tion with proton energy of the features of the angular distributions.

Results obtained for DWBA and optical-model calculations for the higher energies, with the same set of optical parameters, are quite similar although the value of the parameter V_1 seems to be consistently lower in the optical-model analysis.

Finally, the wide resonances observed at 5.5, 6.50, 7.65, and 9.00 MeV have been interpreted as due to single-particle levels in O^{16}. This does not contradict the experimental evidence[9] that compound-nucleus levels are also present; they will have been detected with high resolution in the proton energy. One can visualize the size resonance, whose peak is at the position of the single-particle level, as the envelope of all the narrow compound-nucleus resonances that occur in the energy interval corresponding to the width of the size resonance.

ACKNOWLEDGMENTS

β-γ Circular-Polarization Correlation Study of Sc46

John A. Miskel, Lloyd G. Mann, and Stewart D. Bloom

Lawrence Radiation Laboratory, University of California, Livermore, California

(Received 1 April 1963)

A series of β circularly polarized γ angular-correlation measurements on Sc^{46} in seven different chemical and physical forms has been conducted at this laboratory to investigate a possible chemical effect reported by Boehm and Rogers. According to their findings, this effect attenuates the observed angular correlation. We have found no indication of such an effect. The average of all the present measurements ($A = +0.097 \pm 0.012$) is in excellent agreement with our earlier result as well as with many other independent measurements. Our conclusion is that there is no evidence for a chemical attenuation effect.

I. INTRODUCTION

SINCE the work of Boehm and Wapstra[1] on the circular polarization of the γ rays following β decay in Sc^{46}, which apparently demonstrated a large Fermi component in the β decay, many similar measurements have been performed at several laboratories. The early reports[2-4] agreed reasonably well with the original findings, but all subsequent measurements until very recently have shown only a very small Fermi component.[5-9] However, within the last year Boehm and Rogers[10] have reported new results which confirm their original findings, and they suggest that a strong attenuation of the angular correlation in certain chemical states is responsible for the small polarizations. The existence of such an attenuation is especially surprising in view of the short half-life of the intermediate state at 2.01 MeV in Ti^{46}, which in a recent measurement[11] was found to be less than 5×10^{-12} sec. Also the sum total of recent experimental findings on other nuclei[5] suggests a significantly smaller degree of breakdown of isotopic-spin conservation, in general, than this result implies (see below). For these reasons we have performed an extensive reinvestigation of Sc^{46}. The data do not confirm the results of Boehm and Rogers.

The statistical validity of all the results obtained in this investigation was determined by application of Pearson's χ^2 test, as described by Evans.[12] The test shows all the results to be fully self-consistent without regard to chemical form or time history of the source. In addition, the final value for the asymmetry parameter, $A = 0.097 \pm 0.012$, agrees with our original result[5] and with the other independent measurements.[6-9]

II. SOURCES

The first group of measurements in this present work was made with sources prepared in a manner identical to that of Boehm and Rogers.[10] They very kindly

[1] F. Boehm and A. H. Wapstra, Phys. Rev. **109**, 456 (1958).

[2] A. Lundby, A. P. Patro, and J. P. Stroot, Nuovo Cimento **6**, 745 (1957).

[3] W. Jüngst and H. Schopper, Z. Naturforsch. **13A**, 505 (1958).

[4] R. M. Steffen, Phys. Rev. **115**, 980 (1959).

[5] S. D. Bloom, L. G. Mann, and J. A. Miskel, Phys. Rev. **125**, 2021 (1962).

[6] H. Daniel and M. Kuntze, Z. Physik **162**, 229 (1961).

[7] E. L. Haase, H. A. Hill, and D. B. Knudsen, Bull. Am. Phys. Soc. **7**, 342 (1962).

[8] M. Chabre and L. de Pommier (private communication).

[9] Jean Berthier, thesis, University of Paris, 1962 (unpublished).

[10] F. Boehm and J. Rogers, Nucl. Phys. **33**, 118 (1962).

[11] Y. K. Lee and C. S. Wu, Bull. Am. Phys. Soc. **7**, 341 (1962).

[12] Robley D. Evans, *The Atomic Nucleus* (McGraw-Hill Book Company, Inc., New York, 1955), Chap. 27, p. 775.

supplied us with some of their Sc[46] source material and a detailed description of their source preparation and handling technique, as used in the work of Ref. 10. The principal feature of this technique is that the sources are prepared by evaporation of strong nitric-acid solutions of scandium to dryness at essentially room temperature (very little heat is applied). The sources are renewed (in chemical form) every two days by the addition of a small amount of concentrated nitric acid.

In a second group of measurements we used liquid sources of scandium dissolved in concentrated sulfuric acid. Sulfuric acid was used because of its low vapor pressure—thin sources would last for many days without drying up. Some of these sources were sandwiched between two thin layers of mica,[13] while others (oriented horizontally) were open on the side toward the β detector. The open liquid sources were prepared by spreading a known amount of the sulfuric acid-scandium solution over a given area. The support for the source was glass of about 10 mg/cm². The area to be covered by the solution was defined by sand-blasting with very fine grit; the solution spread only to the edge of the sand-blasted boundary.

A third group of measurements was made with solid polycrystalline sources designed to have cubic symmetry about the Sc[46] atoms. In these sources the electric-field gradient at the positions of the Sc[46] nuclei should be zero, thus preventing any depolarization due to the nuclear quadrupole moment. Sources of ScF_3 and $Sc(OH)_3$ were used. $Sc(OH)_3$ forms cubic crystals and ScF_3 forms crystals which are *almost* cubic.[14] The edges of the unit cell in ScF_3 form angles of 89°34′; if this angle were 90° the crystals would be cubic. The fluorine ions would then form octahedra with scandium ions at the center. It does not seem likely that this slight rhombohedral distortion of the cubic symmetry would result in the very high fields necessary to attenuate the angular correlation, and the other properties of ScF_3 made it very attractive for this experiment.

Apparently it is not easy to guarantee the chemical behavior of scandium.[15] However, the fluorides of all the rare-earths (which are chemically similar to scandium) are much more stable and insoluble than the other rare-earth halides. ($ScCl_3$, incidentally, has a hexagonal close-packed structure rather than cubic, so even if one could be sure of making it free from water it would still be less desirable for angular correlation work.) We produced thin sources of ScF_3 by dissolving Sc_2O_3 in concentrated HF and evaporating to dryness. One source was dried at an elevated temperature (but well under 100°C) in the hope that the decomposition of $HScF_4$ into $HF+ScF_3$ would be more certain. This source was then placed in vacuum for two days to help

[13] R. I. Johnson, Rev. Sci. Instr. **33**, 1474 (1962).
[14] Ralph W. G. Wyckoff, *Crystal Structures* (Interscience Publishers, Inc., New York, 1960), Vol. 2, Chap. 5, pp. 14, 256.
[15] R. C. Vickery, *The Chemistry of Yttrium and Scandium* (Pergamon Press, Inc., New York, 1960), Chap. 7.
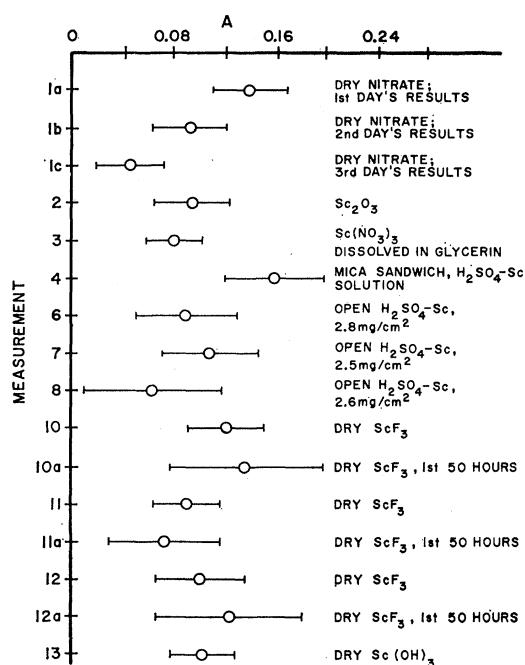
FIG. 1. Measurements of the asymmetry parameter A made in the present experiment, arranged by groups according to the chemical/physical nature of the sources and also chronologically.

remove any HF that might have been trapped in the lattice.

We feel that ScF_3 offers one of the best possibilities of producing cubic crystals that will remain free from water. The $Sc(OH)_3$ may have water, either from the original formation or picked up from the air. During the measurements all of the sources were contained in a dry helium atmosphere with water present in concentrations of less than 1 ppm (part per million).

Finally, a source of Sc_2O_3 on beryllium was prepared for comparison purposes because Boehm and Rogers reported that this form gave one of the largest chemical effects. This source was made by heating the dry $Sc(OH)_3$ in air to 550°C.

III. RESULTS

A complete summary of the results may be seen in Table I and Fig. 1. Although there might appear to be a slight time dependence in the $Sc(NO_3)_3$ data, it is not statistically significant; a χ^2 analysis of all the results reveals no statistical significance of any of the deviations.

The formula used in the χ^2 analysis was

$$\chi^2 = \sum_j (y_j - t_j)^2 / (e_j)^2 ,$$

where y_j is an experimental result, e_j the associated error, and t_j the theoretically expected answer. In our case the average value of A is substituted for t_j, since the "expected" value is the same for every experiment.

The value of χ^2 characterizing the final calculated

TABLE I. Experimental measurements leading to A, the β-γ circular-polarization correlation parameter for the various kinds of chemical forms of Sc[46] used in the present work. A fuller explanation of the significance of the various columns may be found in Ref. 5.

| | | Correction factors | | | | | | E, absolute | | | A, asymmetry |
		f_{PE}[a]	f_{VC}[b]	f_{RC}[c]	f_{GG}[d]	f_{NP}[e]	f_T[f]	raw effect[g]	$f_T \times E$	Source type[h]	parameter
(1a)	Sc[46]	1.08	1.51	1.05[i]	1.10	1.35	2.54	0.129±0.022	0.328±0.056	Dry nitrate; 1st day's results	0.140±0.029
(1b)	Sc[46]	1.08	1.51	1.05	1.10	1.35	2.54	0.086±0.022	0.218±0.056	Dry nitrate; 2nd day's results	0.093±0.029
(1c)	Sc[46]	1.08	1.51	1.05	1.10	1.35	2.54	0.042±0.020	0.107±0.051	Dry nitrate; >3rd day's results	0.046±0.027
(2)	Sc[46]	1.08	1.51	1.03	1.10	1.35	2.49	0.088±0.023	0.223±0.058	Sc₂O₃ on beryllium backing	0.095±0.030
(3)	Sc[46]	1.08	1.52	1.03	1.10	1.35	2.55	0.074±0.014	0.189±0.036	Sc(NO₃)₃ dissolved in glycerine	0.081±0.022
Standard[j]				See below					0.778±0.029	Chlorides[j]	0.333, standard[j]
										Mica sandwich of H₂SO₄-Sc solution:	
(4)	Sc[46]	1.08	1.51	1.02	1.09	1.35	2.44	0.111±0.018	0.279±0.044	3.5 mg/cm²	0.160±0.042
(5)	Co[60]	1.00	1.55	1.05	1.13	1.55	2.85	0.198±0.019	0.564±0.054	3.5 mg/cm²	0.333, standard[k]
										Open H₂SO₄-Sc liquid solutions:	
(6)	Sc[46]	1.08	1.50	1.01	1.10	1.35	2.43	0.074±0.025	0.125±0.093	2.8 mg/cm²	0.091±0.040
(7)	Sc[46]	1.08	1.50	1.04	1.10	1.35	2.50	0.086±0.020	0.180±0.060	2.5 mg/cm²	0.109±0.038
(8)	Sc[46]	1.08	1.50	1.01	1.10	1.35	2.67[l]	0.047±0.035	0.215±0.050	2.6 mg/cm²	0.064±0.055
(9)	Co[60]	1.00	1.54	1.04	1.14	1.55	2.82	0.231±0.019	0.650±0.053	2.4 mg/cm²	0.333, standard[m]
(10)	Sc[46]	1.08	1.47	1.07	1.10	1.35	2.52	0.113±0.024	0.285±0.060	Dry ScF₃	0.122±0.030
(11)	Sc[46]	1.08	1.47	1.06	1.10	1.35	2.50	0.086±0.019	0.215±0.048	Dry ScF₃	0.092±0.026
(12)	Sc[46]	1.08	1.47	1.04	1.10	1.35	2.45	0.095±0.028	0.233±0.069	Dry ScF₃	0.102±0.034
(10a)	Sc[46]	1.08	1.47	1.07	1.10	1.35	2.52	0.129±0.054	0.325±0.136	Dry ScF₃, 1st 50 h	0.138±0.060
(11a)	Sc[46]	1.08	1.47	1.06	1.10	1.35	2.50	0.069±0.039	0.172±0.098	Dry ScF₃, 1st 50 h	0.074±0.044
(12a)	Sc[46]	1.08	1.47	1.04	1.10	1.35	2.45	0.119±0.050	0.292±0.120	Dry ScF₃, 1st 50 h	0.126±0.057
Standard[j]				See below					0.778±0.029	Chlorides[j]	0.333, standard[j]
(13)	Sc[46]	1.08	1.44	1.06	1.10	1.35	2.45	0.099±0.019	0.243±0.047	Dry Sc(OH)₃	0.104±0.026
Standard[j]				See below					0.778±0.029	Chlorides[j]	0.333, standard[j]
(14)	Co[60]	1.00	1.54	1.07	1.15	1.55	2.95	0.267±0.011	0.789±0.032	Dry chloride	0.333, standard[j]
(15)	Na[22]	0.98	1.31	1.05	1.06	1.55	2.21	0.326±0.034	0.720±0.076	Dry chloride	0.333, standard[j]

[a] Change in magnetic polarization efficiency with gamma energy.
[b] Polarization dependence on β-ray velocity.
[c] Random coincidences.
[d] Gamma-gamma coincidences.
[e] Real coincidences produced by scattering from nonpolarized material.
[f] Total correction factor, i.e., the product $f_{PE} \times f_{VC} \times f_{RC} \times f_{GG} \times f_{NP}$.
[g] Only the absolute value is given here, although Co[60] is negative and Sc[46] and Na[22] are positive.
[h] Dry sources are $\lesssim 0.1$ mg/cm². Otherwise numerical figures given are mean thickness.
[i] This is a mean value, as several different sources are grouped together here.
[j] Co[60] (14) and Na[22] (15) are taken to be standards with $|A| = 0.333$.
[k] In this case Co[60] was dissolved in H₂SO₄ and enclosed in a mica sandwich for a standard.
[l] A larger than normal source in this case required an additional 10% correction factor for the attenuation of E.
[m] As in the case of sources (4) and (5), a Co[60]-H₂SO₄ solution of the same thickness as Sc[46] sources (6), (7), and (8) was prepared and used as a reference standard.

answer for A is 9.9, which for 12 degrees of freedom (13 measurements) corresponds to a probability of about 60% that χ^2 would be bigger than this if the series of measurements were repeated. This is a completely acceptable situation, statistically speaking. If we include the result of Boehm and Rogers[10] ($A \geq 0.215 \pm 0.019$) the value of χ^2 then becomes 48.5, corresponding to a probability of <0.1% that χ^2 could be bigger. Thus it does not appear possible that a statistical fluctuation can account for the disagreement between our data and those of Boehm and Rogers. Similar conclusions result from a comparison of the present experimental results with all the earlier measurements[2–4] on Sc[46], previously discussed.

The average value of all the present measurements is $A = 0.097 \pm 0.012$.

IV. CONCLUSIONS

Based on the above work, the discrepancy between our results on Sc[46] and those of the early experimenters[1–4] remains unexplained. This disagreement is shown in Fig. 2, a plot of A versus $y \equiv C_V M_V / C_A M_A$ (see Ref. 5). The larger values of the asymmetry parameter require a large interference between the A and V components in the β-decay Hamiltonian. It is this possibility of interference which makes the Sc[46] measurement of some crucial interest, since the A-V form[16] of β decay requires interference and, therefore, receives

[16] M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. **120**, 1829 (1960). See also other references given in this paper.

support from this result. Our measurements do not admit this interpretation.

However, the experimental finding that the Fermi matrix element is apparently always very small in $\Delta T=1$ transitions is still fully consistent with the A-V form of β decay ("old" β-decay theory). Furthermore, the inclusion in the theory of the conserved vector current hypothesis and of the empirical observation that isotopic-spin impurities are of the order of a few tenths percent or less requires that the $M_F=0$, which is also in agreement with our results. The former is well supported now by many different pieces of evidence.[16–19] The latter is suggested by the other circular-polarization measurements mentioned above and in particular by the recent experiments[19,20] comparing the β-$\gamma(CP)$ correlations of Na^{24} and Al^{24} in the manner described by Bouchiat.[21] These experiments show that the theoretical estimate[22] for M_F in the case of Na^{24} is too large by about an order of magnitude. Thus, it appears that the theoretical estimates made to date on isotopic-spin impurities in nuclear wave functions are not reliable. In any case, however, it is clear that there is to date no measurement of a β-$\gamma(CP)$ correlation (or a similar measurement) incontrovertibly demonstrating the presence of isospin impurities exceeding at most a few tenths of a percent.

Note added in proof. After this paper was submitted, publications on Sc^{46} by R. M. Singru and R. M. Steffen [Nucl. Phys. **43**, 537 (1963)] and by H. Daniel, O. Mehling, O. Muller, P. Schmidlin, H. Schmitt, K. S. Subudhi, and E. Neuburger [Nucl. Phys. **45**, 529 (1963)] have appeared. Singru and Steffen used ScCl$_3$ sources in vacuum and obtained $A=0.19\pm0.03$, with no indication of a time-dependent attenuation. Daniel
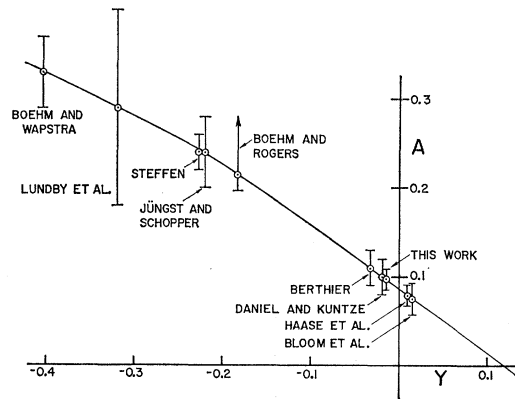
[17] R. P. Feynman and M. Gell-Mann, Phys. Rev. **109**, 193 (1958).

[18] Y. K. Lee, L. W. Mo, and C. S. Wu, Phys. Rev. Letters **10**, 253 (1963).

[19] E. L. Haase, H. A. Hill, and D. B. Knudsen, Phys. Letters **4**, 338 (1963).

[20] S. D. Bloom, L. G. Mann, R. Polichar, J. R. Richardson, and A. Scott (to be published).

[21] C. C. Bouchiat, Phys. Rev. Letters **3**, 516 (1959).

[22] C. C. Bouchiat, Phys. Rev. **118**, 540 (1960).

FIG. 2. Asymmetry parameter A versus $y \equiv C_V M_V / C_A M_A$ in the case of Sc^{46} β decay under the assumption of the $(A$-$V)$ form for the β-decay Hamiltonian.

et al. measured 15 sources, including 6 different solid chemical forms and three liquid forms. They conclude that all sources were in agreement with $A=0.113 \pm0.008$, independent of time. Both these groups conclude that an attenuation of A due to static quadrupole effects is impossible.

After learning of the Singru and Steffen result we have measured four new sources, one of mass separated Sc^{46} ions collected on 1-mil Be foil, and three of ScCl$_3$ on $\frac{1}{4}$-mil mylar in vacuum. The results are: $A=0.113 \pm0.013$ for the mass separated source; $A=0.083\pm0.018$ for the average value of the first run ($\approx$23-h duration) on each ScCl$_3$ source; and $A=0.081\pm0.011$ for the ScCl$_3$ total average. The χ^2 test on all the ScCl$_3$ measurements gives $P=0.21$ for the probability that a repetition of the series of 13 measurements would yield a larger value of χ^2.

ACKNOWLEDGMENTS