing switch shown in the magnetic circuit. By periodically reversing this switch (about once a day) we store the "north" counts in the left-hand set of scalers half of the time and in the right-hand scalers the other half of the time, so differences in the scalers should cancel out completely. Finally, each scaler shown in Fig. 2 consists of a pair of identical scalers with parallel inputs to eliminate the possibility that a single scaler failure may go undetected.

Lucite light pipes of $\approx$10-inches length and solenoidal bucking coils are used to reduce the magnetic field at the photomultipliers. The change in counting rates is normally only a few hundredths of one percent when the field is reversed. Typical counting rates have been 10^6 to 5×10^6 betas/min, 10^4 to 10^5 gammas/min, and 100 to 1000 coincidences/min. The accuracy of the system has been tested on numerous occasions by replacing the magnet with a dummy resistive load and comparing the north and south data during an otherwise normal run. In these tests both the singles rates and the coincidence rates have invariably agreed within the statistical accuracies. The singles have been checked to better than 0.01% in this way. The 60-cps monitor counts agree within 0.01% at the end of each 24-hr period at least 9 times out of 10. The difference is always corrected in the calculations, although it is always negligible.

III. SOURCES

Our sources have all been of the order of 25 μC in strength. Co^{60} and Sc^{46} were obtained from the Oak Ridge National Laboratory; Na^{22} was obtained from the Nuclear Science and Engineering Corporation. Mn^{52} and Sc^{44} were produced in the Crocker Laboratory 60-in. cyclotron at Berkeley by the reactions $Cr(p,n)Mn^{52}$ and $K(\alpha,n)Sc^{44}$, respectively. Carrier-free samples of each isotope were obtained by standard radiochemical procedures. Ar^{41} and Na^{24} were produced in the Livermore Pool Type Reactor by neutron capture in natural argon and NaF. These sources were transferred directly to our source holders.

Most of the sources were mounted on uncoated Mylar films of $\approx$1 mg/cm^2. These sources were deposited by solution evaporation. The Na^{22} source and some of the Sc^{46} sources were deposited on aluminum of 3.5 mg/cm^2 by evaporation from a hot filament in vacuum. These sources are completely free from lumps and are among the thinnest we have produced. The Ar^{41} was transferred by means of a Töppler pump into a cylindrical source holder $\frac{1}{2}$-in. long by $\frac{3}{8}$-in. in i.d. The walls were $\frac{1}{16}$-in. Pyrex and the ends were aluminum foils of 7 mg/cm^2. The larger amounts of material involved in the structure of the Ar^{41} source are of no particular consequence because of the comparatively high β energy (1.24 Mev) characterizing this nuclide.

The gamma spectra and decay curves (over several half-lives) of all sources were examined in order to detect the presence of any radioactive impurities. No appreciable impurities were found.

IV. RESULTS

At the beginning of this work it was decided to compare all our measurements with Na^{22} and Co^{60} so that an absolute calculation of the magnet polarization efficiency would not be necessary. We assume that the magnitude of the asymmetry parameter for each of these pure Gamow-Teller decays is $\frac{1}{3}$. The support for this assumption is now very good both on theoretical grounds[8] and experimentally.[9] It is then only necessary to rely on an approximate calculation of the rather slow dependence of polarization efficiency on γ-ray energy. However, the absolute efficiency calculation has also been made and agrees with the observed results for Na^{22} and Co^{60} within 10%. The Na^{22} and Co^{60} sources were used as standards throughout the work and were remeasured as nearly simultaneously with each new source as possible. The fluctuations among all these data have been $\lesssim$5%.

The data are given in Table I. Those in the top section of the table were obtained using a scattering cylinder of $\frac{3}{8}$-in. thickness and those in the bottom section with a cylinder of $\frac{1}{4}$-in. thickness. All of the data obtained on a given nuclide have been added together, since in general more than one source of each nuclide was measured.

The raw effect, which is the difference between the "north" and "south" coincidences divided by their sum, is given with the statistical error only. Several correction factors and their product, f_T, which is the total correction, are listed in the next columns. It is easy to see that most of these corrections are either so small that only an approximate determination is necessary, or else they are easily determined with high accuracy. All of the factors f_{PE} and f_{BS}, the corrections for energy dependence of the polarimeter efficiency and backscattered electrons, are in the former category except for Ar^{41}. The correction f_{PE} is based on a calculation using the polarization-dependent Compton scattering cross section. For Ar^{41} the large value of f_{BS} arises because of electron scattering from the Pyrex walls of the source holder. The rather crude assumption was made that scattered electrons are associated with completely nonpolarized γ rays. This scattering was measured by placing point sources of Na^{24} at various positions inside a dummy source holder and observing the change in beta counting rates when the source holder was removed. The beta spectrum of Na^{24} is quite similar to that of Ar^{41}. The correction f_{BS} for Sc^{46} is due almost entirely to one of the sources that was mounted on thick carbon.[1] The factor f_{VC}, the ratio of the speed of light to the average speed of the detected electrons, is calculated using the theoretical beta spectrum and the beta

TABLE I. Experimental results for A, the β-γ circular-polarization correlation parameter. The results are presented in two blocks because two separate series of measurements were conducted. The first (Na^{22}, Co^{60}, Mn^{52}, Na^{24}, and Sc^{44}) was done using a $\frac{3}{8}$-in. iron liner-scatterer (see Fig. 1). The second (Na^{22}, Co^{60}, Sc^{46}, and Ar^{41}) was done using a $\frac{1}{4}$-in. liner, and actually preceded the first (see reference 1). The correction factors in columns (3) through (9) take account of the following phenomena: (3) f_{PA}, annihilation radiation coincidences; (4) f_{PE}, change in magnetic polarization efficiency with γ energy; (5) f_{BS}, beta backscattering from source mounting material; (6) f_{VC}, polarization dependence on β-ray velocity; (7) f_{RC}, random coincidences; (8) f_{GG}, gamma-gamma coincidences; (9) f_{NP}, real coincidences produced by scattering from nonpolarized material. f_T is the product of all seven of these correction factors. Column (2), the raw effect measured (actually divided by 2 in our presentation), goes into column (11) via multiplication by f_T. Column (12) averages the A_r (relative asymmetry parameter) of Na^{22} and Co^{60} together under the assumption that both of these must correspond to an absolute value, $A=\frac{1}{3}$. Also column (11) reflects the statistical inaccuracy *plus* the inaccuracy in f_{NP}, our most uncertain correction factor ($\pm15\%$), except in the cases of Na^{22} and Co^{60}, which (relative to each other) are presumed to have the same f_{NP}. This total uncertainty is necessarily passed on to the final measured value for A in column (14). Column (13), the calculated value of A_r (normalized at the Co^{60} gamma energy), is regarded as correct to about $\pm15\%$.

Source (1)	Raw Effect[a] $\frac{Nn-Ns}{Nn+Ns}$ (%) (2)	Individual Correction Factors f_{PA} (3)	f_{PE} (4)	f_{BS} (5)	f_{VC} (6)	f_{RC} (7)	f_{GG} (8)	f_{NP} (9)	Total Correction f_T (10)	Relative Asymmetry Parameter A_r (11)	Average[b] A_r (12)	Calculated A_r (13)	Absolute Asymmetry Parameter[b] A (14)
Na^{22}	$+0.336\pm0.017$	1.00	0.98	1.01	1.28	1.12	1.06	1.55	2.33	$+0.78\ \pm0.04$	0.77 ± 0.10	0.80	$\frac{1}{3}$
Co^{60}	-0.241 ± 0.012	1.00	1.00	1.01	1.49	1.10	1.23	1.55	3.16	$-0.76\ \pm0.04$			
Mn^{52}	-0.071 ± 0.019	1.00	0.91	1.01	1.29	1.18	1.41	1.50	2.96	-0.210 ± 0.066	...	...	-0.091 ± 0.028
Na^{24}	$+0.105\pm0.030$	1.00	0.84	1.00	1.16	1.05	1.08	1.70	1.88	$+0.197\pm0.064$	...	...	$+0.085\pm0.027$
Sc^{44}	-0.191 ± 0.028	1.07	1.08	1.02	1.10	1.07	1.01	1.30	1.82	-0.348 ± 0.072	...	...	-0.151 ± 0.030
Na^{22}	$+0.319\pm0.036$	1.00	0.98	1.01	1.29	1.11	1.06	1.60	2.40	$+0.77\ \pm0.09$	0.76 ± 0.10	0.80	$\frac{1}{3}$
Co^{60}	-0.226 ± 0.017	1.00	1.00	1.01	1.52	1.10	1.22	1.60	3.30	$-0.75\ \pm0.05$			
Sc^{46}	$+0.057\pm0.011$	1.00	1.08	1.06	1.47	1.16	1.10	1.40	3.01	$+0.171\pm0.041$	...	...	$+0.075\pm0.018$
Ar^{41}	$+0.06\ +0.07$	1.00	0.98	1.30	1.11	1.00	1.00	1.60	2.26	$+0.14\ \pm0.16$	...	...	$+0.061\pm0.070$

[a] Statistical errors.
[b] Total error including 15% error in f_{NP}.

detector energy threshold. The correction f_{RC} for accidental coincidences is measured by inserting an artificial delay in one leg of the coincidence system; where several sources of a given nuclide were measured a properly weighted average value of f_{RC} has been entered in the table. The correction f_{GG} for γ-γ coincidences is measured by placing a beta absorber in front of the beta counter. In this measurement a small ($\lesssim10\%$) correction was made for the change in dead time losses of the beta counter when the electrons were removed. The factor f_{PA}, which corrects for positron annihilation radiation, was appreciable only for Sc^{44} where the γ-ray discriminator setting (at 540 kev) was not high enough to reject all annihilation radiation. The correction was determined by measuring the coincidence rate with Cu^{64}, which emits positrons but no coincident γ rays. For our other positron emitters the γ-ray discriminator was set at 670 kev, well above the energy of annihilation radiation.

The correction f_{NP} arises because some γ rays reach

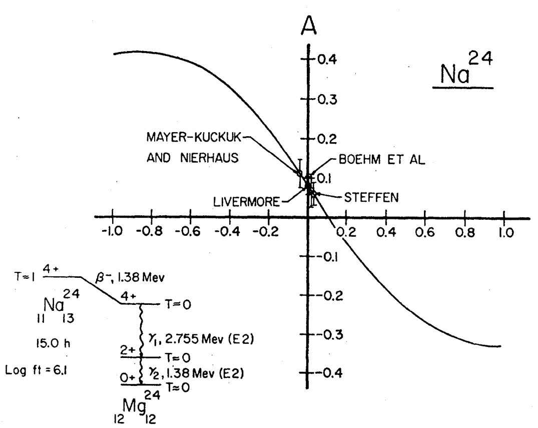

FIG. 3. Asymmetry parameter A vs $C_VM_V/C_AM_A\equiv y$, in the case of Na^{24}. The solid curve is theoretically computed assuming the $(A$-$V)$ form for the β-decay interaction Hamiltonian with time-reversal invariance [see Eq. (2′)].

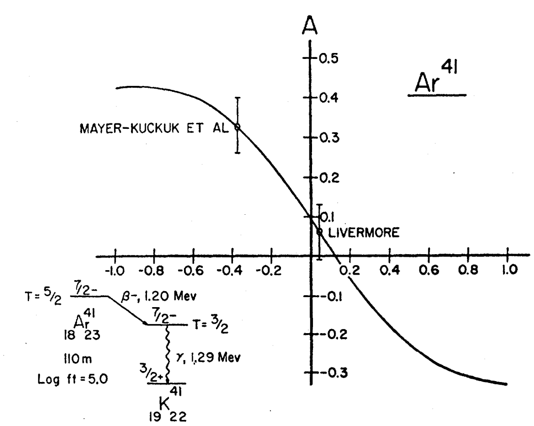

FIG. 4. A vs y in the case of Ar^{41}. The solid curve is computed under the same assumptions as in Fig. 3. These data definitely rule out the possibility of spin $\frac{5}{2}$ or $\frac{3}{2}$ for the excited state in K^{41} at 1.29 Mev, since the expected values for A would then be -0.33 or $+0.38$, respectively.

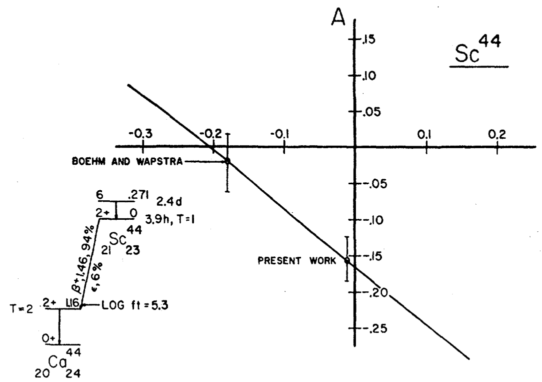

FIG. 5. A vs y in the case of Sc^{44}. The solid curve is computed under the same assumptions as in Fig. 3.

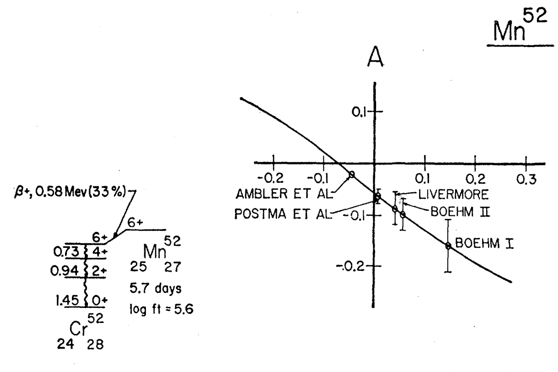

FIG. 7. A vs y in the case of Mn^{52}. The results of Ambler *et al.*[25] and Postma *et al.*,[26] obtained by looking at the anisotropy of β emission from oriented nuclei, have been converted to the corresponding values they imply for A, the β-γ asymmetry parameter. The solid curve was computed as in Fig. 3.

the detector without having scattered from the magnetized iron. This effect is enhanced by the small size of our magnet and the relatively thin scattering cylinder. It was measured in two ways. In one method the entire magnet was replaced by an iron cylinder similar to the one in the magnet. After a small correction for transmission through the Hevimet plug, the counting rate obtained with this arrangement must then be the true counting rate with all spurious counts removed. In the second method the counting rates were measured with the scattering cylinder removed from the magnet. This method, after correction for attenuation effects produced when the iron cylinder is in place, gives only the spurious counts which should be subtracted from the normal runs. The f_{NP}'s obtained by these two methods differed in some cases by as much as $\approx 20\%$, so we have averaged the results and assigned an error of ± 0.2 to each f_{NP} in the table.

The fully corrected relative effects are shown with the estimated total errors (standard deviations) except for Na^{22} and Co^{60}. We believe that the statistical errors only should be used for comparison purposes between Na^{22} and Co^{60}, because the similarity in γ-ray energies implies that the f_{NP}'s should be the same. (A discrepancy between the absolute values of A for Na^{22} and Co^{60} which characterized an earlier publication[1] was resolved when it was discovered that f_{RC} had been incorrectly measured for Co^{60}.) The calculated result agrees very well with the average of the observed results. The asymmetry parameters given in the last column of Table I are obtained by a renormalization such that the Co^{60} and Na^{22} average magnitude equals $\frac{1}{3}$.

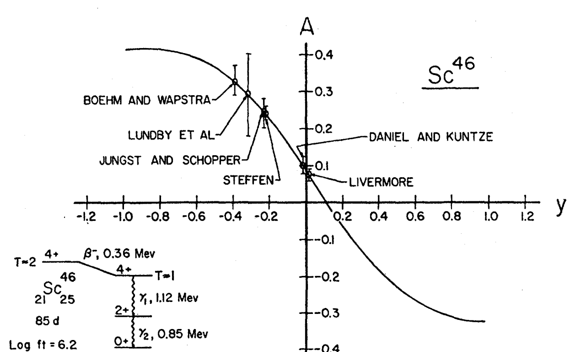

FIG. 6. A vs y in the case of Sc^{46}. The solid curve is computed under the same assumptions as in Fig. 3. Although the spin of Sc^{46} has never been measured directly, the only other possible value permitted by the β-decay characteristics is 5. This would lead to a value of $A=-0.33$, as in Co^{60}. The above data clearly reject the spin-5 possibility, and in addition the results of Livermore and Daniel and Kuntze equally reject spin 3 ($A=0.416$).

In Figs. 3 through 7 the results of all the measurements to date on Na^{24}, Sc^{46}, Ar^{41}, Sc^{44}, and Mn^{52} are shown with the curves which represent the theoretical relation between the asymmetry parameter and the ratio $C_V M_V / C_A M_A$ [Eq. (2′)]. All of the measurements were made by the circular polarization method except those of Ambler *et al.*[25] and Postma *et al.*[26] on Mn^{52}. These were made by the completely independent method of measuring the angular distribution of β rays from polarized nuclei. We have calculated the β-γ asymmetry parameter implied by their results, as shown in Fig. 7.

The agreement among various measurements on Ar^{41}, Sc^{44}, Sc^{46}, and Mn^{52} is not good.[27] The disagreement of our results on Sc^{46} with those of other experimenters has seemed especially bad; all of the previous measurements showed reasonable consistency and gave a strong indication of interference between Gamow-Teller and Fermi matrix elements. Because of this we have measured several different sources of Sc^{46} with special attention to the possibility that source thickness might be affecting the results.[1] Since these results on Sc^{46} were first reported[1] a great deal of new data and experience have been obtained at this laboratory on various nuclides. The consistency of these results coupled with

[25] E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. **110**, 787 (1958).

[26] H. Postma, W. J. Huiskamp, A. R. Miedema, M. J. Steenland, H. A. Tolhoek, and C. J. Gorter, Physica **24**, 157 (1958).

[27] In a private communication H. Schopper has informed the authors that the result of Appel and Schopper on Na^{24} is probably not reliable.

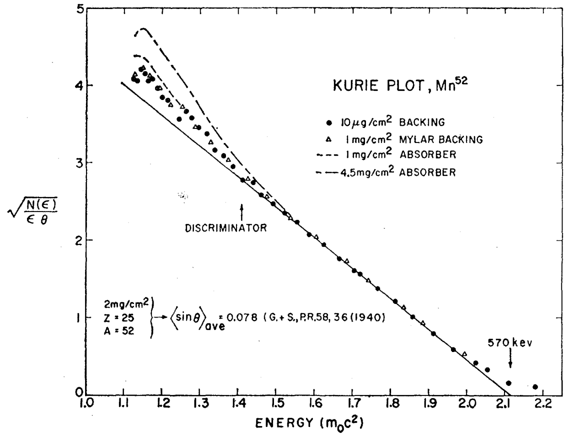

FIG. 8. Kurie plot of the beta spectrum from a source of Mn^{52} giving an idea of the source thickness. All electrons above the indicated discriminator level were accepted in the circular polarization experiments. The average value of the sine of the scattering angle for 200-kev electrons, calculated from reference 29, is shown. This value should read 0.21 instead of 0.078.

the arguments in Sec. II have greatly increased our confidence in the present work. It is seen that the present results give no values that differ significantly from zero for the ratio C_VM_V/C_AM_A. Recently our result on Sc^{46} has been confirmed by work at Heidelberg.[28] We now feel that there is only a very remote chance that the reliability of our results is any worse than the quoted standard deviations would indicate.

The beta spectra from most of our sources have been examined in an axial focusing β-ray spectrometer in order to determine the source thicknesses. In Figs. 8 and 9 the Kurie plots for Mn^{52} and one of the Sc^{46} sources are shown. From the data on Mn^{52} it is concluded that the backing of 1-mg/cm² Mylar has negligible effect and that the source is not over 2 mg/cm². (Some of the curvature is probably caused by source charging rather than thickness.) The scattering from this source is negligible.[29] Visual inspection with a binocular microscope indicates that the Mn^{52} was our thickest source except for Na^{24}. The Sc^{46} sources were probably less than one-tenth as thick.

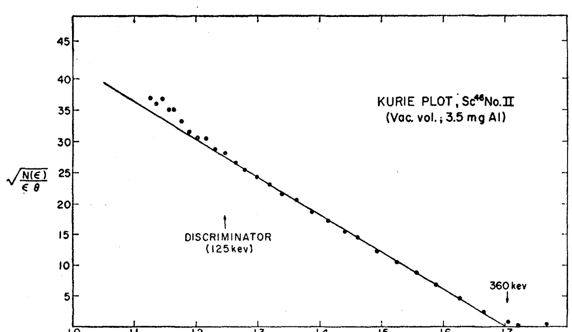

FIG. 9. Kurie plot of the beta spectrum from a source of Sc^{46}. All electrons above 125 kev were accepted in the circular polarization experiments.

In Table II all of the values obtained so far for C_VM_V/C_AM_A are listed, in the order of increasing ratios. (Additional results for the cases of V^{48}, Co^{56}, Fe^{59}, and Cs^{134} will be presented in the near future.[30]) The Livermore results range from 1% to 5% in magnitude and, as can be seen, are all compatible with zero. Only in the case of Na^{24} are all experimenters in agreement with this result and with each other.[17,19,31,32]

V. DISCUSSION

The connection between a zero or near-zero value for C_VM_V/C_AM_A and the validity of the conserved vector-current theory has already been noted in the introduction to this paper. However, the extent of this connection is strongly dependent on how reliable a calculation can be made of the theoretical expectation for M_V, assuming only isospin impurities in the nuclear wave functions. Accordingly, in Table III we have gathered together all the theoretical results known to us for the Fermi matrix element in the cases which have been measured here. Also listed are the present experimental results.

It will be seen in Table III that the agreement is not too good in general, not merely between theory and experiment but also to a considerable extent between the two different theoretical computations as well. (A possible exception to this might be Sc^{44}.) The disagreement between the two different theories is explained to some extent by the fact that the Kelly and Moszkowski calculation[10] took into account two additional effects beyond the basic proton-proton Coulomb force whereas the Bouchiat calculation[11] did not. One of these effects grew out of the assumption of a small degree of breakdown of charge independence. This effect is left out in the values marked with an asterisk in Table III since it is regarded as still speculative.

In the cases of Sc^{44} and Mn^{52} the validity of charge independence seems to be somewhat better supported by the present experimental results. Although it would be very premature to form conclusions with regard to both the conserved vector-current theory and the concept of charge independence on the basis of this agreement, it still illustrates how powerful a diagnostic probe a truly reliable calculation could be in exploring these very basic physical ideas. Unfortunately there exist many obstacles between such reliability and present-day capability, a good example of which is the question of the validity of the extreme j-j coupling model used for all the calculations shown in Table III.

In spite of these difficulties the theoretical indications are clear that M_F in general must still be small ($\lesssim 0.01$)

[28] H. Daniel and M. Kuntze, Z. Physik **162**, 229 (1961).
[29] S. A. Goudsmit and J. L. Saunderson, Phys. Rev. **58**, 36 (1940).
[30] L. G. Mann, S. D. Bloom, and R. J. Nagle, Nuclear Phys. (to be published).
[31] T. Mayer-Kuckuk and R. Nierhaus, Z. Physik **154**, 383 (1959).
[32] H. Appel and H. Schopper, Z. Physik **149**, 103 (1957).

TABLE II. Tabulation of the results obtained here (Livermore) and elsewhere. The value listed for $C_V M_V/C_A M_A$ is derived from the measured value of A (the β-γ asymmetry parameter) assuming the validity of the (A-V) theory (see Figs. 3–7).

Source	Reference	A		$C_V M_V/C_A M_A$	
Na^{24}	Mayer-Kuckuk and Nierhaus[a]	+0.12	±0.03	−0.05	±0.04
	Livermore	+0.085	±0.028	0.00	±0.02
	Boehm *et al.*[b]	+0.07	±0.04	+0.02	±0.05
	Steffen	+0.06	±0.03	+0.03	±0.05
	Appel and Schopper[c]	−0.063	±0.047	+0.21	±0.07
Ar^{41}	Mayer-Kuckuk *et al.*[d]	+0.33	±0.07	−0.38	±0.15
	Livermore	+0.061	±0.070	+0.04	±0.09
Sc^{44}	Boehm and Wapstra[b]	−0.02	±0.04	−0.18	±0.05
	Livermore	−0.151	±0.030	−0.020	±0.035
Sc^{46}	Boehm *et al.*[e]	+0.33	±0.04	−0.39	±0.07
	Lundby *et al.*[f]	+0.29	±0.11	−0.32	±0.14
	Jungst *et al.*[g]	+0.24	±0.04	−0.22	±0.08
	Steffen[h]	+0.24	±0.02	−0.22	±0.04
	Daniel and Kuntze[i]	+0.10	±0.02	−0.02	±0.02
	Livermore	+0.075	±0.018	+0.020	±0.025
Mn^{52}	Ambler *et al.*[j,k]	−0.023	±0.003	−0.048	±0.004
	Postma *et al.*[j,l]	−0.062	±0.006	+0.004	±0.010
	Livermore	−0.089	±0.028	+0.040	±0.040
	Boehm II[m]	−0.10	±0.03	+0.060	±0.040
	Boehm I[n]	−0.16	±0.03	+0.150	±0.060

[a] See reference 31.
[b] See reference 19.
[c] See reference 32.
[d] See reference 20.
[e] See reference 15.
[f] See reference 14.
[g] See reference 16.
[h] See reference 17.
[i] See reference 28.
[j] These experiments gave $A(\beta)$. We list here the $A(\gamma)$ to which the results correspond.
[k] See reference 25.
[l] See reference 26.
[m] See reference 33.
[n] See reference 18.

compared to M_{GT} (≈ 0.1). However, Na^{24} seems to be somewhat of an exception to this theoretically,[11,12] though all experiments (including the present one) imply that even in this case there is no exception, M_F being indicated as very small, $\lesssim 0.001$ (see Table II). For this reason Bouchiat[12] has suggested the experiment on the mirror nucleus of Na^{24}, which is Al^{24}. This should shed light on the question of the conserved vector-current concept without requiring a theoretical calculation of M_F or M_{GT}. Aside from the Na^{24} exception, however, the expectation would be much the same as the findings at this laboratory imply in Table II, i.e., that $|C_V M_V|/|C_A M_A| \lesssim 0.02$ in general.

Thus results such as that of Mayer-Kuckuk *et al.*[20] for Ar^{41}, Boehm *et al.*,[15] Lundby *et al.*,[14] Jungst *et al.*,[16] and Steffen[17] for Sc^{46}, Boehm and Wapstra[19] for Sc^{44}, and Boehm[18] for Mn^{52} pose important questions which can be resolved only by further experimentation and (hopefully) calculation. In the case of Ar^{41} theoretical considerations[21] tend to support our result—if the conserved vector-current theory is correct. In the case of Sc^{46} the most recent experimental work (Daniel and Kuntze[28]) also supports our result, although here the smallness of M_F is somewhat surprising theoretically,[21] much as in the case of Na^{24}. For Mn^{52} a later measurement by Boehm[33] is in very good agreement with our result and also a smaller value for M_F. For Mn^{52}, however, there remains a serious disagreement between the result of Ambler *et al.*[25] and the other results. In the case of Sc^{44}, both theoretical calculations indicate a much smaller result for M_F than the experiment by Boehm and Wapstra[19] would require, but agree very well both in sign and magnitude with our results. Because this is a relatively rare situation, however, it would be difficult to use in a convincing argument. By and large, therefore, the tenor of the results obtained here is best described as being definitely consistent with the conserved vector-current theory, no more.

[33] F. Boehm (private communication).

Finally, it would be interesting to compare the sensitivity of the present method in the detection of the presence of a Fermi component in the β-decay with the

TABLE III. Comparison of theoretical computations for $C_V M_V/C_A M_A$ and present experimental results. Values marked with an asterisk are derived frim the results of Kelly and Moszkowski[a] with the added assumption of charge independence of nuclear forces. $\int 1$ is the symbol for the Fermi matrix element.

Nuclide	Reference	$C_V M_V/C_A M_A$	$\int 1$
Na^{24}	C. C. Bouchiat[b]	+0.197	0.013
	Present experimental result	0.00 ±0.02	···
Sc^{44}	Kelly and Moszkowski[a]	−0.034	0.0060
	Kelly and Moszkowski	−0.014*	0.0025*
	C. C. Bouchiat	−0.003	0.0006
	Present experimental result	−0.020±0.035	···
Mn^{52}	Kelly and Moszkowski	−0.025	0.0061
	Kelly and Moszkowski	−0.006*	0.0014*
	C. C. Bouchiat	−0.042	0.010
	Present experimental result	+0.040±0.040	···

[a] See reference 10.
[b] See reference 11.

TABLE IV. Tabulation of impurity coefficients describing admixing into the parent (daughter) state of the analog state of the daughter (parent) in the case of positron (electron) decay. $\alpha_{pd}(\alpha_{dp})$ is the symbol used to represent this impurity coefficient (see text and reference 34). In the case of Na^{24} a value for $|M_F/M_{GT}|$ of 0.01 was used in making the calculation instead of 0.00, as was actually measured here, which would have led to a vanishing result for α_{dp}. Since 0.01 is $\frac{1}{2}$ the probable error, it should lead to a reasonable estimate for the order of magnitude of the impurity coefficient at maximum.

Nuclide	log ft	Isospin Parent	Isospin Daughter	Impurity admixture
${}_{11}Na^{24}$	6.1	1	0	α_{dp}, $\lesssim 6\times10^{-4}$
${}_{18}Ar^{41}$	5.0	$\frac{5}{2}$	$\frac{3}{2}$	α_{dp}, $\approx 6\times10^{-3}$
${}_{21}Sc^{44}$	5.3	1	2	α_{pd}, $\approx 2\times10^{-3}$
${}_{21}Sc^{46}$	6.2	2	1	α_{dp}, $\approx 1\times10^{-3}$
${}_{25}Mn^{52}$	5.6	1	2	α_{pd}, $\approx 2\times10^{-3}$

method used by Alford and French.[34] In the latter method one compares the observed ft values in $J=0$, $\Delta J=0$ decays (such as ${}_{32}Ge^{66}\to{}_{31}Ge^{66}\to{}_{30}Zn^{66}$) with the superallowed values for ft which would exist if the parent and daughter possessed the same value for T, the total isospin. By then assuming that the observed ft value is, in fact, due to the mixture into the parent of the analog state of the daughter (in positron decay) one gets a direct measure of the square of the amplitude ratio of the contaminating state in the principal state. Alford and French find impurity mixtures of the order of 1% or less on the basis of the application of this reasoning.

If, in fact, the nonzero value of M_F in mixed transitions is again due to an isospin contaminant in the daughter (parent) of the analog state of the parent (daughter) it should be possible to use the Alford-French method once more, if one only knew the *exact* value of $|M_{GT}|^2$. But, of course, this knowledge does not exist and since in general $|M_F|\ll|M_{GT}|$ (at least for allowed transitions) one cannot determine M_F from the ft value alone. However, in the case of the β-γ circular-polarization technique, the measurement made is essentially of M_F/M_{GT}. This information in addition to the ft value then makes it possible to determine both M_F and M_{GT}. Since we actually measure M_F and not $|M_F|^2$, this would tend to make our method somewhat more sensitive than the Alford-French method, which, besides, is only applicable to the relatively rare $0\to0$ allowed decays.

[34] W. P. Alford and J. B. French, Phys. Rev. Letters 6, 119 (1961).

In order to see how the results obtained by using the ft value alone[34] compare with ours, insofar as assessing isospin impurity mixtures is concerned, it is best to refer to Table IV. Therein we have gathered together the results on the isospin contamination coefficients, α_{ij}, as derived from the measurement of A at this laboratory for the nuclides given in Table II. The values range from 6×10^{-4} (for ${}_{11}Na^{24}$) to 6×10^{-3} (for ${}_{18}Ar^{41}$). Our highest number agrees with the lowest number given by Alford and French (5×10^{-3}). The somewhat smaller values for α_{ij} indicated by our results might be connected with the lower range of atomic weights associated with our measurements. In any case, the two sets of results are quite consistent with each other, which tends to strengthen the case for isospin as a valid quantum number for describing nuclear states. This in turn further supports the argument offered here that the measurement of A constitutes an important tool in the testing of the theory of a conserved vector current in β decay.

Note added in proof. After the completion of this paper we received a preprint of an article by F. Boehm and J. Rogers [Nuclear Phys. (to be published)] which described a series of experiments with Sc^{46} wherein sources of several different chemical species were investigated. They found that in the oxide form (regardless of thickness) a depolarization occurs which attenuates the observed asymmetry. They further report that hydrolysis of chloride and nitrate sources occurs during the measurement giving rise to the attenuated effect also. We are in the process of performing a series of experiments to investigate this possibility. Similar experiments are also being carried out by Rolf Steffen (private communication).

ACKNOWLEDGMENTS

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