Shapes of Beta-Ray Spectra

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A survey of the existing data on the shapes of β -ray spectra is given, mostly from the experimental point of view. The majority of the empirical facts accumulated during the past 12 years is reproduced in tables. The problems of Fierz-type and energy-proportional deviations, time reversal, pseudoscalar-type interaction, conservation of vector and axial-vector currents, and neutrino degeneracy are treated.

1. FORMULATION OF ALLOWED β DECAY

The shape of β -ray spectra in the allowed approximation is given by¹

$$N(W)dW = \frac{1}{4}(\xi/\pi^3)F(Z, W)pW(W_0 - W)^2(1 \pm b/W)dW, \quad (1)$$

where

$$\xi = (|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2) |M_F|^2 + (|C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2) |M_{GT}|^2 \quad (2)$$

and

$$b\xi = \gamma(C_S^*C_V + C_S C_V^* + C_S'^*C_V' + C_S' C_V'^*) |M_F|^2 + \gamma(C_T^*C_A + C_T C_A^* + C_T'^*C_A' + C_T' C_A'^*) |M_{GT}|^2. \quad (3)$$

The plus sign in front of b/W is for β^- decay, and the minus sign for β^+ decay. The Fermi function² F includes the finite-size effect. The symbols have their usual meaning: $C_S(C_S')$ is the parity conserving (parity nonconserving) scalar coupling constant, etc., γ is a Coulomb correction term which is almost unity, $M_F(M_{GT})$ is the Fermi (Gamow-Teller) matrix element, and b is the Fierz interference coefficient. In the case of pure Fermi or pure Gamow-Teller transitions, one has

$$b_F = \gamma \frac{C_S^*C_V + C_S C_V^* + C_S'^*C_V' + C_S' C_V'^*}{|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2} \quad (4)$$

and

$$b_{GT} = \gamma \frac{C_T^*C_A + C_T C_A^* + C_T'^*C_A' + C_T' C_A'^*}{|C_T|^2 + |C_A|^2 + |C_T'|^2 + |C_A'|^2}. \quad (5)$$

If the electron polarization is complete ($\mp v/c$ for $\beta^\mp$ decay) the Fierz interference terms vanish auto-

matically. This is particularly true for the generally accepted form of the β interaction, the $V-A$ interaction. In fact, the Fierz terms even vanish for any $V-A$ interaction. On the other hand, the Fierz terms are the most sensitive means of checking experimentally whether these assumptions are correct, in the sense that the experimental upper limit for a Fierz coefficient b , deduced from the experimental evidence on β -interaction type and electron polarization, is larger than from a direct measurement of the Fierz coefficient. This is *a fortiori* true for β^+ decay and for Fermi transitions. The best method for the experimental determination of Fierz coefficients consists of measuring spectral shapes, and not K/β^+ branching ratios. If $b=0$ in Eq. (1), the spectral shape is called statistical, because it depends on the statistical sharing of momentum between electron and neutrino in the phase space.³

Besides Fierz interference, there are other reasons why the spectrum of an allowed β transition, i.e., a transition with spin change $\Delta I=0, \pm 1$ and no parity change, may differ from the statistical shape:

(a) The conservation of vector current⁴ implies small correction terms which, however, are of second order and therefore vanish in the allowed approximation. They are usually barely observable, but are definitely observed in favorite cases⁵ (^{12}B , ^{12}N).

(b) Second-order effects are always present, but usually observable only if the allowed matrix element is extremely small. This effect has been established⁶ for ^{32}P (Gamow-Teller transition). It is generally expected to occur in pure Fermi transitions with isospin change, e.g., ^{66}Ga .

(c) If the neutrino or antineutrino rest mass does not exactly vanish, there will be a deviation at the upper end of the spectrum. Qualitatively, the same will be true for neutrino degeneracy, i.e., if there are

³ E. J. Konopinski and M. E. Rose, *α , β and γ -Ray Spectroscopy*, K. Siegbahn, Ed. (North-Holland Publ. Co., Amsterdam, 1965), Vol. 2, Chap. XXIII.

⁴ M. Gell-Mann, Phys. Rev. **111**, 362 (1958).

⁵ T. Mayer-Kuckuk and F. C. Michel, Phys. Rev. **127**, 545 (1962); N. W. Glass and R. W. Peterson, Phys. Rev. **130**, 299 (1963); Y. K. Lee, L. W. Mo, and C. S. Wu, Phys. Rev. Letters **10**, 253 (1963).

⁶ For a detailed compilation of data, the reader is referred to Tables II-IV.

* Revised version of an invited paper given at the Symposium on Nuclear Beta Decay and Weak Interactions, Zagreb, Yugoslavia, September 1967.

¹ T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956).

² B. S. Dzelepov and L. N. Zyrianova, *The Influence of the Atomic Electron Field on the β Decay* (Akademii Nauk SSSR, Moscow, 1956).

filled neutrino states above zero energy or empty states below zero energy.⁷

(d) Deviations of the b/W type [Eq. (1)], but with a b differing in its meaning from Eqs. (3), (4), and (5), have been reported as results of experimental work with no satisfactory theoretical explanation.^{6,8}

2. FORMULATION OF FORBIDDEN β DECAY

The forbidden β decay is a decay which does not take place in the allowed approximation, but in a higher-order approximation. The first forbidden β decay may again be defined by its selection rules $\Delta I=0, 1$, or 2 with parity change, while the first-forbidden approximation contains first-order terms in λ/R , where λ is the lepton wavelength and R is the nuclear radius, in v_N/c , where v_N is the nucleon velocity in the nucleus, and in the Coulomb term. Correspondingly, the higher-forbidden transitions are defined by their selection rules, and the higher-order approximations by the order of the terms.

This review does not give the formulas for forbidden β decay in full detail, as was done in Eq. (1) for the allowed approximation. Instead, $V-A$ interaction will be assumed unless otherwise stated. The reason is that the basic questions underlying the full description were mostly studied, and are best studied, in allowed β decay.

It is the general custom to describe the shape of a forbidden β spectrum by a correction factor³

$$S_n = \sum_J S_n^{(J)}, \quad (6)$$

where the subscript n refers to the degree of approximation ($n=0$: allowed; $n=1$: first forbidden, etc.), and J refers to the total angular momentum carried away by the two leptons: $J=\Delta I, \Delta I+1, \dots, I_i+I_f$. The meaning of S_n is as follows:

$$N(W)dW = \frac{1}{4}(\xi/\pi^3)F(Z, W)pW(W_0-W)^2S_n(W)dW. \quad (7)$$

In the case of first-forbidden β decay, one has in general

$$S_1 = S_1^{(0)} + S_1^{(1)} + S_1^{(2)}.$$

In a particular transition, one or two of the $S_1^{(i)}$ may vanish. Table I summarizes the selection rules and nuclear matrix elements in allowed and first-forbidden β decay for $V-A$ interaction.⁹

A particular class of forbidden transitions are the unique transitions where a unique angular momentum $J=n+1$ contributes only. Neglecting a Coulomb

correction factor of about unity, one has³

$$S_n^{(n+1)} = \text{const} \sum_{\nu=0}^n p^{2\nu} q^{2(n-\nu)} / [(2\nu+1)!(2n-2\nu+1)!]. \quad (8)$$

This reads for first-, second-, and third-forbidden decays, respectively,

$$S_1^{(2)} = \text{const} (p^2 + q^2), \quad (9)$$

$$S_2^{(3)} = \text{const} [p^4 + (10/3)p^2q^2 + q^4], \quad (10)$$

$$S_3^{(4)} = \text{const} [p^6 + 7p^2q^2(p^2 + q^2) + q^6]. \quad (11)$$

Taking Coulomb corrections into account more properly, Eq. (9) is replaced by

$$S_1^{(2)} = \text{const} (q^2 + 9L_1). \quad (12)$$

[In connection with this formula, $F(Z, W)$ includes the normal finite-size effect, cf. Sec. 1.]

In the case of nonunique transitions, the situation is at first glance even simpler: all first-forbidden non-unique spectra are expected to show roughly a statistical shape. In practice, however, this statement, which was considered to be valid for most transitions for many years, is no longer true. If the famous *RaE* spectrum, whose peculiar shape was known for a long time, is excluded, then the first nonunique first-forbidden spectra, where a deviation from the statistical shape was reported, are the ¹⁸⁶Re spectra.¹⁰ Nowadays, a large number of such spectra are known. Most of them are of interest in connection with nuclear structure, but not weak interaction. They are treated briefly in Sec. 5. Some cases are important for special aspects of weak interaction, such as time-reversal invariance, pseudoscalar interaction, or conserved axial vector current. They will be treated in Secs. 6, 7, and 8. Particularly with regard to the nuclear-structure work, it is often useful to fit the spectral shapes with the formula

$$S_1 = \text{const} [1 + aW + (b/W) + cW^2]. \quad (13)$$

For the connection between the parameters a , b , and c on the one hand, and the matrix elements (Table I) on the other, the paper by Kotani and Ross¹¹ is recommended.

Several papers have appeared¹² which deal with a reformulation of the theory of β decay in terms of form factors. In particular, the aim was to separate more clearly the weak-interaction effects and the nuclear-structure effects. This is certainly important, not only from the point of view of internal consistency. These

¹⁰ F. T. Porter, M. S. Freedman, T. B. Novey, and F. Wagner, Phys. Rev. **103**, 921 (1956).

¹¹ T. Kotani and M. Ross, Progr. Theoret. Phys. (Kyoto) **20**, 643 (1958).

¹² W. Bühring, Nucl. Phys. **40**, 472 and **49**, 190 (1963), and **61**, 110 (1965); B. Stech and L. Schülke, Z. Physik **179**, 314 (1964); L. Schülke, Z. Physik **179**, 331 (1964).

⁷ S. Weinberg, Phys. Rev. **128**, 1457 (1962).

⁸ O. E. Johnson, R. G. Johnson, and L. M. Langer, Phys. Rev. **112**, 2004 (1958).

⁹ H. A. Weidenmüller, Rev. Mod. Phys. **33**, 574 (1961).

formulations are not reviewed here, however, as up to now no unique terminology has been achieved and the great bulk of the experimental information has been evaluated in terms of the old formulation only. The theory in its old formulation is, for example, reviewed by Weidenmüller⁹ and in Siegbahn's handbook,³ while Schopper's book¹³ contains both ways of representation and the connection between the two.

3. EXPERIMENTAL METHODS

The classical instrument for the study of β -ray spectra is the magnetic spectrometer. If it is iron-free, the field strength is strictly proportional to the current, and the field shape does not at all depend on the field strength. However, instruments with iron were also used successfully. One may have a somewhat larger *a priori* confidence in data coming from iron-free instruments. In the same way, a lens spectrometer seems to be more suitable than a spectrometer with transverse field because of a smaller risk of backscattering from the vacuum chamber walls and, in particular, end plates.

Besides the magnetic spectrometer, other types of spectrometers are important and are becoming even more and more important. These are mainly 4π devices such as the scintillation spectrometer, which seems to be most reliable though also most tedious to operate with the activity distributed homogeneously during the crystal-growing process over the total crystal volume. Semiconductor setups are used, preferably in the sandwich arrangements. For low energies, proportional counters may be used.

In a magnetic spectrometer, the corrections which have to be applied to the directly measured intensity distribution are clearly separated and most easily treated. They are mainly caused by source thickness, backing thickness, finite resolving width, and energy-dependent detector efficiency. Other error sources, such as variation of field shape with field strength, backscattering from walls and baffle edges, appearance of ghost lines, etc., are not inevitable. The finite thickness of the source usually leads to an increase of intensity, at least in the case of a fairly thin source and an electron energy not very low. Over most of the usual spectral range this electron excess increases with decreasing electron energy. It is a result of multiple-directional scattering of the electrons, a process which scatters more electrons into the accepted fractional solid angle than out of it.¹⁴ The process is quantitatively understood.¹⁵ At very low energies it is overcompensated by the absorption of electrons in the source material, and an intensity drop results. The shift of electrons due to

the energy loss in the source material must also be taken into account. In most cases it will be sufficient to replace the integral over the Landau distribution by the mean loss for the same energy.

The effect of backscattering from the source backing is subject to some controversy. Though most authors agree that no appreciable backscattering takes place if the backing is, say, two orders of magnitude thinner than the saturation density for electrons of the lowest measured energy, a conflicting result has been reported.¹⁶ The effect of the finite-resolving width is, at least in principle, accurately calculable if the resolution function of the spectrometer is known for all energies occurring in the β spectrum.^{15,17} The main difficulty is the determination of this resolution function. In practice, approximations are sufficient. The resolution correction is most important near the maximum energy W_0 . The detector efficiency is hard to calculate and not easy to measure, in particular, if the detector itself has a real entrance baffle. Measurements on scintillation detectors have been made most exhaustively by Paul.¹⁵

The effect of crystal size on the measured spectral shape in a scintillation spectrometer with built-in activity was investigated by Leutz.¹⁸

Also in the future, the choice of the right or wrong instrument will furnish material for many discussions. The only general, and generally accepted, conclusion from the experimental results is, however, that there exists no strong correlation between results and types of instruments.

4. EXPERIMENTAL DATA ON ALLOWED SPECTRA

During the last decade, many attempts were made to measure the shape of allowed spectra with highest-possible accuracy. Although conflicting results were reported, the situation may be characterized by the statement that in all cases where the allowed approximation is applicable, the spectra show very accurately statistical shapes. Some transitions have been studied most thoroughly either because they are physically most interesting or because the experimental conditions are the most favorable. The following examples will be discussed: ^{22}Na and ^{114}In (Gamow-Teller β^+ and β^- decays, respectively) and ^{13}N (Fermi+Gamow-Teller β^+ decay).

The most accurate shape-factor measurements of ^{22}Na were done by Leutz and co-workers with an NaI crystal, where the activity was built in during the crystal-growing process. Figure 1 shows a recent result.¹⁹ The shape factor is plotted as a function of the β energy.

¹³ H. Schopper, *Weak Interaction and Nuclear Beta Decay* (North-Holland Publ. Co., Amsterdam, 1966).

¹⁴ D. Fehrentz and H. Daniel, *Nucl. Instr. Methods* **10**, 185 (1961).

¹⁵ H. Paul, *Nucl. Instr. Methods* **37**, 109 (1965).

¹⁶ R. Quivy and J. Franeau, *J. Phys. (France)* **26**, 241 (1965).

¹⁷ H. Paul, *Nucl. Instr. Methods* **31**, 307 (1964).

¹⁸ H. Leutz, *Z. Physik* **164**, 78 (1961).

¹⁹ H. Leutz (private communication); H. Wenninger, J. Stiewe, and H. Leutz, *Nucl. Phys.* **A109**, 561 (1968).

FIG. 1. Shape factor of the ^{22}Na β spectrum as measured with a 4π -scintillation spectrometer (one of several runs).¹⁹

As the shape factor is a horizontal straight line and the errors are small, the spectrum follows closely that of the statistical shape. There is no room for Fierz interference or any other deviations whatsoever. The value of b is given in Table II. The work of Leutz *et al.*¹⁹ confirms earlier work with a magnetic spectrometer.²⁰

Although the experimental situation in ^{22}Na is now very clear, the interpretation is not as clear as one may wish with respect to the small experimental errors. The comparative half-life (the ft value) of this decay is somewhat large for an allowed transition. Therefore, noticeable interference with second-order contributions is not *a priori* excluded. It might be, by mischance, that a small Fierz term present in the allowed approximation just cancels with a second-order term. Therefore it is very valuable that a completely statistical shape was also found for the pure Gamow-Teller transition of ^{114}In which has a low ft value.

Figure 2 shows the shape factor²¹ of ^{114}In . Again it is a horizontal straight line.

The transitions of ^{22}Na and ^{114}In are pure Gamow-Teller transitions. There are no pure Fermi transitions which offer favorable experimental conditions. However, ^{13}N is known to decay to $70 \pm 2\%$ by Fermi and to

FIG. 2. Shape factor of the ^{114}In β spectrum as measured with a double-lens spectrometer.²¹

²⁰ H. Daniel, Nucl. Phys. **8**, 191 (1958).

²¹ H. Daniel, G. T. Kaschl, H. Schmitt, and K. Springer, Phys. Rev. **136**, B1240 (1964).

$30 \pm 2\%$ by Gamow-Teller interaction. These figures come from the ft value, the known value of the vector coupling constant, and the model-independent value of the Fermi matrix element. As the experimental conditions are not bad, ^{13}N is a suitable nucleus for checking the shape of a Fermi spectrum, the Gamow-Teller contribution to b being known from, say, ^{22}Na and ^{114}In . Figure 3 shows the ^{13}N shape factor,²² which is also a straight line.

Figure 4 is a shape-factor plot¹⁴ of ^{32}P . There is not much doubt left that this spectrum deviates substantially from the statistical shape. However, there are still arguments regarding the exact form of this deviation—in particular, whether or not the deviation varies linearly with the energy—and about its exact size.⁶ These questions are not immaterial: if the deviation is linear, the polarization is still expected²³ to be $-v/c$; if not, no such conclusion can be drawn. Although details of the interpretation are still the subject of discussions, the deviation can, in general, be understood in terms of nuclear-structure effects.

Besides these examples, other spectra have been carefully examined. Table II gives a compilation. Although no attempt was made to include every allowed β spectrum ever investigated, this compilation was thought²⁴ to include at least the majority of recent results.

Inspection of Table II shows that, as mentioned at the beginning of this section, β -ray transitions,²⁵ which

FIG. 3. Shape factor of the ^{13}N β spectrum as measured with a double-lens spectrometer.²²

²² H. Daniel and U. Schmidt-Rohr, Nucl. Phys. **7**, 516 (1958).

²³ G. Schatz, H. Rebel, and W. Bühring, Z. Physik **177**, 495 (1964).

FIG. 4. Shape factor of the ^{32}P β spectrum as measured with a double-lens spectrometer.¹⁴ Note the small but nonnegligible influence of the source thickness on the slope.

can be expected to show a statistical shape, really do have it. The unexplained b/W deviations reported by some groups were shown not to be present by a large number of experimenters.⁶

5. EXPERIMENTAL RESULTS ON FORBIDDEN β DECAY

This section deals with the general results obtained in forbidden β decay on the basis of the $V-A$ interaction.

Much work was done in order to check the shape of unique first-forbidden β -ray spectra. They are most reliably studied in transitions where one state (initial or final) has spin zero. In this case, J [Eq. (6)] must be 2. These transitions, mostly of the type $2^- \rightarrow 0^+$, are also experimentally very favorable in the sense that many suitable β^- transitions are available. Unfortunately, no suitable β^+ transitions are available.

The most frequently and perhaps also the most carefully studied decay is $^{90}\text{Y}-^{90}\text{Zr}$, where ^{90}Y may or

may not be separated from its parent ^{90}Sr . Figure 5 shows its shape factor²⁴ where, other than with allowed decays (Sec. 4), the expected correction factor $S_1^{(2)}$ [Eq. (12)] is already included in the denominator; hence a horizontal straight line is again expected if $S_1^{(2)}$ [Eq. (12)] describes the shape correctly.

According to Fig. 5 this is not the case. Therefore, the work of Riehs confirms earlier findings^{6,21,25} that a slight deviation exists. In fact, a survey of four $2^- \rightarrow 0^+$ spectra, all with normal ft values (^{42}K , ^{86}Rb , ^{90}Sr , ^{90}Y), showed, within the respective errors, the same percentage-wise decrease of the shape factor between 0 and maximum kinetic electron energy.²¹ An explanation may be found in weak magnetism terms, as Eman *et al.*²⁶ have pointed out (Fig. 6). It would be very interesting to see whether the sign of deviations is opposite for β^+ decay, but there are the experimental difficulties mentioned above. For a report of a large deviation in the β^- decay of ^{166}Ho , cf. Sec. 8.

FIG. 5. Shape factor of the ^{90}Y β spectrum as measured with an intermediate-image spectrometer.²⁴

²⁴ P. Riehs, Nucl. Phys. **75**, 381 (1966).

²⁵ R. T. Nichols, R. E. McAdams, and E. N. Jensen, Phys. Rev. **122**, 172 (1961).

²⁶ B. Eman, F. Krmpotić, D. Tadić, and E. Nielsen, Nucl. Phys. **A104**, 386 (1967).

FIG. 6. Shape factors of first-order unique forbidden β -ray spectra²¹ and fitted theoretical curves.²⁶

Higher-forbidden unique spectra show the expected behavior: ^{10}Be follows Eq. (10)²⁷ and ^{40}K follows Eq. (11).⁶ The experiments, at least on ^{10}Be , are not accurate enough to prove or disprove the existence of small Coulomb corrections or deviations such as that shown in Fig. 4.

Table III is a compilation of unique forbidden-shape factors.

Many nonunique first-forbidden spectra were found to show substantial deviations from the statistical shape. They are summarized in Table IV, as well as the spectra showing a statistical shape and the non-unique higher-forbidden spectra. The spectra of ^{144}Ce , ^{144}Pr , ^{166}Ho , and $^{210}\text{Bi}(\text{RaE})$ are treated in special sections.

6. BETA DECAY OF RaE AND TIME-REVERSAL INVARIANCE

Time reversal in nuclear β decay can be checked in a most straightforward manner by correlation experiments on the decaying free neutron. This was done and yielded a value of $\Theta_{V-A} = 5 \pm 9^\circ$ for the deviation from $V-A$ (the stated error is the standard deviation).²⁸

²⁷ L. Feldman and C. S. Wu, Phys. Rev. **78**, 318 (1950).

²⁸ M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. **120**, 1829 (1960).

In the RaE decay, thanks to a very peculiar destructive interference, there is also a chance to test this very important symmetry principle. The experiments can be performed with a much better statistical accuracy than in the free neutron case. On the other hand, the interpretation of the experimental data is not so straightforward.

A most thorough evaluation of all experimental information which is available includes both the spectral shape and the electron polarization as a function of the energy or, more adequately, of c/v . Figure 7 shows the RaE spectral shape factor.²⁹ As this is not at all a straight line, the spectrum deviates very strongly from the statistical shape. This abnormal behavior makes the analysis very unpleasant. With the help of the very elaborate theory of Fujita *et al.*,³⁰ the present author analyzed his shape-factor measurement and treated both the matrix elements and Θ_{V-A} as completely free parameters. The result was $\Theta_{V-A} = 4.5 \pm 1.0^\circ$. This is, however, no real indication of a violation of time reversal, as Θ_{V-A} vanishes within three times the experimental standard deviation. The reason why this is so is the large curvature of Θ_{V-A} as function of the

FIG. 7. Shape factor of the RaE β spectrum as measured with a double-lens spectrometer.²⁹

²⁹ H. Daniel, Nucl. Phys. **31**, 293 (1962).

³⁰ J. Fujita, M. Yamada, Z. Matumoto, and S. Nakamura, Progr. Theoret. Phys. (Kyoto) **20**, 287 (1958).

experimentally determined quantity α_{V-A} . Therefore the usually applied linear-error computation fails completely in this special case. As stated in the original paper of the RaE spectrum, the experimental result is in agreement with time-reversal invariance. Recent analyses of the RaE decay by Sodemann and Winther, and Vinduška and Šott³¹ came to the same conclusion. We can deduce that $\Theta_{V-A} < 6^\circ$ with a confidence level of 95%, in comparison with $\Theta_{V-A} < 23^\circ$ with the same confidence level from the free neutron decay.

A very recent experiment³² on a polarized ^{19}Ne beam yielded $\Theta_{V-A} = -0.2 \pm 1.6^\circ$. This results in $|\Theta_{V-A}| < 3.4^\circ$, again with a 95% confidence level.

As the nuclear β decay is leptonic and the decays of the long-lived K meson into two π mesons ($K_L^0 \rightarrow \pi^+\pi^-$ and $K_L^0 \rightarrow \pi^0\pi^0$) are nonleptonic, there is no direct connection whatsoever between T (or CP) violation in the latter case and Θ_{V-A} for nuclear β decay.

7. PSEUDOSCALAR INTERACTION

By means of a large number of experiments, the weak interaction was shown to be of the $V-A$ type. All evidence is also in favor of the interaction being universal. If one believes in this universality *a priori*, then the most crucial test of a pseudoscalar part in the weak interaction is the branching ratio of the π decay, $R = (\pi \rightarrow e + \nu_e) / (\pi \rightarrow \mu + \nu_\mu)$, where the theoretical estimate for $V-A$ interaction and experimental value³³ $R = (1.24 \pm 0.03) 10^{-4}$ coincide very nicely. R is small, as the $\pi-e$ decay is greatly hindered by the helicity requirement for the e . If the interaction would be pseudoscalar, i.e., with opposite helicity $+v/c$ for the negative electron, then R would be about 5 due to phase-space effects.

If one does not believe in the universality of the Fermi interaction *a priori*, one has to look for direct experimental evidence in favor of or against pseudoscalar interaction in nuclear β decay. Because of the selection rules, this cannot be done in allowed β decay, but it can be done in first-forbidden β decay, particularly 0-0 transitions. Besides this primary pseudoscalar interaction, there may also be an induced pseudoscalar interaction which arises from the strong interaction. Both imply the same experimental consequences. Induced pseudoscalar interaction apparently takes place in μ capture.

When searching for pseudoscalar interaction in nuclear β decay, the $0^- \rightarrow 0^+$ transition $^{144}\text{Pr} \rightarrow ^{144}\text{Nd}$ is particularly suitable—if it is allowed to call any β

transition suitable for this purpose. Bhalla and Rose³⁴ first outlined an elaborate theory and compared it with experiments. They concluded $|C_P|/|C_A| < 90$ —which is a large number for an upper limit. Later experimental work done in Heidelberg³⁵ also yielded no evidence for a pseudoscalar contribution. An upper limit of $|C_P|/|C_A| < 5$ was reported, but this was due to a numerical error (caused by a computer with a too low capacity), as kindly pointed out to the author by Porter.³⁶ Therefore a reevaluation with a more suitable computer is planned.

8. CONSERVATION OF VECTOR AND AXIAL-VECTOR CURRENT AND G PARITY

The concept of a conserved vector current⁴ (CVC) is recommended by electrodynamics, as the vector-current part of the weak interaction is analogous to electrodynamics, and there the electric charge is conserved. It is also experimentally recommended in order to explain the fact that muon and nuclear vector β -decay coupling constants are equal, with no renormalization due to strong interaction [leaving a difference of about 2% to be explained by the Cabibbo angle].³⁷ Experimental evidence, amongst other, came also from spectral shape measurements of suitable β transitions (^{12}B , ^{12}N), where, due to a large energy release and a large $M1$ matrix element, this twice-forbidden correction to the allowed approximation becomes measurable.⁵

Another way of verifying the CVC theory is even more tightly connected with electrodynamics and is an extension of the Siegert theorem in electrodynamics. In fact, first evidence from experiment for the CVC theory was obtained by Fujita from the RaE spectrum.³⁸ Many attempts were undertaken later to prove or disprove this theorem on a large number of β transitions, particularly by J. Deutsch and co-workers. As the CVC theory predicts a ratio of matrix elements to have a given value and matrix elements usually cannot be determined from spectral shapes only, this work is not a subject for detailed treatment in this paper; in the case of RaE, however, the spectral shape alone is sufficient.

The axial-vector-current part of the weak interaction has no analog in electrodynamics. It is not surprising that it is not completely conserved. This is manifested by the ratio $|C_A|/|C_V| = 1.19 \pm 0.02$ ³⁹ or 1.23 ± 0.01 ⁴⁰ instead of unity.

There may, however, be a partially conserved axial-

³¹ J. Sodemann and A. Winther, Nucl. Phys. **69**, 369 (1965); M. Vinduška and M. Šott, preprint, Nuclear Research Institute; Režů Praha, Czechoslovakia (unpublished).

³² F. P. Calaprice, E. D. Commins, H. M. Gibbs, G. L. Wick, and D. A. Dobson, Phys. Rev. Letters **18**, 918 (1967).

³³ A. H. Rosenfeld, A. Barbaro-Galtieri, W. J. Podolsky, L. R. Price, M. Roos, P. Soding, W. J. Willis, and C. G. Wohl, Rev. Mod. Phys. **39**, 1 (1967).

³⁴ C. P. Bhalla and M. E. Rose, Phys. Rev. **120**, 1415 (1960).

³⁵ H. Daniel and G. T. Kaschl, Nucl. Phys. **76**, 97 (1966).

³⁶ F. T. Porter (private communication).

³⁷ N. Cabibbo, Phys. Rev. Letters **10**, 531 (1963).

³⁸ J. I. Fujita, Phys. Rev. **126**, 202 (1962).

³⁹ H. Daniel and H. Schmitt, Nucl. Phys. **65**, 481 (1965).

⁴⁰ C. J. Christensen, A. Nielsen, A. Bahnsen, W. K. Brown, and B. M. Rustad, Phys. Letters **26B**, 11 (1967).

FIG. 8. ${}^3\text{H}$ Fermi plot as measured with a 180° shaped-field spectrometer,⁴⁶ for the determination of the antineutrino rest mass.

vector current (PCAC). Krmpotić and Tadić⁴¹ made attempts to draw conclusions from spectral shapes of $0^- \rightarrow 0^+$ transitions.

Unfortunately, the experimental situation which is the basis of theoretical analysis is not at all clear for the three transitions which are suitable: ${}^{144}\text{Ce} \rightarrow {}^{144}\text{Pr}$, ${}^{144}\text{Pr} \rightarrow {}^{144}\text{Nd}$, and ${}^{166}\text{Ho} \rightarrow {}^{166}\text{Er}$. The most favorable experimental conditions are those found in the decay of ${}^{144}\text{Pr}$. Here, a recent result from Heidelberg³⁵ is in fair agreement with earlier work,^{6,42} but there are small differences which may lead to conflicting conclusions.⁴¹ No experimental differences exist for ${}^{144}\text{Ce}$, as there is only one measurement,³⁵ but the spectrum was obtained by subtracting the ${}^{144}\text{Pr}$ spectrum extrapolated down to low energies from the measured (${}^{144}\text{Ce} + {}^{144}\text{Pr}$) spectrum. This extrapolation procedure is, of course, doubtful in the case of a complicated and not yet understood spectrum such as that of ${}^{144}\text{Pr}$. The Heidelberg³⁵ result for ${}^{166}\text{Ho}$ is also obtained by subtraction of a computed component from the measured sum spectrum. Here the component is of the first-forbidden unique type. Its shape should be known, except for an uncertainty coming from the presence or nonpresence of a small correction term, treated in Sec. 5. However, a recent direct measurement⁴³ of this unique component yielded a large deviation. If this is really true, then the new shape factor must be taken for the subtraction, and a differing shape for the $0^- \rightarrow 0^+$ component will result from the measurement of the sum spectrum.

The ${}^{144}\text{Pr}$ shape as measured at Argonne⁴² can be explained with a PCAC and with no G -parity violation, while the ${}^{144}\text{Pr}$ and ${}^{166}\text{Ho}$ shapes as measured in Heidelberg³⁵ can be explained only with G -parity violation.⁴¹

⁴¹ F. Krmpotić and D. Tadić, preprint, Institute "Ruđer Bošković", Zagreb, Yugoslavia (unpublished); and Phys. Letters **21**, 680 (1966).

⁴² F. T. Porter and P. P. Day, Phys. Rev. **114**, 1286 (1959).

⁴³ H. Beekhuis, thesis, University of Groningen, Groningen, 1967 (unpublished).

9. NEUTRINO REST MASS AND NEUTRINO DEGENERACY

The question of the neutrino rest mass has always been interesting since the first postulation of this particle by Pauli.⁴⁴ As a particle with vanishing rest mass always moves with the velocity of light, but a particle with nonvanishing rest mass at small kinetic energy behaves nonrelativistically, one expects the largest deviation to show up near the β end point, where the neutrino energy is very small. As the absolute resolving width ΔE or Δp of any of the suitable spectrometers increases with increasing energy E , it is advantageous to investigate transitions with low maximum energy E_0 . For β^- decay, tritium (${}^3\text{H}$) is best suited. This gives the antineutrino mass. If one does not believe in the particle-antiparticle concept *a priori*, one has also to measure a β^+ emitter. Unfortunately, no β^+ emitter with high intensity and low maximum energy is provided by nature, because of competing electron capture. ${}^{22}\text{Na}$ seems to be a suitable compromise.

Neutrino degeneracy in general, i.e., the availability of empty neutrino or antineutrino states below zero energy and the nonavailability of states above zero energy, gives also deviations at the end of the β spectrum, either below the end point extrapolated from the Fermi plot (states of positive energy are filled) or above the end point (states of negative energy are empty). If the particle-antiparticle concept for neutrino and antineutrino (here defined as the chargeless particle emitted in β^+ and β^- decay, respectively) is correct, then empty neutrino states below zero are connected with filled antineutrino states above zero, and vice versa. Details, also with regard to cosmology, were given by Weinberg.⁷

Experimentally no indications of finite (anti-)

⁴⁴ W. Pauli, in *Proceedings of the Solway Congress, 1933* (Gauthier-Villars, Paris, 1934), p. 324.

TABLES

TABLE I. Allowed and first-forbidden nuclear matrix elements with V and A coupling constants and their selection rules (J designates the rank of the transition operator, when regarded as a tensor).

Matrix element	J	ΔI	$\Delta\pi$
Allowed			
$C_V f_1$	0	0	no
$C_A f_0$	1	0, ± 1 (no $0 \rightarrow 0$)	no
First forbidden			
$C_A f_{\gamma s}$	0	0	yes
$C_A f_{\sigma \cdot r/i}$	1	0, ± 1 (no $0 \rightarrow 0$)	yes
$C_V f_{ri}$			
$C_V f_{\alpha}$			
$C_A f_{(\sigma \times r)}$	2	0, $\pm 1, \pm 2$ (no $0 \rightarrow 0$, no $0 \rightarrow 1$, no $\frac{1}{2} \rightarrow \frac{1}{2}$)	yes
$C_A f_{iB_{ij}}$			

neutrino rest mass or of neutrino degeneracy were found. The presently known upper limit for the anti-neutrino rest mass comes from two experiments on tritium, both performed long ago.^{45,46} Although somewhat lower upper limits are given in the respective papers, the present author is inclined to state only an upper limit of 1 keV, at a confidence level of 90%. However, there are experiments in progress which one can hope will yield a lower upper limit.

Figure 8 shows the ^3H Fermi plot as measured by Langer and Moffat.⁴⁵

For the neutrino (from β^+ decay) no direct value was available until very recently. Now a preliminary result has been obtained in Heidelberg,⁴⁷ $m_\nu < 6$ keV at 90% confidence.

From Fig. 8 one may conclude that the antineutrino Fermi energy is

$$E_F^{(\bar{\nu})} < 1 \text{ keV.}$$

TABLE II. Allowed β spectra.

Nuclide	States	log ft	E_0 (MeV)	Coefficients [a , (mc ²) ⁻¹ ; b , mc ²]	Author and Year	Ref.
^6He	$0^+ \rightarrow 1^+$	2.9	3.50	$-0.20 < b < 0.08$	Schwarzschild	57 T1
^{12}B	$1^+ \rightarrow 0^+$	4.1	13.38	$a = 0.0093 \pm 0.0004$ $a = 0.0027 \pm 0.0005$	Mayer-Kuckuk <i>et al.</i> Lee <i>et al.</i>	62 T2 63 T3
^{12}N	$1^+ \rightarrow 0^+$		16.36 16.43	$a = 0.0031 \pm 0.0004$ $a = -0.0026 \pm 0.0003$	Mayer-Kuckuk <i>et al.</i> Lee <i>et al.</i>	62 T2 63 T3
^{13}N	$\frac{1}{2}^- \rightarrow \frac{1}{2}^-$	3.7	1.190	$b = 0.001 \pm 0.024$	Daniel <i>et al.</i>	58 T4
^{14}O	$0^+ \rightarrow 1^+$	7.33	4.12	$a \sim -0.055$ at 3 MeV	Sidhu <i>et al.</i>	66 T5
^{18}F	$1^+ \rightarrow 0^+$	3.6	0.635	$a = 0.0034 \pm 0.0091$	Hofmann	64 T6
^{22}Na	$3^+ \rightarrow 2^+$	7.4	0.543 0.545 0.544	$0.25 < b < 0.35$ $b = -0.016 \pm 0.020$ $b = 0.0008 \pm 0.0020$ $0.1 < b < 0.3$	Hamilton <i>et al.</i> Daniel Leutz Brantley <i>et al.</i>	58 T7 58 T8 61 T9 64 T10
^{24}Na	$4^+ \rightarrow 4^+$	6.1	1.394	$b = 0.001 \pm 0.003$ $-0.026 < b < 0.020$	Leutz <i>et al.</i> Porter <i>et al.</i>	67 T11 57 T12
			1.389	$\left\{ \begin{array}{l} a = -0.0150 \pm 0.0045 \\ \text{or} \\ b = 0.072 \pm 0.023 \end{array} \right\}$	Daniel	58 T8
			1.388	$a = 0.000 \pm 0.005$	Depommier <i>et al.</i>	61 T13
			1.392	$a = -0.012 \pm 0.006$	Paul <i>et al.</i>	63 T14
			1.363	$a = -0.005 \pm 0.007$	Lehmann	64 T15
			1.394	$a = 0.002 \pm 0.010$ [allowed shape within 1%]	Beekhuis <i>et al.</i> Lehmann	65 T16 67 T17
^{32}P	$1^+ \rightarrow 0^+$	7.9	1.712	$b = 0.03 \pm 0.04$	Pohm <i>et al.</i>	56 T18
			1.712	$b = -0.032 \pm 0.045$	Pohm <i>et al.</i>	56 T18
			1.711	$0.05 < b < 0.093$	Porter <i>et al.</i>	57 T12
			1.705	$a = -0.041 \pm 0.013$	Daniel	58 T8
				$a \sim -0.02$	Graham <i>et al.</i>	58 T19
			1.711	$0.2 < b < 0.4$	Johnson <i>et al.</i>	58 T20
				[see original]	Brabec <i>et al.</i>	60 T21
			1.708	$a = -0.0133 \pm 0.0011$	Nichols <i>et al.</i>	61 T22
			1.705	$a = -0.042 \pm 0.010$	Fehrentz <i>et al.</i>	61 T23
			1.706	$a = -0.03$	Depommier <i>et al.</i>	61 T13
				$\left\{ \begin{array}{l} a = -0.025 \pm 0.007 \\ \text{and} \\ b = 0.12 \pm 0.05, \\ \text{or} \\ b = 0.195 \pm 0.020 \end{array} \right\}$	Ch'ing-Ch'eng Jui <i>et al.</i>	62 T24
			1.700	$a = -0.025$	Sharma <i>et al.</i>	63 T25
				$a \sim 0$	Quivy <i>et al.</i>	65 T26
				$a = 0 \pm 0.01$	Persson <i>et al.</i>	65 T27
			1.71	$\left\{ \begin{array}{l} a = -0.09 \text{ (300-600 keV)} \\ a = -0.01 \text{ (600-1650 keV)} \end{array} \right\}$	Lehmann	65 T28
			1.697	$a \sim 0.003$	Canty <i>et al.</i>	66 T29

⁴⁵ L. M. Langer and R. J. D. Moffat, Phys. Rev. **88**, 689 (1952).

⁴⁶ D. R. Hamilton, W. P. Alford, and L. Gross, Phys. Rev. **92**, 1521 (1953).

⁴⁷ E. Beck and H. Daniel, *Symposium on Nuclear β Decay and Weak Interactions*, Zabreb, Yugoslavia (1967).

TABLE II (Continued)

Nuclide	States	log ft	E_0 (MeV)	Coefficients [$a, (mc^2)^{-1}; b, mc^2$]	Author and Year	Ref.
^{41}A	$\frac{7}{2}^- \rightarrow \frac{7}{2}^-$	5.0	1.198	$a = -0.017 \pm 0.005$	Paul	64 T30
^{47}Ca	$\frac{7}{2}^- \rightarrow \frac{7}{2}^-$	8.5	1.979	$0 < b < 0.3$	Langer <i>et al.</i>	63 T31
		8.5	1.981	[shape nearly statistical]	Hsue <i>et al.</i>	67 T32
^{56}Mn	$3^+ \rightarrow 2^+$	7.2	2.838	$0 < b < 0.3$	Howe <i>et al.</i>	62 T33
^{56}Co	$4^+ \rightarrow 4^+$	8.7	1.46	$0.2 < b < 0.3$	Hamilton <i>et al.</i>	61 T34
^{58}Co	$2^+ \rightarrow 2^+$	6.6	0.474	$b = 0.3$	Rhode <i>et al.</i>	63 T35
^{60}Co	$5^+ \rightarrow 4^+$	7.5	0.32	$a \sim 0$	Bonhoeffer	59 T36
^{66}Ga	$0^+ \rightarrow 0^+$	7.8	4.153	[complicated]	Camp <i>et al.</i>	63 T37
		7.9	4.15	[$\sim 7\%$ decrease (1.8–3.8 MeV)]	van Neste <i>et al.</i>	67 T38
^{89}Zr	$\frac{9}{2}^+ \rightarrow \frac{9}{2}^+$	6.1	0.90	$0.25 < b < 0.45$	Hamilton <i>et al.</i>	60 T39
^{110m}Ag	$6^+ \rightarrow 6^+$	8.2	0.529	$a = -0.01 \pm 0.03$	Daniel <i>et al.</i>	63 T40
^{114}In	$1^+ \rightarrow 0^+$	4.4	1.996	$0.2 < b < 0.3$	Johnson <i>et al.</i>	58 T20
			1.989	$a = 0.0036 \pm 0.0021$	Nichols <i>et al.</i>	61 T22
			1.987	$b = 0.05 \pm 0.02$	Daniel <i>et al.</i>	61 T41
			1.988	$a = -0.0015 \pm 0.0030$	Daniel <i>et al.</i>	64 T42
				$\text{or } b = 0.005 \pm 0.022$		
				$a = -0.0005 \pm 0.0020$	André <i>et al.</i>	64 T43
^{131}I	$\frac{7}{2}^+ \rightarrow \frac{5}{2}^+$	6.6	0.606	$a = 0.02 \pm 0.02$	Daniel <i>et al.</i>	64 T44
^{134}Cs	$4^+ \rightarrow 4^+$	8.8	0.658	[statistical shape]	Hsue <i>et al.</i>	68 T45
				(0.415–0.658 MeV)		
	$4^+ \rightarrow 3^+$	9.5	0.415	[statistical shape]		
				(0.090–0.415 MeV)	Hsue <i>et al.</i>	68 T45
^{156}Eu	$0^+ \rightarrow 0^+$	9.8	2.48	[$\sim 2\%$ decrease]	van Neste <i>et al.</i>	67 T46
				(1.42–2.25 MeV)		

TABLE III. Unique forbidden β spectra.

Nucleus	States	log ft	Forbidden	E_0 (MeV)	Coefficients ^a [$a, (mc^2)^{-1}; b, mc^2$]	Author and Year	Ref.
^{41}A	$\frac{7}{2}^- \rightarrow \frac{3}{2}^+$	8.6	1st	2.48	$a = 0.00 \pm 0.01$	Kartashov	61 T47
^{42}K	$2^- \rightarrow 0^+$	8.4	1st	3.52	$a = -0.010 \pm 0.004$	Daniel <i>et al.</i>	64 T42
^{84}Rb	$2^- \rightarrow 0^+$	8.5	1st	1.657	$b = 0.2$	Langer <i>et al.</i>	64 T48
^{86}Rb	$2^- \rightarrow 0^+$	8.4	1st	1.774	$a = -0.017 \pm 0.002$	Daniel <i>et al.</i>	64 T42
^{90}Sr	$0^+ \rightarrow 2^-$	8.3	1st	0.546	$a = -0.054 \pm 0.019$	Daniel <i>et al.</i>	64 T42
^{88}Y	$4^- \rightarrow 2^+$	8.6	1st	0.76		Rhode	63 T49
^{90}Y	$2^- \rightarrow 0^+$	8.3	1st	2.261	$0.2 < b < 0.3$	Johnson <i>et al.</i>	58 T20
				2.265	$b = 0.025$	Yuasa	57 T50
				2.271	$a = -0.0047 \pm 0.0008$	Nichols <i>et al.</i>	61 T22
				2.268	$b = 0.26 \pm 0.03$	André <i>et al.</i>	64 T43
				2.273	$0.3 < b < 0.4$	Langer <i>et al.</i>	64 T51
				2.284	$a = -0.0072 \pm 0.0032$	Daniel <i>et al.</i>	64 T42
				2.280	$a = -0.0066 \pm 0.0013$	Riehs	66 T52
^{91}Y	$\frac{1}{2}^- \rightarrow \frac{5}{2}^+$	8.5	1st	1.545	$0.3 < b < 0.4$	Langer <i>et al.</i>	64 T51
^{142}Pr	$2^- \rightarrow 0^+$	7.8	1st	2.164	$a = -0.025 \pm 0.003$	Beekhuis	66 T53
^{166}Ho	$0^- \rightarrow 2^+$	8.0	1st	1.78	$a = -0.105 \pm 0.010$	Beekhuis	66 T53
^{172}Tm	$2^- \rightarrow 0^+$	8.6	1st	1.87	[shape like ^{90}Y]	Hansen <i>et al.</i>	66 T54
^{172}Tm	$2^- \rightarrow 4^+$	9.8	1st	1.61	[shape like ^{90}Y]	Hansen <i>et al.</i>	66 T54
^{187}Re	$\frac{5}{2}^+ \rightarrow \frac{1}{2}^-$		1st	0.0026	$[q^2 + \lambda_2 p^2]$	Huster <i>et al.</i>	67 T55
^{198}Au	$2^- \rightarrow 0^+$	11.3	1st	1.37	[see original paper]	Elliott <i>et al.</i>	54 T56
^{204}Tl	$2^- \rightarrow 0^+$	9.0	1st	0.76	$a \sim -0.02$	Egelkraut	60 T57
					[deviation at $E < 90$ keV]	Leutz <i>et al.</i>	62 T58
^{10}Be	$0^+ \rightarrow 3^+$	14.5	2nd	0.555	[upper $\frac{3}{4}$ 2nd unique shape]	Feldman <i>et al.</i>	50 T59
^{22}Na	$3^+ \rightarrow 0^+$	~ 13	2nd	1.83	[2nd unique shape]	Wright	53 T60
^{60}Co	$5^+ \rightarrow 2^+$	12.7	2nd	1.48	$[p^2 + 5.79 q^2]$	Keister	54 T61
				1.48	[2nd unique shape]	Wolfson	56 T62
^{40}K	$4^- \rightarrow 0^+$	18.1	3rd	1.30	[3rd unique shape]	Leutz <i>et al.</i>	65 T63

^a Deviations from unique shape.

TABLE IV. Nonunique forbidden β spectra.

Nucleus	States	log ft	Forbidden	E_0 (MeV)	Coefficients [$a, (mc^2)^{-1}; b, mc^2; c, (mc^2)^{-2}$]	Author and Year	Ref.
^{42}K	$2^- \rightarrow 2^+$	7.5	1st	1.98	$0 < a < 0.01$	Pohm <i>et al.</i>	56 T18
				2.00	$\left\{ \begin{array}{l} a = -0.12 \pm 0.04 \text{ and} \\ b = 0.67 \pm 0.06 \text{ and} \\ c = 0.013 \pm 0.008 \end{array} \right\}$	André <i>et al.</i>	64 T64
				2.00	$\left\{ \begin{array}{l} a = 0.15 \pm 0.26 \text{ and} \\ b = 0.81 \pm 0.47 \text{ and} \\ c = -0.02 \pm 0.03 \end{array} \right\}$	Daniel <i>et al.</i>	65 T65
^{72}Ga	$3^- \rightarrow 2^+$	9.2	1st	3.15	$[q^2 + 0.95p^2 + 15 \pm 10]$	Langer <i>et al.</i>	60 T66
^{72}Ga	$3^- \rightarrow 2^+$	8.7	1st	2.52	$[q^2 + 0.95p^2 \pm 7]$	Langer <i>et al.</i>	60 T66
^{76}As	$2^- \rightarrow 2^+$	8.2	1st	2.42	$a = 0.00 \pm 0.04$	Pohm <i>et al.</i>	56 T18
^{84}Rb	$2^- \rightarrow 2^+$	7.1	1st	0.78	$b \sim 0.3$	Langer <i>et al.</i>	64 T48
^{86}Rb	$2^- \rightarrow 2^+$	7.7	1st	0.72	$0.4 < b < 0.6$	Robinson <i>et al.</i>	58 T67
				0.722	$a \sim 0.00 \pm 0.05$	Deutsch <i>et al.</i>	61 T68
					$\left\{ \begin{array}{l} a = -0.7 \pm 0.8 \text{ and} \\ b = -0.5 \pm 0.7 \text{ and} \\ c = 0.14 \pm 0.15 \end{array} \right\}$	Daniel <i>et al.</i>	65 T65
					[shape essentially statistical]	Spejewski	66 T69
^{91}Y	$\frac{1}{2}^- \rightarrow \frac{1}{2}^+$	8.8	1st	0.32	$a \sim 0$	Johnson <i>et al.</i>	60 T70
^{111}Ag	$\frac{1}{2}^- \rightarrow \frac{1}{2}^+$	7.8	1st	1.028	$a = 0.00 \pm 0.01$	Lehmann	67 T17
^{111}Ag	$\frac{1}{2}^- \rightarrow \frac{3}{2}^+$	7.9	1st	0.69	$a \sim -0.17$	Robinson <i>et al.</i>	58 T67
		7.3		0.685	$a = -0.023 \pm 0.03$	Lehmann	67 T17
^{115m}Cd	$11/2^- \rightarrow \frac{3}{2}^+$	8.7	1st	1.618	$a = -0.78 \text{ and } b = -17.2$	Sharma <i>et al.</i>	63 T25
^{115m}Cd	$11/2^- \rightarrow 11/2^+$	8.3	1st	0.34	$a \sim 0$	Johnson <i>et al.</i>	59 T71
^{124}Sb	$3^- \rightarrow 2^+$	10.2	1st	2.32	$[q^2 + 0.874p^2 + 15 \pm 5]$	Langer <i>et al.</i>	60 T66
				2.30	$[q^2 + \lambda_1 p^2 + (16 \pm 2)]$	Hsue <i>et al.</i>	65 T72
				2.30	$[q^2 + \lambda_1 p^2 + (7 \pm 2)]$	Canty <i>et al.</i>	66 T29
^{130}I	$5^- \rightarrow 5^+$	6.5	1st	1.04	$a \sim 0.00 \pm 0.04$	Daniel <i>et al.</i>	65 T73
^{130}I	$5^- \rightarrow 6^+$	5.7	1st	0.62	$a \sim 0.00 \pm 0.04$	Daniel <i>et al.</i>	65 T73
^{140}La	$3^- \rightarrow 2^+$	9.2	1st	2.175	$[q^2 + 0.845p^2 + 10 \pm 5]$	Langer <i>et al.</i>	60 T66
^{141}Ce	$\frac{7}{2}^- \rightarrow \frac{7}{2}^+$	6.9	1st	0.432	$a = 0.00 \pm 0.15$	Deutsch <i>et al.</i>	61 T74
^{144}Ce	$0^+ \rightarrow 0^-$	7.5	1st	0.316	$a = -0.342 \pm 0.008$	Daniel <i>et al.</i>	66 T75
^{143}Pr	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^-$	7.6	1st	0.933	$0.1 < b < 0.35$	Hamilton <i>et al.</i>	58 T77
					$\left\{ \begin{array}{l} a = -0.018 \pm 0.01 \text{ or} \\ b = 0.06 \pm 0.03 \end{array} \right\}$	Persson <i>et al.</i>	65 T27
					$b = 0.3$	Spejewski	66 T69
^{144}Pr	$0^- \rightarrow 0^+$	6.5	1st	2.99	[see original paper]	Laubitz	56 T78
				2.984	$[\lambda = i f \gamma_5 / f \sigma r > 0]$	Graham <i>et al.</i>	58 T19
				2.992	$[0 < \lambda < 10]$	Freeman	59 T79
				2.996	$[\lambda = 5 \pm 2]$	Porter <i>et al.</i>	59 T80
				3.000	$\left\{ \begin{array}{l} a = 0.0376 \text{ and} \\ b = -0.118 \text{ and} \\ c = -0.0077 \end{array} \right\}$	Daniel <i>et al.</i>	66 T75
^{147}Nd	$\frac{5}{2}^- \rightarrow \frac{5}{2}^+$	7.4	1st	0.790	$a = -0.02$	Sharma <i>et al.</i>	62 T81
				0.806	$a = -0.07 \pm 0.01$	Beekhuis <i>et al.</i>	66 T82
^{147}Nd	$\frac{5}{2}^- \rightarrow \frac{5}{2}^+$	7.0	1st	0.360	$a \sim 0$	Sharma <i>et al.</i>	62 T81
				0.364	$a = -0.20 \pm 0.15$	Beekhuis <i>et al.</i>	66 T82
^{147}Pm	$\frac{5}{2}^+ \rightarrow \frac{7}{2}^-$	7.4	1st	0.22	[allowed shape]	Langer <i>et al.</i>	50 T83
					$0 < b \lesssim 0.3$	Hamilton <i>et al.</i>	58 T7
^{148}Pm	$1^- \rightarrow 0^+$	9.1	1st		$[f \sigma \times r / f i r = -2.2 \pm 0.4]$	Baba <i>et al.</i>	63 T84
^{150}Eu	$1^-, 0^- \rightarrow 0^+$	6.2	1st	1.020	$a \sim 0$	Yoshizawa <i>et al.</i>	63 T85
^{152}Eu	$3^- \rightarrow 2^+$	12.3	1st	1.48	$[q^2 + 0.79p^2 + 5 \pm 2]$	Langer <i>et al.</i>	60 T66
				1.49	[as above]	Schneider	60 T86
^{154}Eu	$3^- \rightarrow 2^+$	11.8	1st	1.855	$[q^2 + 0.807p^2 + 20 \pm 5]$	Langer <i>et al.</i>	60 T66
		12.4		1.84	$[(1.0 \pm 0.3) + S_1^{(2)}]$	Hansen <i>et al.</i>	66 T87

TABLE IV (Continued)

Nucleus	States	log ft	Forbidden	E_0 (MeV)	Coefficients [$a, (mc^2)^{-1}; b, mc^2; c, (mc^2)^{-2}$]	Author and Year	Ref.
^{166}Ho	$0^- \rightarrow 0^+$	8.0	1st	1.857	$[1 - 0.87W - 1.03/W + 0.225W^2 - 0.021W^3]$	Daniel <i>et al.</i>	66 T75
				1.846	$\left\{ \begin{array}{l} a = -0.21 \pm 0.03 \text{ and} \\ c = 0.038 \pm 0.004 \end{array} \right\}$	Beekhuis	67 T88
^{170}Tm	$1^- \rightarrow 2^+$	9.3	1st	0.88	$\left\{ \begin{array}{l} a = 1.11 \text{ and} \\ b = -0.85 \text{ and} \\ c = -0.24 \end{array} \right\}$	Spejewski	66 T69
^{172}Tm	$2^- \rightarrow 2^+$	8.4	1st	1.79	[shape like ^{90}Y]	Hansen <i>et al.</i>	66 T54
^{176m}Lu	$1^- \rightarrow 2^+$	6.5	1st		$a = -0.005 \pm 0.010$	Deutsch	65 T89
^{186}W	$\frac{3}{2}^- \rightarrow \frac{5}{2}^+$	6.5	1st		[statistical shape]	Spejewski	66 T69
^{186}Re	$1^- \rightarrow 0^+$	7.7	1st	1.071	$a \sim 0.12$	Porter <i>et al.</i>	56 T90
^{186}Re	$1^- \rightarrow 2^+$	8.0	1st	0.934	$a \sim 0.12$	Porter <i>et al.</i>	56 T90
^{194}Ir	$1^- \rightarrow 2^+$	8.6	1st		$a = -0.01 \pm 0.02$	Deutsch <i>et al.</i>	65 T91
^{198}Au	$2^- \rightarrow 2^+$	7.3	1st	0.966	$a = -0.110 \pm 0.017$	Wapstra <i>et al.</i>	59 T92
				0.968	$a \sim -0.05$	de Vries <i>et al.</i>	60 T93
				0.964	$a = -0.046 \pm 0.010$	Graham	60 T94
				0.962	$a = -0.062 \pm 0.007$	Chabre <i>et al.</i>	61 T95
				0.957	$a \sim -0.02$	Sharma <i>et al.</i>	62 T81
				0.960	$a = -0.33 \text{ and } c = 0.074$	Hamilton <i>et al.</i>	62 T96
					$a = -0.30 \text{ and } c = 0.07$	Newbolt	64 T97
				0.965	$a = -0.155 \pm 0.015$	Lehmann <i>et al.</i>	64 T15
				0.960	[statistical shape]	Keeler <i>et al.</i>	65 T98
					$a = -0.014 \pm 0.024$	Lewin	65 T99
				0.960	$\left\{ \begin{array}{l} a = -0.33 \pm 0.09 \\ \text{and} \\ c = 0.068 \pm 0.022 \end{array} \right\}$	Parsignault	65 T100
				0.962	$\left\{ \begin{array}{l} a = -0.34 \pm 0.04 \\ \text{and} \\ c = 0.10 \pm 0.02 \end{array} \right\}$	Lachkar <i>et al.</i>	65 T101
				0.961	$a = -0.031 \pm 0.006$	Paul	65 T102
				0.962	$a = -0.050 \pm 0.010$	Beekhuis <i>et al.</i>	65 T16
					$a = -0.073 \pm 0.008$	Spejewski	66 T69
^{199}Au	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	7.6	1st	0.46	$-0.2 > a > -0.4$	Lehmann	66 T103
^{206}Tl	$0^- \rightarrow 0^+$	5.2	1st	1.57	$a = -0.154 \text{ and } b = -0.484$	Howe <i>et al.</i>	61 T104
^{207}Tl	$\frac{3}{2}^+ \rightarrow \frac{1}{2}^-$	5.13	1st	1.44	$a = 0.024 \pm 0.008$	Trischuk <i>et al.</i>	67 T105
^{210}Bi	$1^- \rightarrow 0^+$	8.0	1st	1.155	[$\sim$ below]	Plassmann <i>et al.</i>	54 T106
				1.160	$\left\{ \begin{array}{l} a = 0.578 \text{ and} \\ b = 28.466 \text{ and} \\ c = -0.658 \end{array} \right\}$	Daniel	62 T107
^{36}Cl	$2^+ \rightarrow 0^+$	13.3	2nd	0.714	$[p^2 + 0.6q^2]$	Feldman <i>et al.</i>	52 T108
				0.714	$[p^2 + (0.57 \pm 0.03)q^2]$	Johnson <i>et al.</i>	56 T109
				0.709	[$^{\text{exact}}$ J_2 (see original paper)]	Spejewski <i>et al.</i>	67 T110
^{46}Sc	$4^+ \rightarrow 2^+$	13	2nd	1.48	$[\sim(p^2 + 0.6q^2)]$	Wolfson	56 T62
^{59}Fe	$\frac{3}{2}^- \rightarrow \frac{7}{2}^-$	10.9	2nd	1.573	$[p^2 + 3.3q^2]$	Wortman <i>et al.</i>	63 T111
^{58}Co	$2^+ \rightarrow 0^+$	12.9	2nd	1.3	$[\sim p^2]$	Daniel	58 T112
^{94}Nb	$6^+ \rightarrow 4^+$	12	2nd	0.47	$[p^2 + (1.75 \pm 0.15)q^2]$	Snyder <i>et al.</i>	66 T113
^{99}Tc	$\frac{9}{2}^+ \rightarrow \frac{5}{2}^+$	12.3	2nd	0.290	$[p^2 + (2.0 \pm 0.5)q^2]$	Feldman <i>et al.</i>	52 T108
^{129}I	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$	13.5	2nd	0.150	$[p^2 + 10q^2]$	derMateosian <i>et al.</i>	53 T114
^{135}Cs	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$	13.2	2nd	0.205	$[p^2 + (10 \pm 1)q^2]$	Lidofsky <i>et al.</i>	53 T108
^{137}Cs	$\frac{7}{2}^+ \rightarrow \frac{3}{2}^+$	12	2nd		$[q^2 + 0.0085p^2]$	Langer <i>et al.</i>	51 T115
					$[q^2 + 0.003p^2]$	Yamazaki <i>et al.</i>	58 T116
					$[q^2 + (0.015 \pm 0.004)p^2]$	Daniel <i>et al.</i>	62 T117
					$[q^2 + (0.004 \pm 0.002)p^2]$	Hsue <i>et al.</i>	66 T118
^{87}Rb	$\frac{3}{2}^- \rightarrow \frac{9}{2}^+$	17.6	3rd	0.275	[see original paper]	Egelkraut <i>et al.</i>	61 T119

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Erratum: Measurements of the Neutron-Proton and Neutron-Carbon Cross Sections at Electron Volt Energies

[Rev. Mod. Phys. **39**, 546 (1967)]

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We have discovered a gross program error in our computation of the neutron-proton total cross section from our data, and a minor error in the program energy scale. Correcting these errors, we find 20.442 ± 0.023 b for the free neutron-proton cross section, taking data from 6.50 to 329 eV. Table I gives the corrected n - p cross section and new values of the numbers dependent on it. A misprint of a_H , column 1, is also corrected. Two conclusions drawn in the paper are corrected as follows:

Page 547, next-to-last paragraph, first sentence, read:

"We have changed σ_H by 0.4%; ..."

Page 547, next-to-last paragraph, last (fourth) sentence, read:

"The new higher value of $\rho_s(0, 0)$ equals the p - p effective range, allowing for the $\pi^\pm$ - π^0 mass splitting."

[†] H. P. Noyes, Nucl. Phys. **74**, 508 (1965).

TABLE I. Table of results.

	This work plus old a_c/a_H	Previous work	Koester's work plus this work
σ_H	20.442 ± 0.023 b	20.36 ± 0.05 b	
σ_c	4.7534 ± 0.0045 b	4.704 ± 0.019 b	
a_c	Corrected for possible C^{13} spin incoherence		Direct
	6.656 ± 0.010 F	6.622 ± 0.017 F	6.656 ± 0.004 F
a_c/a_H		-1.7718 ± 0.0031	-1.7904 ± 0.0006
a_H	-3.756 ± 0.009 F	-3.737 ± 0.011 F	-3.719 ± 0.002 F
a_H	Parahydrogen	-3.80 ± 0.05 F	
	NaH crystal	-3.9 ± 0.1 F	
a_t	5.405 ± 0.006 F	5.399 ± 0.011 F	5.425 ± 0.004 F
a_s	-23.728 ± 0.013 F	-23.680 ± 0.028 F	-23.714 ± 0.013 F
$\rho_t(0, -\epsilon)$	1.738 ± 0.007 F	1.732 ± 0.012 F	1.763 ± 0.005 F
$\rho_s(0, 0)$	2.56 ± 0.10 F	2.48 ± 0.11 F	2.704 ± 0.095 F