Submitted to Nuclear Physics

UCRL-19536
Preprint

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W. D. Brewer and D. A. Shirley

January 1970

AEC Contract No. W-7405-eng-48

LAWRENCE RADIATION LABORATORY
UNIVERSITY of CALIFORNIA BERKELEY

BETA-PARTICLE AND GAMMA-RAY ANGULAR DISTRIBUTIONS FROM ^{186}Re, ^{188}Re, AND ^{194}Ir POLARIZED IN IRON AT LOW TEMPERATURES[†]

W. D. Brewer[††] and D. A. Shirley

Department of Chemistry and
Lawrence Radiation Laboratory
University of California,
Berkeley, California 94720

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Abstract: Nuclei of ^{186}Re, ^{188}Re, and ^{194}Ir have been polarized in iron at low temperatures. The angular distributions of electrons from the first-forbidden beta decays were observed as functions of particle energy, using Li-drifted germanium detectors. The anisotropies of the gamma rays which de-excite the 2^+ levels in the daughter nuclei were also measured. The information obtained is sufficient to permit an analysis for the nuclear matrix elements and possibly to use as a test of the conserved vector current hypothesis, but no detailed analysis has as yet been made. The beta particle angular distributions of the Re cases were in general agreement with previous results, but the experimental accuracy was greatly improved.

[†] Work performed under the auspices of the U. S. Atomic Energy Commission.

[††] NSF Graduate Fellow, 1968-69. Present Address: I. Physikalisches Institut, Freie Universität Berlin, Berlin, West Germany.

Introduction

In recent years interest has arisen in the study of certain first-forbidden beta decays. Analysis of these decays yields the magnitudes of the nuclear matrix elements, which are not only of interest in nuclear structure theory, but also may provide a test of the conserved vector current[1]). Two decays which do not follow the ξ approximation, and may thus give information on the nuclear matrix elements, are those of ^{186}Re and ^{188}Re.[2]) In both cases, the principal decay branch is from a 1^- state to the 0^+ ground state in the daughter nucleus; in addition, about 20% of each decay proceeds to the 2^+ first excited state of the daughter. Both decays have been studied extensively by observation of the beta spectrum shapes[3]), measurement of electron polarizations[4]), and beta-gamma correlations[5]). Some work on angular distributions of electrons from polarized nuclei has also been done[6]). The last method gives a relatively sensitive measure of the matrix elements, although the experiments are difficult to perform and subject to certain systematic errors. In the present work, the electron angular distributions from polarized ^{186}Re and ^{188}Re were observed using an axial and an equatorial Ge(Li) detector, with the intention of extending and improving earlier results on these decays. The decay of ^{194}Ir was similarly studied[7]). Observations of the anisotropies of the gamma rays which de-excite the 2^+ levels in the daughter nuclei were also made, to determine the admixture of the unique (B_{ij}) matrix element in the $1^- \rightarrow 2^+$ beta decays. Fig. 1 shows decay schemes for the three isotopes.

Experimental

Isotopically enriched ^{185}Re, ^{187}Re, and ^{193}Ir were obtained as powdered metals and alloyed with iron by melting. Two alloys of each Re isotope and one of the Ir were made, having concentrations of from 0.2 to 0.8 at.%. The alloys were hammered and rolled to about 2 mg/cm^2 thickness and were irradiated for one hour each in a flux of 2.5×10^{14} thermal neutrons/sec-cm^2. During irradiation the foils were masked with Cd so that the activation occurred primarily in a well-defined small spot in the center of each piece. After irradiation, they were etched, annealed 6-10 hrs. at 900°C, coated on one side with 7 mg/cm^2 of copper, and soldered at the edges to wires in thermal contact with a cooling salt slurry. The copper backing served to prevent thermal inhomogeneities in the foils. The salt slurry, containing cerium magnesium nitrate, was demagnetized from an initial H/T of 40 kOe/deg K and could cool the source foils to ca. 5 mdeg K and maintain them below 10 mdeg for up to six hours.

The two Ge(Li) detectors used to count the beta particles were enclosed in vacuum-tight copper housings equipped with thin (1 mg/cm^2) aluminized mylar windows. The detectors had sensitive depths of about 2.5 MeV for electrons and showed excellent stability of pulse height and resolution, and moderately good resolution. (5 keV FWHM for 1 MeV electrons, corrected for scattering in the source.) A typical spectrum from ^{207}Bi is shown in fig. 2. The detector operating temperature was about 16.5°K,$^{8)}$ and the copper housings, which were thermally anchored at 1°K, prevented warming of the source foil by radiation from the detectors. The gamma rays were detected by 3×3" NaI(Tl) scintillation counters in axial and equatorial positions relative to the polarizing magnetic field, which was produced by a small superconducting Helmholtz coil. The polarizing field could be raised to 3 kOe, and the samples were completely polarized below 1 kOe.

Because of the low temperatures attainable with the nuclear orientation apparatus, the Re nuclei were essentially completely polarized during the first 4-5 hours of each experiment. The same was true of the Ir nuclei for about the first hour of each run. Thus exact knowledge of the source foil temperatures was not needed, and the results obtained were insensitive to small variations of temperature or internal field within the foils. This simplified the experiments and also increased the accuracy obtainable, by eliminating thermometry. The spectra from the four detectors were collected in a 1600 channel analyzer and stored on magnetic tape for subsequent analysis.

Results

The angular distribution of electrons from first-forbidden beta decays of polarized nuclei was given by Morita and Morita.9) For a $1^- \to 0^+$ decay (and describing the nuclear orientation by statistical tensors B_k (Ref. 10)) their formula reduces to

$$\begin{aligned} W(1\to 0,\theta) &= 1 - B_1 P_1(\cos\theta)(b^{(1)}_{1,1}/b^{(0)}_{1,1}) + B_2 P_2(\cos\theta)(b^{(2)}_{1,1}/b^{(0)}_{1,1}) \\ &= 1 + B_1 P_1 A_1(1\to 0) + B_2 P_2 A_2(1\to 0) \quad . \end{aligned} \qquad (1)$$

Here $W(\theta)$ is the anisotropy at angle θ, $P_k(\cos\theta)$ are the Legendre polynomials of rank k, and the $b^{(k)}_{L,L'}$ are particle parameters which are functions of the nuclear matrix elements and the lepton functions associated with the decay. For a $1^- \to 2^+$ decay, an $L = 2$ component is present as well as $L = 1$, and a more complicated expression results:

$$W(1\to2,\theta) = 1 + B_1P_1(\cos\theta)\,\frac{\left[b^{(1)}_{1,1} - \left(3/\sqrt{5}\right)b^{(1)}_{1,2} + \left(1/\sqrt{5}\right)b^{(1)}_{2,2}\right]}{2\left[b^{(0)}_{1,1} - \left(\sqrt{3/5}\right)b^{(0)}_{2,2}\right]}$$

$$+ B_2P_2(\cos\theta)\,\frac{\left[b^{(2)}_{1,1} - 3b^{(2)}_{1,2} + \left(\sqrt{21}\right)b^{(2)}_{2,2}\right]}{10\left[b^{(0)}_{1,1} - \left(\sqrt{3/5}\right)b^{(0)}_{2,2}\right]} = 1 + B_1P_1A_1(1\to2) + B_2P_2A_2(1\to2). \qquad (2)$$

In the decays observed in this work, the two types of transitions are mixed (except at the highest energies) and the combined anisotropy is observed. Denoting the intensity ratio $I(1\to2)/I(1\to0)$ by r, one has for the observed anisotropy:

$$W(r,\theta) = \frac{W(1\to0,\theta) + rW(1\to2,\theta)}{1+r} = 1 + B_1P_1\,\frac{(A_1(1\to0)+rA_1(1\to2))}{1+r}$$

$$+ B_2P_2\,\frac{(A_2(1\to0)+rA_2(1\to2))}{1+r} = 1 + B_1P_1A_1(r) + B_2P_2A_2(r) \quad . \qquad (3)$$

These three equations define the coefficients $A_1^{(r)}$ and $A_2^{(r)}$, which were measured. These coefficients may be compared directly with theory. The anisotropies from two field directions and two counters were used to determine A_1 and A_2 in four independent ways; the values obtained were generally in good agreement and were averaged to obtain final values, which are shown in Table 1 for the three cases studied. The anisotropy data were corrected for electronic dead time, radioactive decay, finite polarization in the "warm" counts, solid angle of the counters, and scattering of the electrons.

The anisotropies of the gamma rays which de-excite the 2^+ states in these decays are given by:

$$W(\theta) = 1 + B_2U_2F_2P_2(\cos\theta) ,$$

where B_2 and P_2 are the same as in the beta-particle expressions, F_2 is the usual gamma-ray angular distribution coefficient, and U_2 is a reorientation parameter of the emitting state[10]. If the emitting 2^+ state is preceeded only by the $1^- \rightarrow 2^+$ beta decay of interest, which is supposed to be a mixture of L = 1 and L = 2 beta transitions, then the average value of U_2 seen in a measurement of the anisotropy is given by

$$\overline{U}_2 = U_2(L = 1)\cdot(1 - R)/(1 + R), \quad U_2(L = 1) = 0.5916$$

where $U_2(L = 1)$ is the value of the reorientation parameter for a pure L = 1 beta decay and R is the ratio of (L = 2):(L = 1) beta intensities in the actual decay. In the case of ^{186}Re, the above approximation holds: the 137 keV 2^+ state in the ^{186}Os daughter is fed 99.7% by the $1^- \rightarrow 2^+$ beta decay and only 0.25% by gamma decay from the 767 keV state. In the ^{188}Re and ^{194}Ir decays, the situation is complicated and allowance must be made for attenuation of the observed anisotropy by preceeding gamma transitions as well as by the $1^- \rightarrow 2^+$ beta decay. The 328 keV transition in the ^{194}Ir decay was studied by Reid et al.[11] using Ge(Li) gamma detectors which could resolve the 301 keV and the 293 keV lines from the 328 keV line being studied. These authors give an analysis for the observed value of U_2 which assumes L = 1 for $1^- \rightarrow 2^+$ beta branches. The present measurements of the 328 keV transition in ^{194}Ir were made with NaI scintillation detectors which could not resolve the three lines in the 300 keV region, and thus the results are dependent on the values of the M1-E2 mixing ratios assumed for the 293 and 301 keV lines and are less accurate than those of Ref. [11].

For the analysis, the gamma ray spectrum photopeaks were divided into ten intervals and the anisotropy in each interval was calculated. To avoid errors from scattering, only the four intervals nearest the center of the peak were used to obtain final values. The gamma anisotropies were corrected for dead time, decay, solid angle, and background. Data were also averaged where necessary when the axial and equatorial anisotropies gave different values for the ratio R. Final axial anisotropies for the three isotopes are shown in Table 2, along with the calculated anisotropies used in deriving values of R, and the derived R values.

The large range in the calculated anisotropy for ^{194}Ir is due to the aforementioned sensitivity to the mixing ratios of the unresolved gamma lines near 300 keV. The observed anisotropy in this case has a rather large uncertainty and it is possible only to set a general limit on values of R which are consistent with the data.

Comparison with Previous Results

Nuclear polarization experiments have been performed previously on both the Re isotopes studied in this work. Kogan *et al.*6) measured the angular distribution of electrons from ^{186}Re polarized in iron, using an anthracene scintillator as beta particle detector; their results were subsequently analyzed by Šott and Vinduška6). Values of A_1 at several energies may be inferred from their data as shown in Table 3.

The angular distribution of electrons from polarized ^{188}Re was studied by Šott, Stone, Templeton, and Vinduška (SSTV)6). Their values for A_1 and A_2 at two energies may be derived from Ref. 6) (see Table 4).

It is clear that the values for A_1 are in agreement within quoted errors in both cases. The A_2 values for ^{188}Re reported by SSTV are systematically higher than those found in the present work. No explanation for the discrepancy is immediately apparent; however, in SSTV only one (Si surface-barrier) beta particle detector was used, while in the present work two Ge(Li) detectors were used, thus reducing the likelihood of systematic errors in the angular distribution measurements.

The anisotropy of the 137 keV gamma ray from ^{186}Re polarized in iron was measured by Kogan and coworkers previously$^{12)}$. One can derive the product U_2F_2 from their results, and the comparison with the present work is as follows:

	Ref. 12)	This Work
$-U_2F_2$	0.266±0.021	0.258±0.007 .

The two results show excellent agreement. There is no previous work on the beta particle angular distribution from ^{194}Ir or the gamma-ray anisotropy from ^{188}Re, although we note that the result of a finite admixture of the unique matrix element in the $1^- \rightarrow 2^+$ branch of the latter decay is in agreement with a recent analysis of spectrum shapes and angular correlation data by André and Liaud$^{13)}$. The ^{194}Ir gamma-ray result from the present work is that the admixture of the unique matrix element in the $1^- \rightarrow 2^+$ transition to the 328 keV level is small or zero. This is in agreement with the results of Ref. $^{11)}$, in which an analysis assuming pure $L = 1$ beta transitions gave consistent results. (The actual anisotropy from the present work, when corrected for interference from the 301 and 293 keV gamma rays, is slightly greater than that found in Ref. [11]). Since a large A_2 term was found in the beta particle angular distribution from ^{194}Ir, however, it seems clear that the ξ approximation is not obeyed in this decay.

The errors quoted in Tables 1-4 were derived from the calculated statistical errors in the anisotropies and from estimates of the errors in measurement of experimental goemetry, decay corrections, etc. based on calculations and on the observed scatter in the data[14]).

Conclusions

It is felt that the use of very thin source foils and mountings, the use of two particle detectors, the thickness and stability of the Ge(Li) particle detectors, and the low temperatures available with our cryostat have all contributed to improving the accuracy of the β angular distribution results over that previously obtainable in nuclear orientation experiments. Statistical accuracy was also improved by collecting a rather large amount of data for each isotope.

The three parameters determined in each case in this work are in principle sufficient to determine matrix element ratios among the (maximum of) four nuclear matrix elements entering each decay (if one makes the assumption that $(b_{1,1}^{(k)}/b_{1,1}^{(0)}$, $k = 1$ or $2)$ has the same value for the $1^- \rightarrow 0^+$ transitions as for the $1^- \rightarrow 2^+$ transitions, and if one knows the intensity ratio r to reasonable accuracy throughout the energy range considered). A more accurate analysis, however, would take into account all other available results such as spectrum shapes and angular correlation measurements (particularly for the two Re cases) and find the best general fit for the matrix elements. It is hoped that such an analysis can be accomplished in the future.

Table 1

Beta angular distribution coefficients $A_1(r)$ and $A_2(r)$, defined in eqs. (1-3).

^{186}Re			^{188}Re			^{194}Ir		
Energy[a] (keV)	$A_1(r)$	$A_2(r)$	Energy (keV)	$A_1(r)$	$A_2(r)$	Energy (keV)	$A_1(r)$	$A_2(r)$
567 ±5	0.5318 ±0.0033	0.0115 ±0.0016	1199 ±10	0.6318 ±0.0049	0.0518 ±0.0070	1234 ±10	0.6958 ±0.0111	0.1058 ±0.0223
619 ±5	0.5544 ±0.0034	0.0122 ±0.0020	1295 ±10	0.6498 ±0.0050	0.0436 ±0.0115	1340 ±10	0.7142 ±0.0114	0.1229 ±0.0283
672 ±5	0.5805 ±0.0035	0.0187 ±0.0022	1391 ±10	0.6658 ±0.0052	0.0559 ±0.0120	1446 ±10	0.7369 ±0.0118	0.1257 ±0.0295
724 ±5	0.6074 ±0.0036	0.0227 ±0.0027	1487 ±10	0.6807 ±0.0055	0.0700 ±0.0070	1551 ±10	0.7516 ±0.0120	0.1082 ±0.0265
777 ±5	0.6437 ±0.0040	0.0362 ±0.0030	1583 ±10	0.7028 ±0.0056	0.0730 ±0.0088	1656 ±10	0.7749 ±0.0124	0.1168 ±0.0292
830 ±5	0.6809 ±0.0042	0.0371 ±0.0035	1679 ±10	0.7180 ±0.0058	0.0722 ±0.0145	1761 ±10	0.7964 ±0.0128	0.1076 ±0.0377
882 ±5	0.7228 ±0.0046	0.0284 ±0.0080	1775 ±10	0.7525 ±0.0058	0.1008 ±0.0130	1867 ±10	0.8518 ±0.0136	0.1570 ±0.0565
935 ±5	0.7804 ±0.0048	0.0364 ±0.0130	1871 ±10	0.7906 ±0.0065	0.0738 ±0.0280	1972 ±10	0.9015 ±0.0162	0.1433 ±0.0745
987 ±5	0.8351 ±0.0053	0.0075 ±0.0175	1967 ±10	0.8376 ±0.0075	0.0570 ±0.0400	2077 ±10	0.9505 ±0.0210	0.1971 ±0.1200
1040 ±5	0.9473 ±0.0064	-0.0714 ±0.0200	2063 ±10	0.9237 ±0.0097	-0.0350 ±0.0250	2182 ±10	1.1419 ±0.0330	0.1952 ±0.1500

[a] The average energies are given for the data intervals from which $A_1(r)$ and $A_2(r)$ were calculated, and the intervals were equal and contiguous. For example, 1679±10 means "the interval from 1631 to 1727 keV, whose midpoint is known to ± 10 keV". The axial anisotropy data from which these coefficients were derived are plotted against beta particle energy in fig. 3.

Table 2

Normalized axial γ-ray intensities for the 2+(E2)0+ transitions following the decay of oriented ^{186}Re, ^{188}Re, and ^{194}Ir.

	^{186}Re	^{188}Re	^{194}Ir
W(axial,obs.)	0.828 ± 0.005	0.902 ± 0.016	0.822 ± 0.047
W(axial,calc.)	$1-(0.3963 \pm 0.0005)\overline{U}_2$	$1.0011-(0.3725 \pm 0.0005)\overline{U}_2$	$(1^{-0.0103}_{+0.0285})-(0.2282)\overline{U}_2$
R	0.158 ± 0.015	0.380 ± 0.071	$\leqslant 0.04$

Table 3

Comparison of results for ^{186}Re with those of Kogan et al. (see Ref. [6])).

Energy	A_1 (Kogan)	A_1 (This Work)
900 keV	0.78±0.11	0.738±0.005
700 keV	0.60	0.594±0.004
550 keV	0.47	0.525±0.003

Table 4

Comparison of ^{188}Re results with those of Šott *et al*. (see Ref. [6])).

Energy	A_1 (SSTV)	A_1 (This Work)	A_2 (SSTV)	A_2 (This Work)
1.3 MeV	0.64±0.03	0.650±0.005	0.12±0.07	0.044±0.012
1.65 MeV	0.76±0.04	0.718±0.006	0.27±0.12	0.072±0.014

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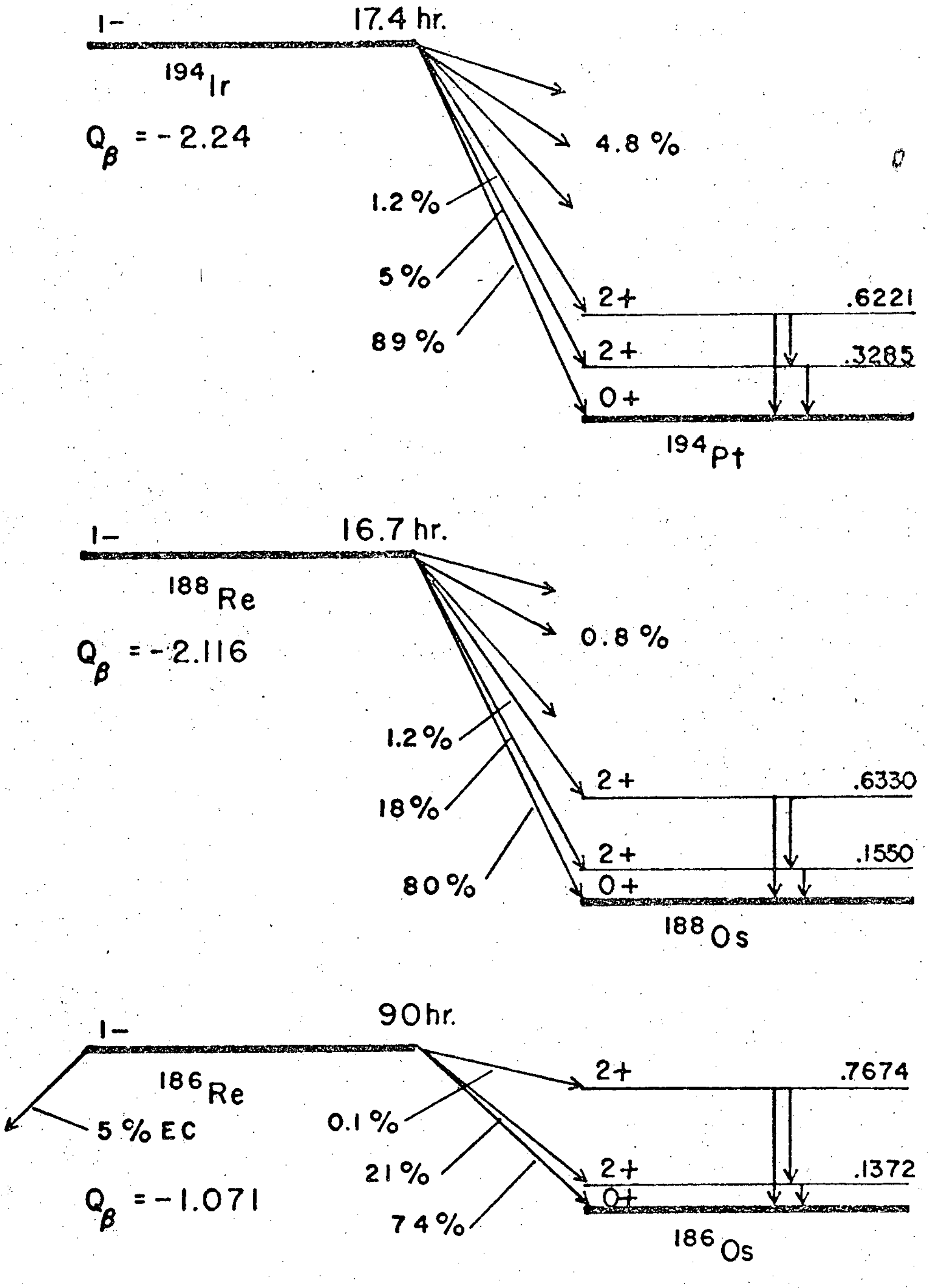
Figure Captions

Fig. 1. Decay schemes of isotopes used in this work.

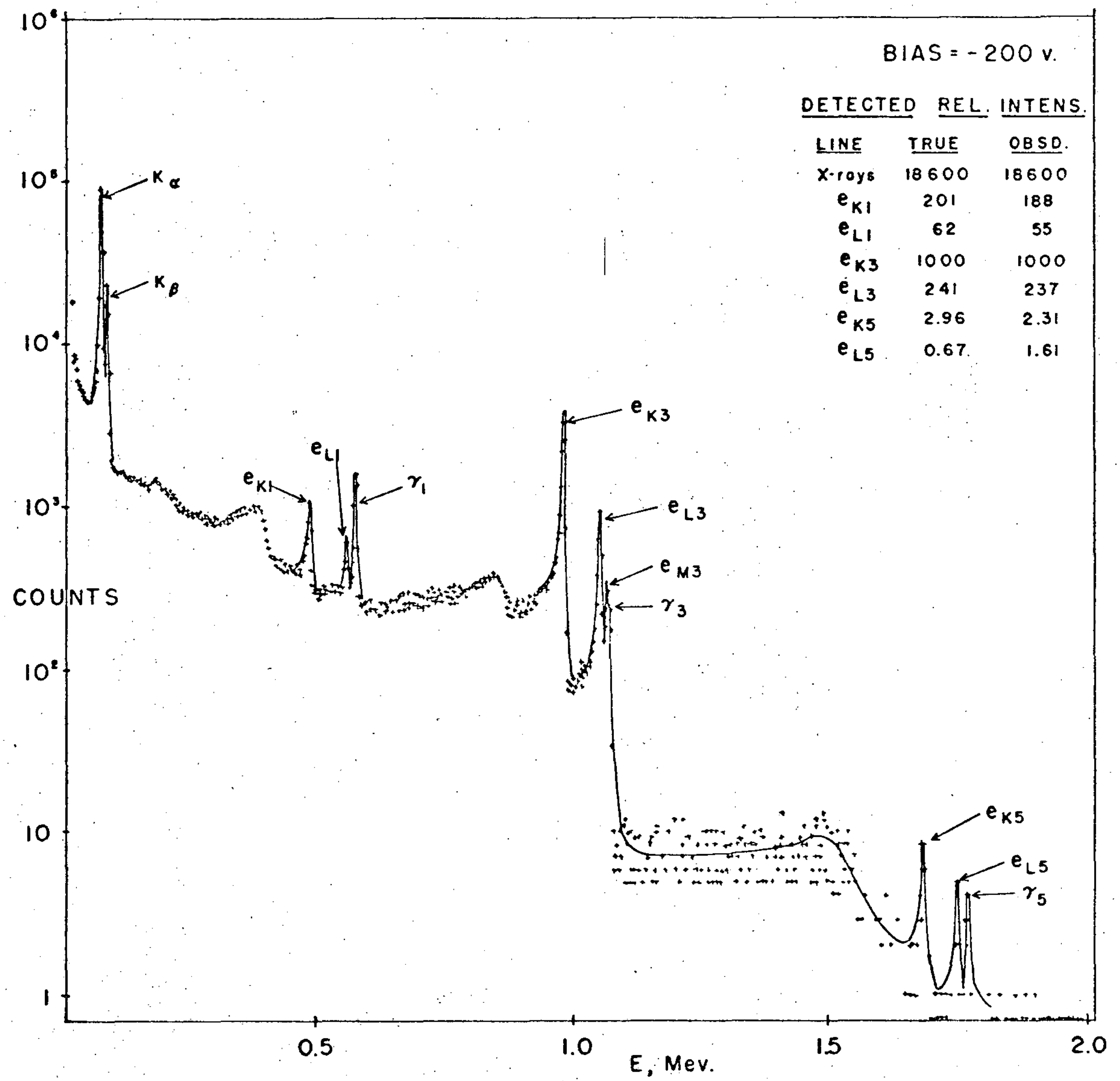
Fig. 2. Response of the particle detectors to ^{207}Bi. The expected and observed intensities of the conversion electron lines are shown in the table. The detector temperature was 16.5°K.

Fig. 3. Axial beta-particle asymmetries $W_+(Ax.) = W(\pi)$ and $W_-(Ax.) = W(0)$ vs. particle energy. The signs correspond to directions of the polarizing field applied to the sample. The upper energy scale is for the ^{186}Re points, while the lower scale refers to the ^{188}Re and ^{194}Ir data. The statistical errors were smaller than the symbols used to represent the data points.



XBL 6912-6720

Fig. 1.



DETECTED	REL. INTENS.	
LINE	TRUE	OBSD.
X-rays	18600	18600
e_{K1}	201	188
e_{L1}	62	55
e_{K3}	1000	1000
e_{L3}	241	237
e_{K5}	2.96	2.31
e_{L5}	0.67	1.61

XBL 6912 -6718

Fig. 2.

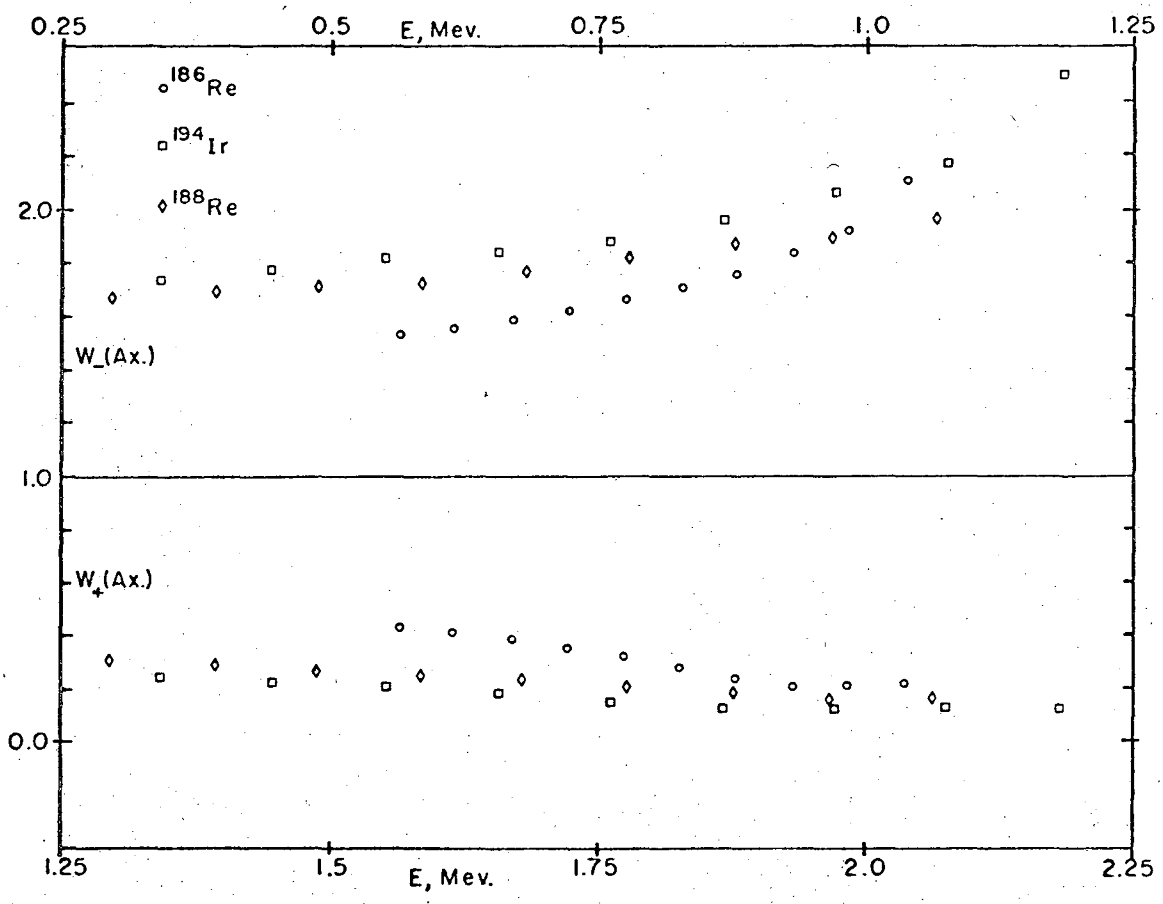


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Fig. 3.

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