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Beta-Spectra of Forbidden Transitions

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The beta-spectra of the forbidden transitions of Y^{91}, Sr^{89}, Y^{90}, Cs^{137}, RaE, Au^{198}, Re^{186}, and P^{32} have been measured with thin sources and high resolution. Forbidden type spectra are found for the first five. Au^{198}, Re^{186}, and P^{32} yield spectra with the allowed shape. Evidence is advanced for the reliability of the nuclear shell structure model and for the validity of G.-T. selection rules. End points found are: Y^{91}, 1.537±0.007 Mev; Sr^{89}, 1.463±0.005 Mev; Y^{90}, 2.180±0.007 Mev; Cs^{137}, 0.51±0.01 Mev; Au^{198}, 0.956±0.005 Mev; Re^{186}, 1.063±0.006; and P^{32}, 1.689±0.01 Mev.

I. INTRODUCTION

SINCE the energy dependence in the allowed form of beta-spectra is mainly determined by the statistical distribution of momentum between the electron and the neutrino, the experimental evidence from measurements of such spectra does not yield information regarding the uniqueness of the Fermi theory or of the possible forms which can be given to it.[1] The spectra of forbidden transitions, however, may, at least in some cases, be expected to have shapes different from that of an allowed transition. The exact form of the momentum distribution in such cases will be determined by the form of the particular interaction between the nucleon and the electron-neutrino field which is assumed. It should be kept in mind, however, that since the forbidden factor may be dominated by terms which are not dependent on energy, it is thus quite possible for once forbidden and even twice forbidden spectra to have the allowed shape. It must also be remembered that selection rules other than those on spin and parity change may operate so as to increase effectively the comparative half-life.[2] Empirical classification of forbiddenness on the basis of such ft values alone may therefore be too high.

Until recently, the beta-spectrum of RaE has been the only distribution which was reported to have a shape unambiguously different from that of an allowed transition.[3]

Although the shape of the RaE spectrum can be accounted for fairly satisfactorily,[2] the explanation involves considerable arbitrariness in the evaluation of the several matrix elements that appear in the forbidden factor. As a result, one cannot come to any definite conclusions regarding the type of interaction on the basis of the RaE results alone.

The present paper reports the results of detailed measurements on the spectra of several transitions, which are empirically classified as forbidden because of their long comparative half-lives. These investigations were instituted for the purpose of determining whether any transition other than RaE might yield a distribution distinctly different from the allowed shape. In particular, it was hoped that some forbidden transition might be discovered which would be consistent with a more specific theoretical description. Such transitions might be expected to occur for example, according to Gamow-Teller selection rules, when the disintegration involves a spin change of one unit higher than the degree of the forbiddenness. For such cases, all but one of the nuclear matrix elements vanish, so that a unique spectrum distribution is predicted. Moreover, the nuclear shell structure analysis[4] can, for certain elements close to the stable configurations, predict the spin and parity of the initial and final states.

The shapes of the spectra reported below for Y^{91} and Sr^{89} are indeed in exact agreement with what is to be expected for transitions involving a spin change of two units and a parity change. These spectra, therefore, are to be classified in terms of spin and parity change as once forbidden in spite of the fact that their comparative half-lives ($ft\sim 5\times 10^8$) would classify them empirically as twice forbidden. These results furnish good evidence for the reliability of the shell model. They also provide evidence for the validity of the G.-T. selection rules, based on spectra shapes. Y^{90} and Cs^{137} are also found to yield forbidden spectra similar to those of Y^{91} and Sr^{89}.

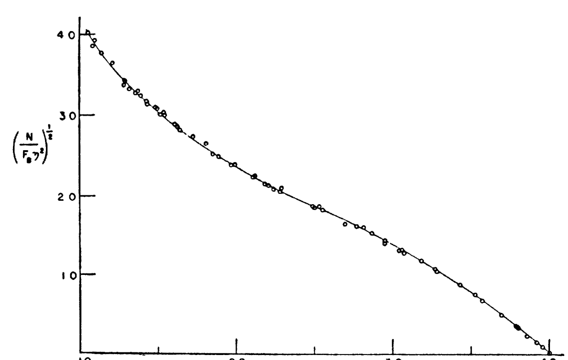

FIG. 1. Conventional Fermi plot for the Y^{91} beta-spectrum.

[1] E. J. Konopinski and G. E. Uhlenbeck, Phys. Rev. **60**, 308 (1941).
[2] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).
[3] G. J. Neary, Proc. Roy. Soc. **A175**, 71 (1940). L. M. Langer, Phys. Rev. **75**, 328 (1949). R. Morrissey and C. S. Wu, Bull. Am. Phys. Soc. **24**, D14 (1948).
[4] E. Feenberg and K. C. Hammack, Phys. Rev. **75**, 1877 (1949).

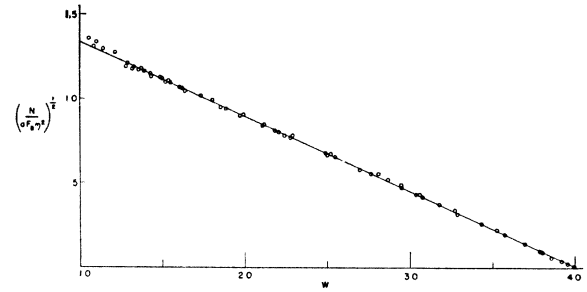

FIG. 2. Forbidden Fermi plot for the Y^{91} beta-spectrum. $a\sim(W^2-1)+(W_0-W)^2$.

The spectra of Re^{186} and Au^{198} were studied because they involve high Z elements in which the half-lives and end points are very similar to those of RaE. Both, however, were found to yield distributions indistinguishable from that of an allowed transition. P^{32} was also found to have the allowed shape.

II. EXPERIMENTAL METHOD

All of the spectra were studied in the 40-cm radius of curvature, shaped field magnetic spectrometer described previously.[5] All sources were 0.4-cm wide and 2.5-cm high. The detecting slit was set at 0.4 cm and the defining slit was set to transmit all particles emerging from the source within an angle of 32 degrees. Under these conditions the resolution is such that, with a thin source, the full width at half maximum for an internal conversion line is 0.5 percent. With such resolution, the influence of the "line" width on the shape of a spectrum is quite negligible.[6] Both grid supported Zapon, and unsupported mica window counters were used in appropriate and overlapping energy regions. Tests show that the presence of the supporting grid, when it is properly designed, does not affect the spectrum distribution. All the sources were supported on a backing of Zapon and LC600 of about 0.02 mg/cm² total thickness. The sources were prevented from acquiring a high electric potential either by means of a grounded graphite covered hair or by a narrow strip of 0.18 mg/cm² aluminum, layed down next to but not touching the end of the radioactive deposit. Insulin was used to help spread the activity over the desired area.[7] The sources were made as thin as was compatible with the activity. Energy determinations are in terms of the 0.5108 Mev annihilation radiation and the 0.411 Mev Au^{198} internally converted gamma-ray.

III. RESULTS

A. Yttrium 91

The source of Y^{91} was obtained carrier free from Oak Ridge, and was further separated from the alkaline earths. The sources used had an average thickness of about 0.15 mg/cm². Our measurements of the decay in terms of a uranium monitor, seem to be in better agreement with the half life of 61 days reported by Grummitt and Wilkinson,[8] than with the previously reported value of 57 days.

The results obtained[9] on the Y^{91} spectrum are shown in terms of the conventional Fermi plot of the data shown in Fig. 1. N is the number of particles per minute per unit momentum interval normalized to constant detector slit acceptance by dividing the actual number detected at any magnetic field strength by the value of

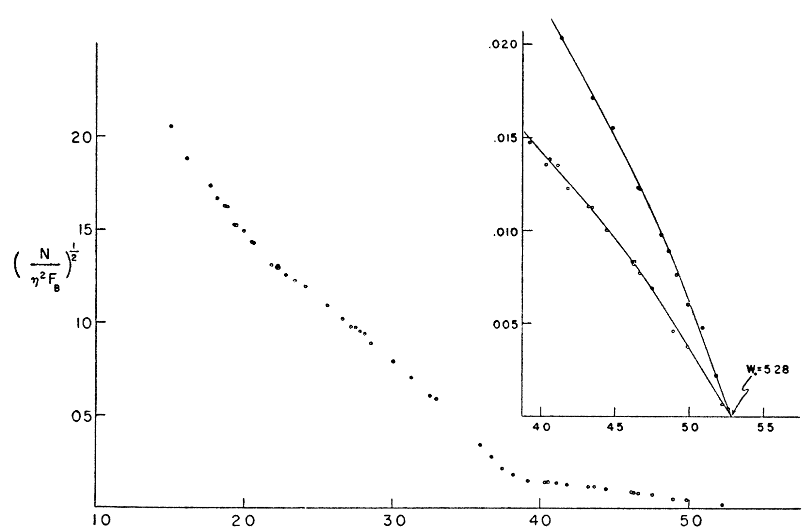

FIG. 3. Conventional Fermi plot for the spectra of Sr^{89} and Sr^{90} in secular equilibrium with Y^{90}. The Y^{90} tail is shown on a larger scale along with data obtained with a stronger source.

[5] L. M. Langer and C. S. Cook, Rev. Sci. Inst. 4, 257 (1948).
[6] G. E. Owen and H. Primakoff, Phys. Rev. 74, 1406 (1948).
[7] L. M. Langer, Rev. Sci. Inst. 20, 216 (1949).
[8] W. E. Grummitt and G. Wilkinson, Nature 158, 163 (1946).
[9] L. M. Langer and H. C. Price, Jr., Phys. Rev. 75, 1109 (1949) is a preliminary report of these results.

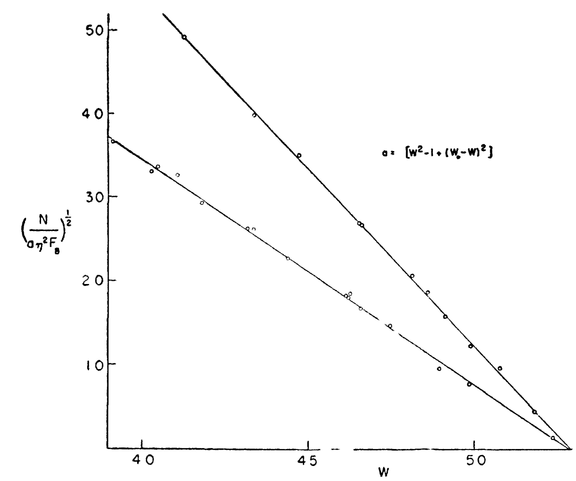

FIG. 4. Forbidden Fermi plot for the Y^{90} spectrum.

the field. η is the electron momentum in units of m_0c and W is the electron energy in units of m_0c^2. F_B is the Coulomb function which has been evaluated by means of the very good approximation given by Bethe and Bacher.[10]

It is apparent from Fig. 1 that the Fermi plot is not the usual straight line which is characteristic of allowed transitions; it is, instead, definitely curved.

Now, according to its comparative half-life ($ft=4.7\times10^8$), one might expect this transition to be twice forbidden. However, Feenberg and Hammack's[4] analysis of nuclear shell structure leads to the prediction of a spin change of 2 units together with a parity change. According to G.-T. selection rules, such a transition is theoretically classified as once-forbidden. According to the theory of forbidden spectra,[1,2] it also has the special property that only one type of nuclear matrix element fails to vanish for it. Thus a unique energy dependence is predicted, differing from the allowed shape by the factor

$$a\sim(W^2-1)+(W_0-W)^2$$

where W_0 is the maximum energy, which in this case is 4.01.

Thus, when the ordinates of the curve of Fig. 1 are divided by $a^{\frac{1}{2}}$, one should obtain a straight line if the above theory is correct. The result of such a plot is shown in Fig. 2.

It is seen that a very good straight line fit is obtained from the end point down to extremely low energies. The slight rise above the straight line below 100 kev may or may not be real.

Y^{91} has been reported as having no γ-radiation.[11] It is found, however, that measurements on a sample which was separated chemically and also by means of an ion exchange column, indicate the presence of extremely weak gamma-radiation with a period of 61 days. Absorption measurements of the gamma-radiation and coincidence absorption of Compton recoils indicate the existence of two quanta, one of 1.22 Mev and the other of about 0.2 Mev. Gamma-gamma-coincidence measurements indicate that these two quanta are in cascade following a beta-transition of less than 0.1 percent the intensity of the main group.† The presence of this feeble gamma-radiation therefore does not affect the interpretation that the main body of the data, reported in Fig. 2, represents the transition directly to the ground state. The Y^{91} end point occurs at 1.537 ±0.007 Mev.

B. Strontium 89 and Yttrium 90

In this case, the source was obtained from Oak Ridge as a mixture of Sr^{89} and about 10 percent Sr^{90} in equi-

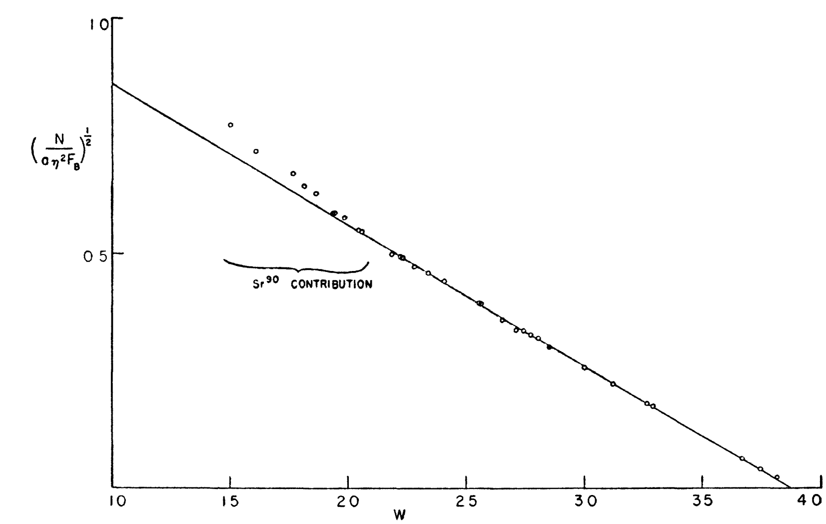

FIG. 5. Forbidden Fermi plot for the Sr^{89} spectrum obtained after correcting for the Y^{90} contribution.

[10] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. 8, 194 (1936).
[11] N. E. Ballou, Plut. Proj. Report CC298D, 4 (1942).
† We are indebted to Mr. E. T. Jurney for kindly making the coincidence measurements and calculations.

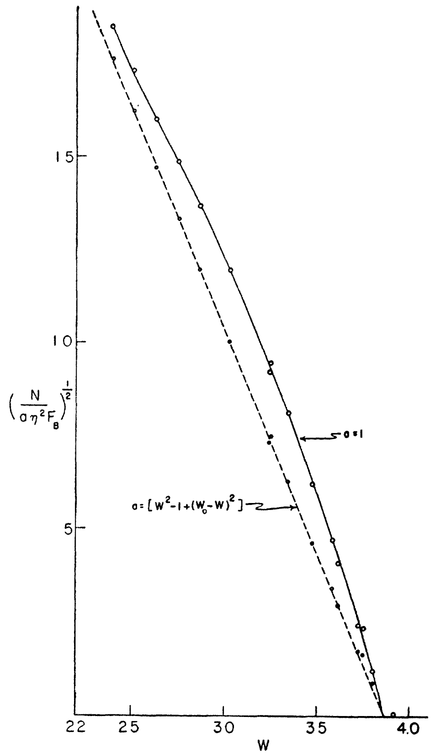

FIG. 6. Conventional and forbidden Fermi plots for data obtained with a source of Sr^{89} from which the Y^{90} had been chemically extracted.

librium with its daughter Y^{90}. Figure 3 shows the conventional Fermi plot of the data obtained with a source of about 0.02 mg/cm² average thickness. A second stronger source was used to obtain somewhat better statistics for the Y^{90} tail.

It is clear from Fig. 3 that both the Y^{90} and Sr^{89} spectra do not yield straight line Fermi plots. Figure 4 shows that application of the same forbidden factor, appropriate to a transition involving a spin change of 2 units and a change of parity, fits the Y^{90} data. After correcting for the Y^{90} contribution in accordance with such a forbidden shape, and again applying the appropriate factor, a, one obtains Fig. 5 for the Sr^{89} distribution. No attempt was made to obtain information about the Sr^{90} shape by means of further subtraction, since such information can be obtained much better with a source from which the shorter lived Sr^{89} isotope has decayed out.[12]

Figure 6 shows both the conventional and forbidden Fermi plots for the Sr^{89} spectrum obtained with a source from which the Y^{90} fraction had been chemically extracted.

It is clear that both Y^{90} and Sr^{89} have forbidden spectra consistent with their being transitions involving a spin change of 2 units and a parity change.

The value of the Sr^{89} end point is 1.463±0.005 Mev. For Y^{90}, we get 2.180±0.007 Mev. This value is somewhat lower than the value recently reported by Meyerhof.[13] His value was obtained on the basis of a straight line interpretation of the conventional Fermi plot, obtained with a thicker source and poorer resolution.*

C. Cesium 137

The data on the Cs^{137} distribution were obtained with several sources, the thinnest of which had an average thickness of 0.03 mg/cm² and the thickest was 0.2 mg/cm². The Fermi plot of the data is shown in Fig. 7. In spite of the fact that there is a very strongly internally converted gamma-ray of 0.663 Mev and a weak

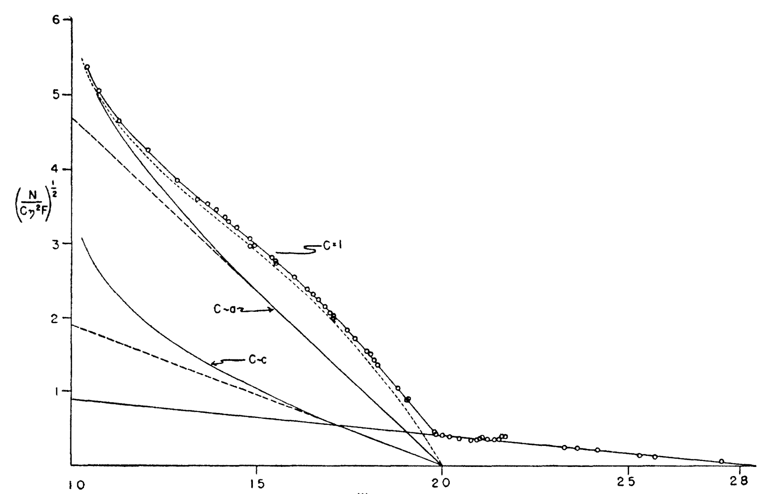

FIG. 7. Conventional and forbidden Fermi plots for the spectrum of Cs^{137}.

[12] Measurements by Jensen and Laslett, Phys. Rev. 75, 1949 (1949), do indeed show that Sr^{90} too has the same forbidden shape satisfied by the factor, a. They are also in agreement with our results on Y^{90}. We are grateful to Dr. Laslett for having made available these results to us prior to publication.

[13] W. E. Meyerhof, Phys. Rev. 74, 621 (1948).

* It is perhaps indicative of the perversity of nature, that thick sources and poor resolution can make straight line Fermi plots appear curved as well as curved Fermi plots appear straight.

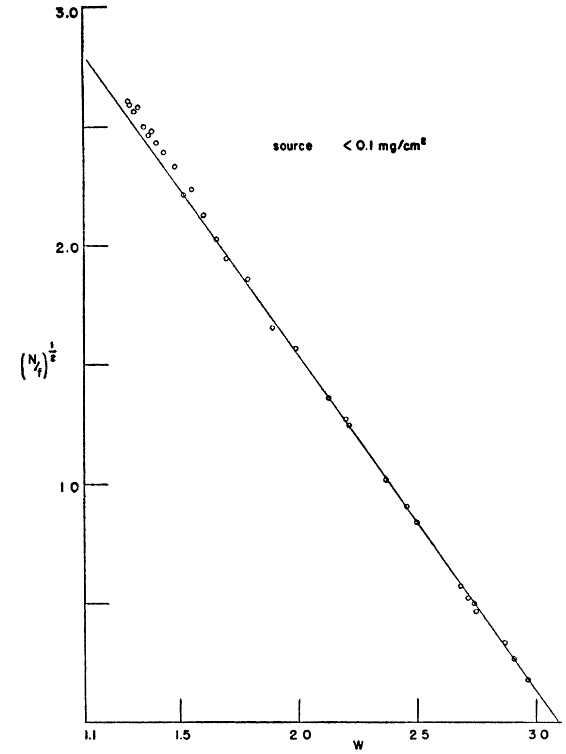

FIG. 8. Conventional Fermi plot for the spectrum of Re^{186}. The Coulomb factor was evaluated by expansion of the complex Γ function.

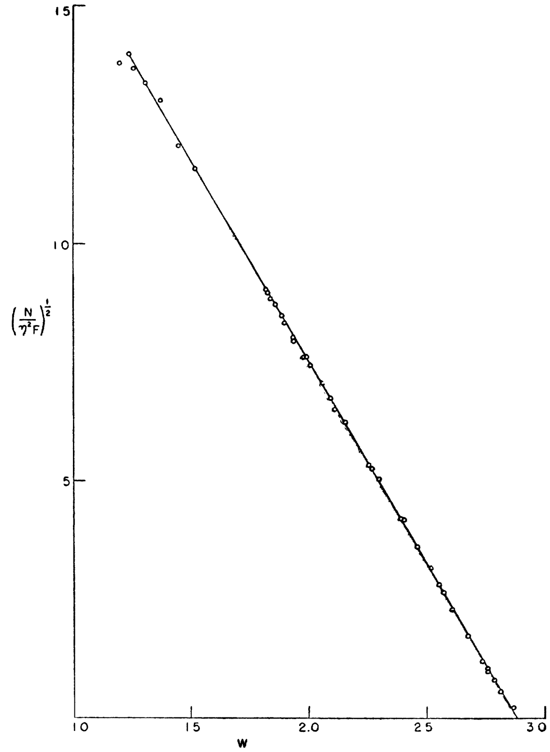

FIG. 9. Conventional Fermi plot for the spectrum of Au^{198}.

high energy group, it is quite apparent that the main spectrum does not give a straight line for the conventional Fermi plot ($C=1$). A detailed investigation of the high energy group seemed to indicate that it might be complex. An ion exchange column separation indicated that at least part of the high energy tail is associated with cesium. Poor statistics prevented a better investigation of this point with a thin source. For purposes of calculation, the high energy contribution has been deducted by assuming that its distribution follows a straight line Fermi plot. The resultant dotted curve obtained for the main transition is not very sensitive to this assumption.

The comparative half-life for Cs^{137} is $\sim 3\times 10^9$. If this transition were twice forbidden with a spin change of 3 units and no parity change, the forbidden factor would again be unique and would have an energy dependence given by

$$C\sim c\sim 3(W^2-1)^2+3(W_0-W)^4+10(W^2-1)(W_0-W)^2.$$

Figure 7 shows the results of applying both $C\sim c$ and $C\sim a$ to the data. It appears that the factor, a, gives a better fit although the agreement is not too good at very low energies.[14] The end point for the main transition to the 0.663 Mev level in Ba^{137} is 0.51 ± 0.01 Mev.

[14] See C. L. Peacock and A. C. G. Mitchell, Phys. Rev. **75**, 1272 (1949).

D. Rhenium 186 and Gold 198

The spectra of Re^{186} and Au^{198}, as mentioned above, were investigated because they are both high atomic number isotopes whose comparative half-lives are very similar to that of RaE. The source of Au^{198}, obtained from Oak Ridge, was chemically separated, particularly from mercury. Sources used for both elements were of the order of 0.1 mg/cm² thick. Figures 8 and 9 show that for both Re^{186} and Au^{198} the ordinary Fermi plot is indistinguishable from a straight line over almost the

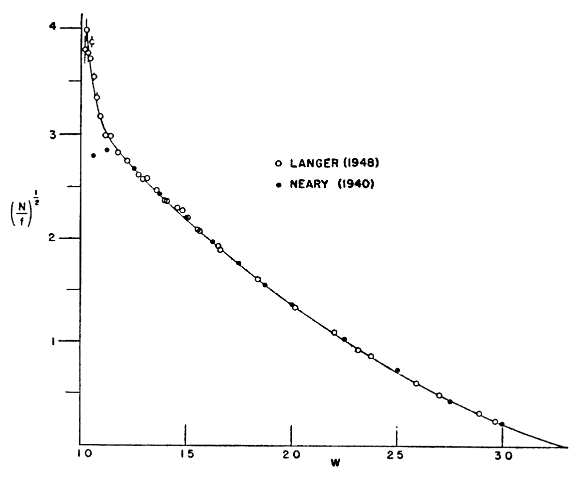

FIG. 10. Conventional Fermi plot for the spectrum of RaE.

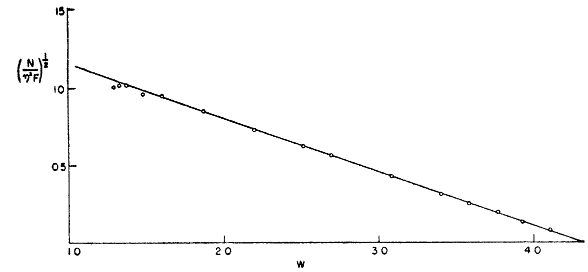

FIG. 11. Conventional Fermi plot for the spectrum of P^{32}.

entire distribution. The value of the end point for Au^{198} is 0.956 ± 0.005 Mev. For Re^{186} we obtain 1.063 ± 0.006 Mev. The spectrum of RaE was remeasured in the same apparatus using an essentially massless source extracted electrolytically from RaD. The ordinary Fermi plot shown in Fig. 10 shows excellent agreement with the earlier work of Neary[3] over the entire distribution. The plot is indeed not satisfied by a straight line. The fact that Neary's curve falls off at low energies may be due to an error in estimating the effect of absorption in the counter window.

E. Phosphorus 32

The spectrum of P^{32} was obtained with an Oak Ridge source of average thickness about 0.2 mg/cm². Here again, a straight line Fermi plot, Fig. 11, is obtained for this apparently forbidden transition. The end point obtained is 1.689 ± 0.01 Mev.

IV. CONCLUSION

The fact that certain forbidden transitions have spectral distributions which can be completely accounted for by means of the forbidden factor $a\sim(W^2-1)+(W_0-W)^2$ is good evidence for the reliability of the nuclear shell structure analysis which predicts a parity change and a spin change of two units for those transitions. It is also evidence for the validity of the G.-T. selection rules. For once-forbidden transitions, a forbidden factor with an energy dependence specified completely by the factor, a, indicates that in those cases, the interaction is of the tensor or axial vector form.

The fact that some apparently forbidden transitions yield spectra having the allowed form, is expected to be quite common for once forbidden transitions. Although it is possible, only for very special conditions should one expect twice forbidden transitions to yield the allowed shape. Since the comparative half-lives may be increased by selection rules other than those applying to spin and parity change, certain apparently twice-forbidden transitions may indeed be only once-forbidden. It would therefore be of interest to examine the spectra of very definitely higher order transitions. The spectra of K^{40}, Be^{10}, Rb^{87}, and Tc^{99} should yield interesting results when measured with high specific activity sources.

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