Improved Limits on Scalar Weak Couplings

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I point out that β-delayed proton spectroscopy is a powerful probe of possible scalar contributions to nuclear β decay, and use Schardt and Riisager's data on the shape of the beta-delayed proton peaks from the superallowed decays of ^{32}Ar and ^{33}Ar to set improved upper limits on such couplings. Implications of these limits for leptoquark masses are mentioned.

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Although there is much experimental evidence for the $V-A$ form of the charged weak current, the constraints on *scalar* couplings (which would occur if a charged scalar boson or a leptoquark [1] were exchanged instead of the $W^{\pm}$) are relatively poor [2, 3]. This state of affairs arises, in part, because the scalar couplings must be inferred from observables (particularly the e-ν correlation) in which they enter quadratically, unless one makes restrictive hypotheses about their parity properties or assumes that they violate time-reversal invariance [4]. The classic e-ν correlation data were obtained by observing the lepton recoil effect on the energy distribution of stable daughter nuclei from ^{6}He, ^{19}Ne, ^{23}Ne, and ^{35}Ar decays (see Ref. [5]). Such experiments are very difficult because the recoil energies are only a few hundred eV, and high-precision results are today available in just a few cases (notably ^{6}He [6] and n decay [7]). None of these is a pure Fermi transition and therefore particularly sensitive to scalar couplings.

Schardt and Riisager [8] recently completed a beautiful study of ^{32}Ar decay in which they measured with high precision the shape of the beta-delayed proton peak following the superallowed decay of ^{32}Ar to its isospin analog 0^+ state in ^{32}Cl. In this case the lepton recoil is delivered to a decaying state, and the c.m.s.-to-lab transformation gives the decay proton an energy spread which exceeds the energy imparted to the beta-decay daughter by a factor of $4mv/MV \approx 60$, where m and v refer to the proton and M and V to the recoiling ^{32}Cl. Because its particle decays are isospin-forbidden, the natural width of the ^{32}Cl daughter level is so small [9] that the shape of the proton peak is dominated by the e-ν-p triple-correlation asymmetry parameter, A, defined, for example, in Refs. [8, 10]. Schardt and Riisager extract

$$A = 1.00 \pm 0.08\ , \qquad (1)$$

where the error is quoted at 2σ. When the decay protons are emitted isotropically in the rest frame of the daughter nucleus (this must be the case in ^{32}Ar decay because the daughter has $J=0$), A is identical to the more familiar quantity a, which describes the e-ν angular correlation,

$$W(\theta_{e\nu}) \propto 1 + a\frac{p}{E}\cos(\theta_{e\nu})\ . \qquad (2)$$

Here p and E refer to the momentum and energy of the beta particle, and the neutrino is taken to be massless. For a pure Fermi transition a is given by [4]

$$a = \frac{|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2}{|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2}\ , \qquad (3)$$

where the subscripts S and V refer to scalar and vector couplings, and the ratio C_i'/C_i determines the lepton helicities: e.g., $C_V' = C_V$ or $C_S' = -C_S$ imply left-handed electrons and right-handed positrons. A time-reversal-violating (TRV) scalar $\times$ vector interference term of order $\alpha Z\langle m_e/p\rangle \approx 0.028$ has been neglected as it is not significant at the current level of experimental precision. [Equation (3) follows because in a vector interaction the helicities of the e^+ and the ν_e are opposite, while in a scalar interaction they are the same.] The Schardt and Riisager result, therefore, sets a 95%-confidence-level upper limit on scalar couplings of

$$\epsilon_S = \frac{|C_S|^2 + |C_S'|^2}{|C_V|^2 + |C_V'|^2} \le 4.2 \times 10^{-2}\ . \qquad (4)$$

It should be noted that this limit is conservative in the sense that if any Gamow-Teller peak had fallen within the ≈ 25 keV width of Schardt and Riisager's superallowed peak it would have reduced their value of A and therefore could not mask a scalar interaction that would necessarily also reduce the value of A.

A more restrictive limit on scalar couplings can be inferred from Schardt and Riisager's data on the broadening of the delayed proton peak following the superallowed $1/2^+ \to 1/2^+$ decay of ^{33}Ar, for which they obtain

$$A = 1.02 \pm 0.04\ , \qquad (5)$$

where the error is again quoted at 2σ. Because the delayed protons were observed with polarization-insensitive detectors, the decays of the $J=1/2$ daughter state are effectively isotropic (any parity violation in the nuclear states is completely negligible in this context) so that a is again identical to A. The ^{33}Ar decay is a mixed Fermi/Gamow-Teller transition so the expression for the e-ν asymmetry becomes [4]

$$a = \frac{(|C_V|^2 + |C_V'|^2 - |C_S|^2 - |C_S'|^2) + (|C_T|^2 + |C_T'|^2 - |C_A|^2 - |C_A'|^2)/(3y^2)}{(|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2) + (|C_T|^2 + |C_T'|^2 + |C_A|^2 + |C_A'|^2)/(3y^2)} , \quad (6)$$

where the subscripts A and T refer to axial and tensor weak couplings and $y^2 = |M_F|^2/|M_{GT}|^2$ is the Fermi/Gamow-Teller mixing ratio. A small TRV tensor × axial-vector interference term of order $\alpha Z\langle m_e/p\rangle/(3y^2)$ has been neglected along with the corresponding TRV scalar × vector interference term mentioned above. The parameter y^2 could be obtained from the ft value for the transition, but it is not known in this case as only *relative* ^{33}Ar β^+ branching ratios were measured [11]. Nevertheless, a lower bound on y^2 can be obtained from a itself because $|C_T|^2$, $|C_T'|^2 \ll 3y^2|C_V|^2$, $3y^2|C_V'|^2$ (this condition will turn out to be consistent with existing [2] constraints on $|C_T|^2$ and $|C_T'|^2$). In this case one finds $y^2 \geq 33$.

The ^{33}Ar result sets a 95%-confidence-level upper limit on the sum of the scalar and axial contributions of

$$\frac{|C_S|^2 + |C_S'|^2 + (|C_A|^2 + |C_A'|^2)/3y^2}{|C_V|^2 + |C_V'|^2 + (|C_T|^2 + |C_T'|^2)/3y^2} \leq 1.4 \times 10^{-2} , \quad (7)$$

where I have followed the prescription [12] of the Particle Data Group for renormalizing the likelihood function in cases where the central value of a measured parameter (A) lies outside the physical region ($-1 \leq A \leq 1$). Using again the relations $|C_T|^2$, $|C_T'|^2 \ll 3y^2|C_V|^2$, $3y^2|C_V'|^2$, I obtain the 2σ constraint

$$\epsilon_S \leq 1.4 \times 10^{-2} . \quad (8)$$

I now place these results in the context of other work and examine what constraints the combined data place on scalar and tensor interactions. First, consider the question of time-reversal violation, i.e., the relative phases of the C_i coefficients. Precise values for the D coefficient in n [13] and ^{19}Ne [14] decay have shown that the vector and axial-vector terms are relatively real to within 0.3°. Constraints on TRV scalar interactions are much poorer. The best previous constraint on TRV scalar interactions was derived from the R coefficient in ^{19}Ne decay [15]. Under the assumptions that $C_V = C_V'$ and $C_A = C_A'$, and that C_T and C_T' are negligible, the observed R sets the 2σ constraint [15] $\mathrm{Im}[(C_S + C_S')C_A^*]/|C_V|^2 = +0.38 \pm 0.51$ where for simplicity I have followed Ref. [15] and assumed that $|C_S/C_V|^2 \ll 1$, $|C_S'/C_V|^2 \ll 1$ even though it is not necessarily consistent with their result. Taking $C_A^* = g_A/g_V C_V^*$, this constraint can be reexpressed as

$$\mathrm{Im}\frac{C_S + C_S'}{C_V} = (+0.38 \pm 0.51)\frac{g_V}{g_A} = -0.30 \pm 0.41 . \quad (9)$$

The ^{33}Ar result in Eq. (8) yields the corresponding 2σ constraints (assuming $|C_V| = |C_V'|$)

$$\left|\frac{C_S}{C_V}\right|^2 + \left|\frac{C_S'}{C_V}\right|^2 \leq 0.028 , \quad (10)$$

$$\left|\frac{C_S}{C_V}\right| \leq 0.167 , \qquad \left|\frac{C_S'}{C_V}\right| \leq 0.167 , \quad (11)$$

which place the tightest experimental bound on TRV scalar interactions [16]. (Note that at this level of precision the TRV scalar × vector interference term in a induced by the Coulomb interaction can indeed be neglected.) The constraints on $\mathrm{Im}(C_S/C_V)$ and $\mathrm{Im}(C_S'/C_V)$ given in Eqs. (10) and (9) are displayed in Fig. 1.

Now consider the constraints on time-reversal-invariant (TRI) interactions. Rather than follow the lead of Boothroyd, Markey, and Vogel [2] who made a comprehensive analysis of all relevant data, I simply consider a set of distinct observables and use the best available results for each type of observable. The "pure Fermi" a coefficient with its 1σ error,

$$a_F = 1.016 \pm 0.018 , \quad (12)$$

obtained by combining the ^{32}Ar and ^{33}Ar results in Eqs. (1) and (5), complements the precise Gamow-Teller a coefficient, a_{GT}, measured in ^{6}He decay. In addition one has the precisely measured Fierz interference terms b_F and b_{GT} from the superallowed $0^+ \to 0^+$ transitions [17] and ^{22}Na decay, respectively, and the β helicities

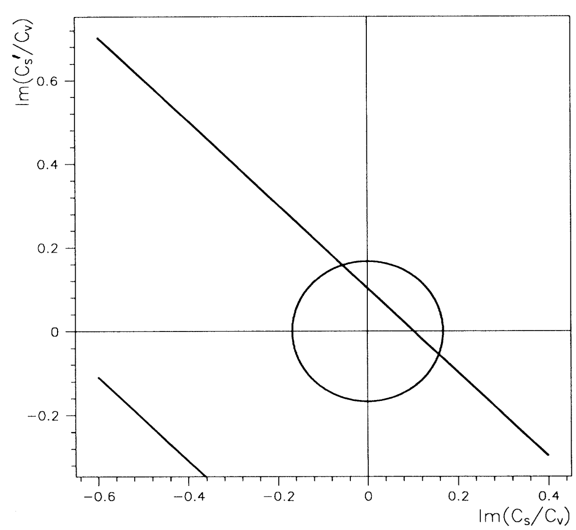

FIG. 1. 2σ constraints on TRV scalar interactions from $a(^{33}\mathrm{Ar})$ and $R(^{19}\mathrm{Ne})$ (Ref. [15]). It is assumed that $C_V = C_V'$. The region betwen the sloping straight lines is consistent with $R(^{19}\mathrm{Ne})$, and the region inside the circle with $a(^{33}\mathrm{Ar})$.

TABLE I. 2σ constraints on TRI scalar and tensor weak interactions.

Quantity	a_F included	a_F omitted
C_S/C_V	0.00 ± 0.12	0.00 ± 0.18
C'_S/C_V	0.00 ± 0.10	0.00 ± 0.15
C_T/C_V	-0.01 ± 0.11	-0.02 ± 0.13
C'_T/C_V	-0.01 ± 0.12	-0.01 ± 0.13

measured in pure Fermi (^{26m}Al) and pure Gamow-Teller (^{60}Co) decays. I adopt Boothroyd, Markey, and Vogel's weighted average values for all these quantities except a_F and b_F. Finally, I include data for the mixed Fermi/Gamow-Teller decay of the neutron—adopting the recommended values in the latest Review of Particle Properties [18] for a_n, A_n (the beta asymmetry with respect to the neutron spin), B_n (the ν asymmetry with respect to the n spin), and for the ratio of the ft_n value to the $\mathcal{F}t = 3073.3 \pm 3.5$ s value [19] inferred from the $0^+ \to 0^+$ transitions.

First I make no assumptions except that the S, V, A, and T interactions are TRI (this is equivalent to Boothroyd, Markey, and Vogel's case I). Then the 10 observables mentioned above are fitted in terms of 7 real parameters, C'_V/C_V, C_A/C_V, C'_A/C_V, C_S/C_V, C'_S/C_V, C_T/C_V, and C'_T/C_V. The individual constraints on the 7 parameters, shown in Table I, were obtained by stepping one parameter at a time and adjusting the remaining 6 parameters so as to minimize χ^2. The 2σ limits correspond to the values of the stepped parameter that yielded $\chi^2 = \chi_0^2 + 4$ where χ_0^2 is the minimum value of χ^2. Figure 2 shows the constraints on Re(C_S) and

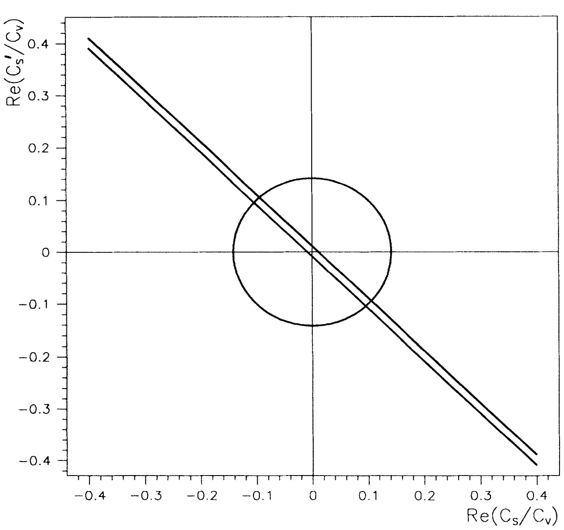

FIG. 2. 2σ constraints on TRI scalar interactions from a_F and b_F (Ref. [17]). It is assumed that $C_V = C'_V$. The region between the straight lines is consistent with b_F, and the region inside the circle with a_F.

TABLE II. 2σ constraints on TRI scalar and tensor weak interactions assuming exact $V-A$ for the vector and axial components.

Quantity	a_F included	a_F omitted
C_S/C_V	$+0.001 \pm 0.086$	$+0.001 \pm 0.114$
C'_S/C_V	$+0.001 \pm 0.086$	$+0.001 \pm 0.114$
C_T/C_V	0.000 ± 0.096	0.000 ± 0.105
C'_T/C_V	0.000 ± 0.096	0.000 ± 0.105
g_A/g_V	-1.263 ± 0.004	-1.263 ± 0.004

Re(C'_S) due solely to a_F and b_F. The main improvements in the scalar constraints over those given by Boothroyd, Markey, and Vogel [2] (2σ limits of $|C_S/C_V| < 0.23$ and $|C'_S/C_V| < 0.19$) come from the ^{32}Ar and ^{33}Ar results.

In the second, more restrictive, scenario I assume that the vector and axial-vector interactions are given by $V-A$ theory (i.e., $C'_V = C_V = g_V$ and $C'_A = C_A = g_A$) but make no assumptions other than time-reversal invariance about the scalar and tensor interactions. Now the 10 experimental values are fitted in terms of only 5 real parameters, C_S/C_V, C'_S/C_V, C_T/C_V, C'_T/C_V, and g_A/g_V. The individual constraints for this scenario are shown in Table II. The central values of all quantities listed in Tables I and II are very close to zero simply because the observables are basically quadratic functions of these quantities and pure $V-A$ theory with $g_A/g_V = -1.262$ already provides a good account of the data ($\chi^2 = 7.7$ for $\nu = 9$).

The utility of these results is illustrated by their implications for leptoquark masses. Leptoquark exchange would influence both the e-ν correlation in β decay and the rate for $\pi \to e\nu$ decay. In principle, six of the leptoquarks discussed in Ref. [1] participate in these decays, but the amplitudes for the six leptoquark exchanges interfere differently in the two processes [3, 20]. To simplify the constraints involving many parameters, consider a scenario where the three participating scalar leptoquarks S_1, $R_2(T_z = -1/2)$, and $\tilde{R}_2(T_z = +1/2)$ have the same mass M_S, the three vector participating leptoquarks U_1, $V_2(T_z = -1/2)$, and $\tilde{V}_2(T_z = +1/2)$ have the same mass M_V, and all coupling constants have the gauge value determined by G_F. Then the Fermi e-ν correlation combined with the $\pi \to \nu e$ rate leads to 90%-confidence lower limits of $M_S > 350$ GeV and $M_V > 700$ GeV.

It is clear that isospin-forbidden β-delayed proton spectroscopy provides a powerful probe of scalar couplings in weak processes, and that the limits on a_F obtained here could be substantially improved by an experiment designed for that purpose. The utility of the delayed-proton method is due to a fortunate combination of circumstances: the substantial amplification of the recoil effect, the small value of the isospin-forbidden proton decay width ($\Gamma_p \approx 100$ eV) compared to the recoil broadening, and the short time scale for proton decay $t = \hbar/\Gamma_p$ compared to the slowing-down time of the nuclear recoils (e.g., the recoiling ^{33}Cl travels only 270 fm before it decays).

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