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K-electron capture to positron emission ratios in allowed transitions—a critical analysis

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Abstract. All available experimental K/β^+ and ϵ/β^+ ratios for allowed transitions are reviewed. A critical comparison is made between experimental and theoretical K/β^+ ratios. The following questions are asked: (i) can these experiments be used to derive the magnitude of a possible induced tensor interaction? (ii) is there a departure from theory, particularly in the high Z region? It is pointed out that more experimental work is necessary, especially for values of $Z > 30$.

1. Introduction

During the past twenty five years experimentalists have been measuring K/β^+ ratios in allowed decays for a variety of reasons. It is true to say that these measurements have been used to test many of the refinements made to beta decay theory over this period.

Initially the results of K/β^+ measurements were used to test the gross structure of beta decay theory. Fair agreement was obtained and the formulation of Fermi's theory of beta decay was accepted—at least to a first order.

In the 1950s the question of the Fierz interference term (b) arose and also which of the five basic interactions, scalar (S), vector (V), tensor (T), axial vector (A) and pseudoscalar (P), predominate in the beta decay process. A critical comparison of experimental and theoretical values of K/β^+ ratios was one of the most sensitive ways to estimate the magnitude of b and hence the magnitudes of C_S/C_V and C_T/C_A, the ratios of coupling constants for the above interactions, see for example Joshi and Lewis (1961) and Scobie and Lewis (1957). Agreement between experiment and theory to within a few per cent without invoking a Fierz interference term indicated that b was zero, or at any rate very small, also implying small values for C_S/C_V and C_T/C_A. Corroborative evidence that this was so came from electron–neutrino correlations, see for example Schopper (1966). To a lesser degree a zero value for b gave one confidence that indeed the electron neutrino had zero mass and that the two-component neutrino theory as well as lepton conservation were viable concepts.

In the 1960s the emphasis again changed. The Fermi formulation with a zero Fierz term was generally accepted. Comparison between experimental and theoretical K/β^+ ratios was then used to test the wavefunctions of K-shell electrons or the corrections to these wavefunctions if exchange and overlap processes were taken into account (Bahcall 1963a, b, Vatai 1970). These corrections were especially important at low values of atomic number Z (about 8 % at $Z = 14$). A series of experiments performed on low Z

nuclei (Ledingham *et al* 1971) indicated that exchange corrections may be smaller than those predicted by Bahcall and more in agreement with those calculated by Vatai.

In the last year or so, as one began to have confidence that the atomic wavefunctions were fairly well determined and that the necessary corrections to these had been established, the question of 'induced effects' imposed by the strong couplings on the V–A weak interaction arose. This idea (Feynman and Gell-Man 1958, Weinberg 1958), not a new one by any means, essentially determines whether the weak interaction can proceed when the nucleons involved are 'dressed', that is, a virtual state in which the 'bare' nucleon is surrounded by a charged pion cloud. In the old beta decay theory only bare nucleons can undergo decays and hence the coupling constants have to be renormalized for the time spent in the virtual state. This renormalization process causes the induced effects mentioned above and introduces the so-called second class interactions (Weinberg 1958). (S, V, T, A interactions are considered first class.)

Vatai (1971) realized that the existence of second class currents affected K/β^+ ratios. In allowed decays with transition energy $W_0 \ll 3\xi$ (where $\xi = \alpha Z/2R$, essentially the Coulomb energy of an electron at the nuclear radius R), he was able to evaluate corrections to the old beta decay theory and present these corrections as a function of Z. Again experimental and theoretical K/β^+ ratios were compared and Vatai concluded that experimental evidence did not support the existence of second class currents.

After all this experimental and theoretical effort spread over many years the question must now be asked: 'does agreement exist between experiment and theory—with or without the above refinements and other corrections not discussed, for example radiative corrections (Wilkinson and Macefield 1970)?'.

2. Experimental techniques

Several methods have been used in the measurement of K/β^+ ratios. These methods can be classified as direct or indirect depending on whether the electron capture events are detected along with the positrons or whether their presence is inferred from some other measured quantity. The main types of measurement and sources of error are outlined below.

2.1. *Direct measurements* (D)

(Measurements of the K/β^+ ratio.)

(*i*) *Internal source proportional counter spectroscopy* (D-ISPC). In this method the radioactive source in gaseous form flows through a proportional counter along with the normal counter gas. The gases may however be static, if the half-life of the isotope is long enough. The capture events are detected as discrete peaks along with the positron continuum. Most of the error in these measurements comes from the procedure adopted in separating the capture peak from the continuum. This technique is especially powerful in short lived, low Z isotopes and ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{19}Ne and ^{30}P have been analysed in this manner with errors ranging from 3% to 6%.

(*ii*) *Internal source scintillation counter spectroscopy* (D-ISSC). The radioactive source in this technique is distributed in a scintillating crystal (usually NaI) by introducing it into the melt from which the crystal is grown. The capture and positron events are then detected in the scintillator, with the x rays and Auger electrons producing a well defined peak, enabling the K/β^+ ratio to be determined. Again, the interpolation of the continuum under the peak is the main source of error. Only two measurements of this type have been reported; namely ^{22}Na with an error of 9 % and ^{58}Co with an error of 2 %.

(*iii*) *Magnetic spectrometer* (D-MS). In this type of measurement the Auger electrons are detected as a peak in the spectrometer and then the positrons analysed for the same number of decays. There were often fairly large errors in the fluorescence yields which limited the accuracy of this method, and corrections had also to be made for the absorption of low energy electrons in source and spectrometer. The ratio of K/β^+ in ^{65}Zn was carried out using this method as were many of the older measurements on other isotopes, but generally today this technique is no longer popular. It must be stated, however, that a great deal of work has recently been carried out on fluorescence yields (Bambynek *et al* 1972) and many of the objections to this method are now no longer valid.

(*iv*) *Other methods* (D-E). Many other methods have been used to determine K/β^+ ratios directly and they normally entail using radioactive sources external to the detectors with the K x rays and positrons being registered in different types of counter. The appeal of these methods is simplicity but fluorescence yields again may limit the accuracy.

2.2. *Indirect measurements* (I)

(Usually measurement of the total capture to positron ratios ϵ/β^+.)

These methods essentially measure the number of positrons leading to an excited state of the daughter nucleus, and the number of gamma rays or conversion electrons leaving that level in a given time interval. Since the total number of gamma rays is equal to the total number of positrons plus electron capture events—corrected with reference to the known decay scheme if necessary—the ratio of total electron capture to positron emission can be found. The errors in this type of measurement can be small especially if the decay scheme is well known, for example the ϵ/β^+ ratios for ^{22}Na and ^{58}Co have been determined to about 0·7 %.

Two important points, however, have to be considered. Firstly, the uncertainties in decay schemes can be large. This fact unfortunately is not taken into account in many of the measurements using this technique and may lead to large systematic errors. Secondly, and sometimes more importantly, how does one obtain a K/β^+ ratio from a measured ϵ/β^+ ratio? We can write ϵ/β^+ as

$$\frac{\epsilon}{\beta^+} = \frac{K}{\beta^+}\left(1+\frac{L}{K}+\frac{M}{L}\frac{L}{K}+\ldots\right)$$

where the total capture is written as the sum of the separate shell captures. Since the number of measured L/K and M/L etc ratios is limited one must often use the theoretical values for these. Now in the region where exchange effects are expected to be largest, the ratios must be corrected for these effects and one can hardly then use the K/β^+ ratios so derived to obtain information on exchange effects. On the other hand if one is sure that these effects are small, then one can probably derive K/β^+ ratios more accurately by this method than the others discussed.

A great variety of techniques have been used under the heading of indirect methods. Scintillators, proportional counters, semiconductor detectors and magnetic spectrometers have been used to measure the positrons and generally scintillators or semiconductor detectors to measure the de-excitation gamma rays. Some very sophisticated coincidence techniques between two or three detectors have been employed to measure positron–gamma coincidences often in an attempt to make the measurements independent of fluorescence yields and decay scheme difficulties. These have been reviewed in greater detail elsewhere (Berenyi 1963).

3. Theoretical K/β⁺ ratios

The theoretical values for the K/β^+ ratios given in table 1 have been calculated using the equation

$$\frac{K}{\beta^+} = \frac{\pi g_K^2 (W_0 + W_K)^2}{2\int_1^{W_0} F(W, Z) W p (W_0 - W)^2 \, dW} \tag{1}$$

where the symbols appearing have their usual meaning (Konopinski and Rose 1965). The values for the orbital electron wavefunctions (g_K^2) were taken from tables of electron radial wavefunctions due to Behrens and Jänecke (1969) and the intensity of the positron spectrum was computed using the Coulomb functions given in this reference. These tables have been calculated assuming a uniform charge distribution throughout the nuclear volume, account being taken of the screening of the nuclear Coulomb field by the orbital electrons. Values of the Coulomb function were interpolated over the total momentum range of the positrons to obtain values equally spaced at momentum intervals of $0{\cdot}1\ m_0c$. The intensity of the positrons was then calculated by numerically integrating the denominator of the above equation using Simpson's rule.

The maximum values for the positron kinetic energies to which equation (1) is so sensitive have been taken from the recent atomic mass tables due to Wapstra and Gove (1971). Any L/K, (M+N+ . . .)/L ratios and exchange corrections to these, needed in the determination of K/β^+ ratios from ϵ/β^+ ratios, have been obtained from the work of Behrens and Jänecke (1969), Wapstra *et al* (1959) and Vatai (1970) respectively.

Finally, any quoted error in the theoretical K/β^+ ratios reflects alone the uncertainty in the quoted maximum value for the positron kinetic energy.

4. Review

In this section the authors have surveyed all available experimental values of ϵ/β^+ and K/β^+ ratios and as is customary to workers in the field the experimental K/β^+ ratios have been divided by the theoretical result for these decays to obtain the quantity B_K. This quantity has been plotted as a function of Z in figures 1 and 2. Because of the vast spread of errors reported, only experiments with a quoted error of 10% or less have been listed in table 1. These were arbitrarily considered more reliable although in some cases the quoted result has been corrected with more recent values of fluorescence yield (Bambynek *et al* 1972). Many other measurements of K/β^+ ratios with errors greater than 10%, with decay schemes which are known to be faulty, and with fluorescence yields unknown or known to be wrong, have been rejected. Most of these measurements

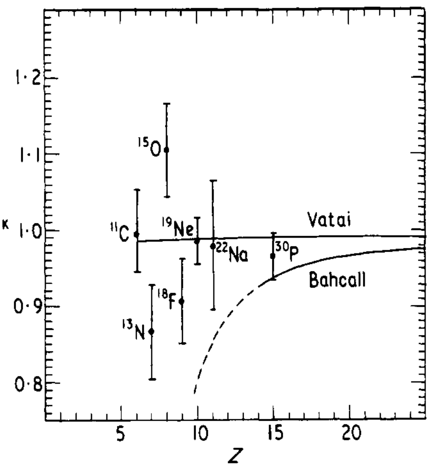

Figure 1. B_K for low Z nuclei. The curves represent the exchange–overlap corrections calculated by Bahcall and Vatai. The theoretical curve of Bahcall has been extrapolated (broken curve) using the empirical formula given by Bahcall (1963a, b).

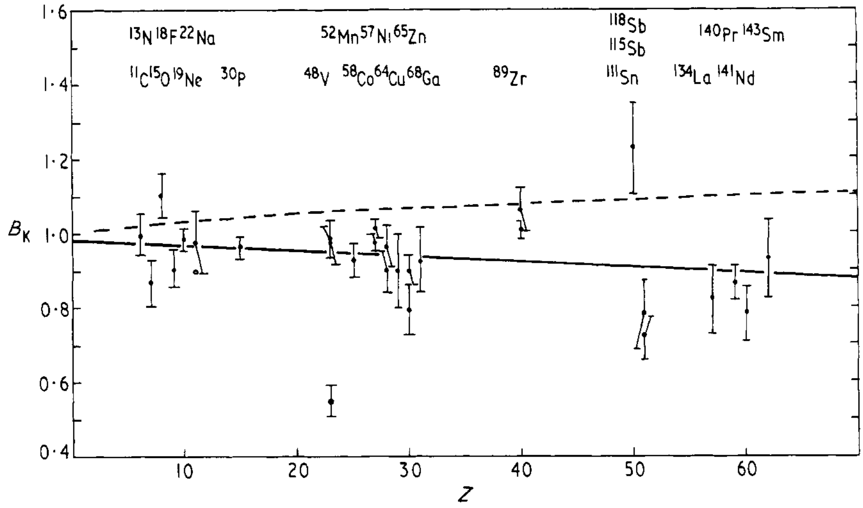

Figure 2. B_K as a function of Z. The broken curve shows the effect of the induced tensor interaction calculated by Vatai using $|g_{IT}/g_A| = 2 \times 10^{-3}$. The straight line is a least squares fit to the points with each point being given a weight inversely proportional to the square of its error.

are reported elsewhere by Depommier *et al* (1960), Bouchez and Depommier (1960) and Berenyi (1963, 1968).

5. Conclusions

The question which was posed in the introduction to this communication may be answered by inspection of figures 1 and 2. For most of the decays B_K is less than 1.

Table 1.

Isotope	Maximum positron kinetic energy (keV)	Transition	Measurement		$(K/\beta^+)_{theory}$	Method	Reference
			ϵ/β^+	K/β^+			
^{11}C	960·2±1·0	$\frac{3}{2}^- \rightarrow \frac{3}{2}^-$		$(2{\cdot}30^{+0{\cdot}14}_{-0{\cdot}11}) \times 10^{-3}$†	$(2{\cdot}316 \pm 0{\cdot}010) \times 10^{-3}$	D-ISPC	Campbell *et al* (1967)
^{13}N	1198·5±0·9	$\frac{1}{2}^- \rightarrow \frac{1}{2}^-$		$(1{\cdot}68 \pm 0{\cdot}12) \times 10^{-3}$†	$(1{\cdot}939 \pm 0{\cdot}006) \times 10^{-3}$	D-ISPC	Ledingham *et al* (1963)
^{15}O	1737·2±0·9	$\frac{1}{2}^- \rightarrow \frac{1}{2}^-$		$(1{\cdot}07 \pm 0{\cdot}06) \times 10^{-3}$†	$(0{\cdot}969 \pm 0{\cdot}002) \times 10^{-3}$	D-ISPC	Leiper and Drever (1972)
^{18}F	633·3±0·9	$1^+ \rightarrow 0^+$		$(3{\cdot}00 \pm 0{\cdot}18) \times 10^{-2}$†	$(3{\cdot}31 \pm 0{\cdot}02) \times 10^{-2}$	D-ISPC	Drever *et al* (1956)
^{19}Ne	2216·2±0·9	$\frac{1}{2}^+ \rightarrow \frac{1}{2}^+$		$(9{\cdot}60 \pm 0{\cdot}30) \times 10^{-4}$†	$(9{\cdot}75 \pm 0{\cdot}02) \times 10^{-4}$	D-ISPC	Leiper and Drever (1972)
^{22}Na	545·7±0·5	$3^+ \rightarrow 2^+$		0·105±0·009†	0·1073±0·0004	D-ISSC	McCann and Smith (1969)
			0·1041±0·0010			I	Williams (1964)
			0·1048±0·0007			I	Leutz and Wenniger (1967)
			0·1042±0·0010			I	Vatai *et al* (1968)
			0·1045±0·0005‡	0·0958±0·0005†§			
^{30}P	3205·4±2·6	$1^+ \rightarrow 0^+$		$(1{\cdot}24 \pm 0{\cdot}04) \times 10^{-3}$†	$(1{\cdot}286 \pm 0{\cdot}005) \times 10^{-3}$	D-ISPC	Ledingham *et al* (1971)
^{48}V	698·0±2·8	$4^+ \rightarrow 4^+$		0·69±0·04†	0·706±0·012	I	Biryukov and Shimanskaya (1970)
			0·43±0·03	0·39±0·03†		I	Ristinen *et al* (1963)
			0·77±0·03‖	0·69±0·03†		I	Konijn *et al* (1967)
^{52}Mn	575·5±3·5	$6^+ \rightarrow 6^+$	1·96±0·07‖	1·76±0·07†	1·89±0·05	I	Konijn *et al* (1967)
^{58}Co	475·5±2·5	$2^+ \rightarrow 2^+$		4·92±0·09	5·05±0·11	D-ISSC	Joshi and Lewis (1961)
				4·83±0·10		D-E	Kramer *et al* (1962)
				5·05±0·09		D-E, I	Bambynek *et al* (1968)
				4·94±0·08		I	Biryukov and Shimanskaya (1970)
				4·94±0·04†‡			
			5·90±0·20			I	Good *et al* (1947)
			5·90±0·20			I	Cook and Tomnovec (1956)
			5·67±0·16			I	Konijn *et al* (1958a)
			5·49±0·18			I	Ramaswamy (1961)
			5·76±0·04			I	Williams (1970)
			5·75±0·04‡	5·13±0·04†			

^{57}Ni	851·0±7·0	$\frac{3}{2}^- \to \frac{3}{2}^-$	0·805±0·04	0·717±0·036†	0·797±0·028	I	Konijn *et al* (1958b)
	731·0±7·0	$\frac{3}{2}^- \to \frac{1}{2}^-$	1·438±0·059	1·281±0·053†	1·325±0·055	I	Konijn *et al* (1958b)
^{64}Cu	655·5±1·8	$1^+ \to 0^+$		1·99±0·22† (revised using ω_k = 0·414±0·028)	2·21±0·03	D-MS	Plassmann and Scott (1951)
^{65}Zn	328·7±1·1	$\frac{5}{2}^- \to \frac{3}{2}^-$		28·0±1·8	30·8±0·4	D-MS	Perkins and Haynes (1953)
				27·7±1·5		I	Hammer (1968)
				27·8±1·2†‡			
			27·6±2·4	24·5±2·1† (revised using ω_k = 0·445±0·009)		I	Gleason (1959)
^{68}Ga	819·4±3·9	$1^+ \to 2^+$		1·28±0·12†	1·38±0·03	D-E	Ramaswamy (1959)
^{89}Zr	904·1±3·0	$\frac{9}{2}^+ \to \frac{9}{2}^+$	3·48±0·15		2·99±0·04	I	Monaro *et al* (1961)
			3·43±0·10			I	Van Patter and Shafroth (1964)
			3·38±0·20			I	Hinrichsen (1968)
			3·44±0·08‡	3·02±0·07†			
	894·1±3·0	$\frac{1}{2}^- \to \frac{3}{2}^-$	3·76±0·19	3·30±0·17†	3·10±0·05	I	Van Patter and Shafroth (1964)
^{111}Sn	1486·0±26·0	$\frac{7}{2}^+ \to \frac{9}{2}^+$	2·60±0·20			I	Snyder and Pool (1965)
			2·20±0·15			I	Rivier and Monet (1969, 1971)
			2·30±0·12‡	2·00±0·10†	1·63±0·14		
^{115}Sb	1509±20	$(\frac{5}{2})^+ \to (\frac{3}{2})^+$		1·22±0·06†	1·70±0·11	I	Kiselev and Burmistrov (1969)
^{118}Sb	291±6	$(8^-) \to 7^-$	624±39	542±25†	693±69	I	Bolotin *et al* (1961)
^{134}La	2688·0±25·0	$1^+ \to 0^+$		0·40±0·04†	0·487±0·022	D-E	Biryukov and Shimanskaya (1970)
^{140}Pr	2366·0±6·0	$1^+ \to 0^+$		0·74±0·03†	0·856±0·026	D-E	Biryukov and Shimanskaya (1970)
^{141}Nd	782·0±15·0	$\frac{3}{2}^+ \to \frac{5}{2}^+$		28·0±1·0†	35·8±3·2	D-E	Biryukov and Shimanskaya (1970)
^{143}Sm	2457·0±28·0	$\frac{3}{2}^+ \to \frac{5}{2}^+$		0·92±0·09†	0·984±0·053	D-E	Biryukov and Shimanskaya (1970)

† Experimental values appearing in figure 1.

‡ Weighted mean and standard error in weighted mean of bracketed results.

§ Data from Behrens and Jänecke (1969) have been extrapolated to give L/K for Z = 11. Due to large uncertainties in the exchange and overlap corrections in the L/K ratio the error quoted here comes solely from the error in ϵ/β^+.

‖ Weighted mean of experimental values given in the corresponding reference.

Figure 1 shows the region where exchange and overlap corrections (Bahcall 1963a, b, Vatai 1970) are greatest. The existing experimental data are by no means accurate enough to distinguish unambiguously the two theories of Bahcall and Vatai although experiment perhaps slightly favours Vatai. It must be pointed out, however, that Bahcall's calculations may not be strictly valid below $Z = 14$.

Figure 2 shows the effect of the second class current (induced tensor) calculated by Vatai (1971) using $|g_{IT}/g_A| = 2\times10^{-3}$. The broken curve on the graph represents the quantity $(B_K)_{\text{theory}}$ defined to be

$$\frac{(\mathrm{K}/\beta^+)_{\text{theory IT}}}{(\mathrm{K}/\beta^+)_{\text{theory}}}$$

where $(\mathrm{K}/\beta^+)_{\text{theory IT}}$ is the theoretical K/β^+ ratio calculated using equation (1) and including the effect of the induced tensor interaction and $(\mathrm{K}/\beta^+)_{\text{theory}}$ is the theoretical K/β^+ calculated using equation (1). For agreement to exist between experiment and the induced tensor-corrected theory, the experimental points should lie along this curve. Obviously they do not and hence experiment does not support an induced tensor interaction of this magnitude (cf Vatai 1971). If one uses the most recent value of $|g_{IT}/g_A|$ (Wilkinson and Alburger 1971) the corrections are smaller by at least a factor of three and the existing experimental data are much less able to prove or disprove the existence of the induced tensor interaction.

It must be emphasized that Vatai's calculation of the effect of the induced tensor on K/β^+ ratios is valid only for pure Gamow–Teller decays or decays in which the Fermi admixture is small and this is not the case for all the decays shown in figure 2, (eg ^{11}C (Scobie and Lewis 1957) and ^{13}N (Ledingham *et al* 1963)).

A straight line has been fitted to the experimental points in figure 2. This line can be seen to be systematically below the value $B_K = 1$, the departure from theory (equation 1) being about 1·5 % at $Z = 0$ increasing to about 12 % at $Z = 70$. The precision point at $Z = 11$ has not been included in the determination of this line due to the large uncertainties mentioned in table 1. If, however, these uncertainties are neglected and this point is included the slope of the line is reversed and the fit is about 10 % below theory at $Z = 0$ and about 5 % below at $Z = 70$.

In conclusion it would appear that, with respect to the theoretical points made in this paper, further work in the low Z region is unnecessary unless the accuracy of the experiments is better than 1 %. Above $Z = 30$ more experimental and theoretical work is essential to prove whether a possible departure from theory has been detected or not.

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