Beta Decay and the Standard Model

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Beta Decay Outline

i) Past

ii) Present

iii) Future

Historical Tour

Beta Decay has influenced the development of the Standard Model for over a century

$\sim$ 1895: Standard Model is periodic table—$\sim$ 100 immutable elements as characterized by Mendeleev

Periodic Table of the Elements

Atomic Number
Symbol
Name
Atomic Mass

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series														
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967

Actinide Series														
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Becquerel and Curies study radioactivity: α, β, γ radiation

Natural transmutation of elements—long the goal of alchemists (even Newton!)

~ 1930 : New standard Model includes radioactivity. Problem in that in beta decay, such as

$$^3H \rightarrow ^3He + e^-$$

energy is not conserved. (Bohr even suggested that perhaps energy is conserved only macroscopically).

Problem solved in 1930 when Pauli "invented" the neutrino.

$\sim$ 1932: Discovery of neutron *and* positron leads to new Standard Model—Fermi explains Beta Decay in terms of current-current interaction

$$\mathcal{H} \sim \frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

with

$$J_\mu = \bar{p}\gamma_\mu n + \bar{e}\gamma_\mu \nu$$

1956: Reines and Cowan discover Pauli's neutrino

1956: Lee and Yang suggest weak interaction does not conserve parity.

1957: Wu et al. observe parity violation in beta decay

$$^{60}Co \rightarrow ^{60}Ni + e^- + \bar{\nu}$$

1958: Feynman and Gell-Mann propose V-A structure

$$J_\mu = \bar{n}\gamma_\mu(1-\gamma_5)p + \bar{e}\gamma_\mu(1-\gamma_5)\nu_e$$

1963/64: Cabibbo proposes universality and Gell-Mann and Zweig invent the quark model

$$J_\mu = \cos\theta\bar{d}\gamma_\mu(1-\gamma_5)u + \sin\theta\bar{s}\gamma_\mu(1-\gamma_5)u$$
$$+\bar{e}\gamma_\mu(1-\gamma_5)\nu_e + \bar{\mu}\gamma_\mu(1-\gamma_5)\nu_\mu$$

1967: Weinberg and Salam unify the weak and electromagnetic interactions.

Discovery of charm (1974) and bottom (1977) leads to present structure of weak current

$$J_\mu = (\bar{d}\ \bar{s}\ \bar{b})\gamma_\mu(1-\gamma_5)\begin{pmatrix} u \\ c \\ t \end{pmatrix}$$
$$+(\bar{e}\ \bar{\mu}\ \bar{\tau})\gamma_\mu(1-\gamma_5)\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

$\sim$ 2015: Use beta decay to seek possible deviations from Standard Model (BSM)

Note general nucleon matrix elements are

$$< p_{p'}|V_\mu|n_p >= \bar{u}_p(p') \left(\gamma_\mu f_1(q^2) - i\sigma_{\mu\nu}q^\nu \frac{f_2(q^2)}{2m_N} \right.$$

$$\left. +q_\mu \frac{f_3(q^2)}{2m_N} \right) u_n(p)$$

$$< p_{p'}|A_\mu|n_p >= \bar{u}_p(p') \left(\gamma_\mu g_1(q^2) - i\sigma_{\mu\nu}q^\nu \frac{g_2(q^2)}{2m_N} \right.$$

$$\left. +q_\mu \frac{g_3(q^2)}{2m_N} \right) \gamma_5 u_n(p)$$

Generalize for arbitrary (allowed) spin nuclei to

$$\ell^\mu < \beta|V_\mu|\alpha >= \left(a(q^2)\frac{P\cdot\ell}{2M} + e(q^2)\frac{q\cdot\ell}{2M}\right)\delta_{JJ'}\delta_{MM'}$$

$$+i\frac{b(q^2)}{2M}C^{M'k;M}_{J'1;J}(\vec{q}\times\vec{\ell})_k$$
$$+C^{M'k;M}_{J'2;J}\left[\frac{f(q^2)}{2M}C^{nn';k}_{11;2}\ell_n q_{n'}\right.$$
$$\left.+\frac{g(q^2)}{(2M)^3}P\cdot\ell\sqrt{\frac{4\pi}{5}}Y^k_2(\hat{\vec{q}})\vec{q}^2+\dots\right]$$

$$\ell^\mu < \beta|A_\mu|\alpha >= C_{J'1;J}^{M'k;M} \epsilon_{ijk}\epsilon_{ij\lambda\eta}\frac{1}{4M}\Big[c(q^2)\ell^\lambda P^\eta$$

$$-d(q^2)\ell^\lambda q^\eta + \frac{1}{(2M)^2}h(q^2)q^\lambda P^\eta q\cdot\ell\Big]$$

$$+C_{J'2;J}^{M'k;M} C_{12;2}^{nn';k} \ell_n \sqrt{\frac{4\pi}{5}} Y_2^{n'}(\hat{\vec{q}})\frac{\vec{q}^2}{(2M)^2} j_2(q^2)$$

$$+C_{J'3;J}^{M'k;M} C_{12;3}^{nn';k} \ell_n \sqrt{\frac{4\pi}{5}} Y_2^{n'}(\hat{\vec{q}})\frac{\vec{q}^2}{(2M)^2} j_3(q^2) + \ldots$$

with

$$\begin{aligned} a &\to f_1, & c &\to g_1 \\ b &\to f_2, & d &\to g_2 \\ e &\to f_3, & h &\to g_3\,. \end{aligned}$$

In addition, there exist terms f, g, j_2, j_3, which have no $J = \frac{1}{2} \to J' = \frac{1}{2}$ analog, since they involve $\Delta J = 2, 3$.

If neglect recoil, then can analyze in terms of only a, c with

$$a = M_F = < f || \sum_i \tau_k^{\pm} | i >$$

$$c = g_A M_{GT} = g_A < f || \sum_k \tau_k^{\pm} \vec{\sigma}_i || i >$$

How to describe BSM effects? First done in 1957 by Jackson, Treiman, and Wyld

$$\mathcal{H}_{eff} = \bar{p}n\bar{e}(C_S + C'_S\gamma_5)\nu_e$$

$$+\bar{p}\gamma^\mu n\bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu_e$$

$$+\frac{1}{2}\bar{p}\sigma^{\mu\nu}n\bar{e}\sigma_{\mu\nu}(C_T + C'_T\gamma_5)\nu_e$$

$$+\bar{p}\gamma^\mu\gamma_5 n\bar{e}\gamma_\mu(C_A + C'_A\gamma_5)\nu_e$$

$$+\bar{p}\gamma_5 n\bar{e}(C_P + C'_P\gamma_5)\nu_e + h.c.$$

Here standard model values are

$$C_S = C'_S = C_T = C'_T = 0$$

and

$$C_V = C'_V = -\frac{1}{\lambda} C_A = -\frac{1}{\lambda} C'_A = \frac{G_F^{(0)}}{\sqrt{2}} V_{ud}$$

where $G_F^{(0)}$ is the Fermi constant and $\lambda \simeq -1.27$ is the ratio of axial and polar vector couplings in neutron beta decay.

Modern view is to write BSM effects via

$$
\begin{aligned}
\mathcal{H}_{eff} = \frac{G_F^{(0)} V_{ud}}{\sqrt{2}} [& (1+\delta_\beta)\bar{u}\gamma^\mu(1-\gamma_5)d\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \\
& + \epsilon_L \bar{u}\gamma^\mu(1-\gamma_5)d\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \\
& + \tilde{\epsilon}_L \bar{u}\gamma^\mu(1-\gamma_5)d\bar{e}\gamma_\mu(1+\gamma_5)\nu_e \\
& + \epsilon_R \bar{u}\gamma^\mu(1+\gamma_5)d\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \\
& + \tilde{\epsilon}_R \bar{u}\gamma^\mu(1+\gamma_5)d\bar{e}\gamma_\mu(1+\gamma_5)\nu_e \\
& + \epsilon_S \bar{u}d\bar{e}(1-\gamma_5)\nu_e + \tilde{\epsilon}_S \bar{u}d\bar{e}(1+\gamma_5)\nu_e \\
& - \epsilon_P \bar{u}\gamma_5 d\bar{e}(1-\gamma_5)\nu_e - \tilde{\epsilon}_P \bar{u}\gamma_5 d\bar{e}(1+\gamma_5)\nu_e \\
& + \epsilon_T \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \\
& + \tilde{\epsilon}_T \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d\bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e] + h.c.
\end{aligned}
$$

Here δ_β is electromagnetic correction, and $\epsilon_i, \tilde{\epsilon}_i$ represent BSM couplings, with canonical size

$$\epsilon_i, \tilde{\epsilon}_i \sim v^2/\Lambda^2_{\mathrm{BSM}}$$

where $v = (2\sqrt{2}G_F^{(0)})^{-\frac{1}{2}} \sim 170$ GeV and Λ_{BSM} is scale of the physics. If $\Lambda_{\mathrm{BSM}} \sim 1$ TeV, then natural size is $\epsilon_i \sim 10^{-3}$, but this must be settled experimentally.

Relation between two representaions is

$$C_i = \frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \bar{C}_i$$

$$\bar{C}_V = g_V(1 + \delta_\beta + \epsilon_L + \epsilon_R + \tilde{\epsilon}_L + \tilde{\epsilon}_R)$$
$$\bar{C}'_V = g_V(1 + \delta_\beta + \epsilon_L + \epsilon_R - \tilde{\epsilon}_L - \tilde{\epsilon}_R)$$
$$\bar{C}_A = g_A(1 + \delta_\beta + \epsilon_L - \epsilon_R - \tilde{\epsilon}_L + \tilde{\epsilon}_R)$$
$$\bar{C}'_A = g_A(1 + \delta_\beta + \epsilon_L - \epsilon_R + \tilde{\epsilon}_L - \tilde{\epsilon}_R)$$
$$\bar{C}_S = g_S(\epsilon_S + \tilde{\epsilon}_S)$$
$$\bar{C}'_S = g_S(\epsilon_S - \tilde{\epsilon}_S)$$
$$\bar{C}_P = g_P(\epsilon_P - \tilde{\epsilon}_P)$$
$$\bar{C}'_P = g_P(\epsilon_P + \tilde{\epsilon}_P)$$
$$\bar{C}_T = 4g_T(\epsilon_T + \tilde{\epsilon}_T)$$
$$\bar{C}'_T = 4g_T(\epsilon_T - \tilde{\epsilon}_T)$$

where constants g_i represent the renormalizations which occur when transforming between quark and nucleon representations.

General neutron-proton matrix elements can be written

$$< p(p_2)|\bar{u}\gamma_\mu d|n(p_1) >= \bar{u}_p(p_2)\left[g_V(q^2)\gamma_\mu\right.$$

$$\left.-g_M(q^2)\frac{i}{2M}\sigma_{\mu\nu}q^\nu + \tilde{g}_S(q^2)\frac{1}{2M}q_\mu\right]u_n(p_1)$$

$$< p(p_2)|\bar{u}\gamma_\mu\gamma_5 d|n(p_1) >= \bar{u}_p(p_2)\left[g_A(q^2)\gamma_\mu\right.$$

$$\left.-g_E(q^2)\frac{i}{2M}\sigma_{\mu\nu}q^\nu + \tilde{g}_P(q^2)\frac{1}{2M}q_\mu\right]\gamma_5 u_n(p_1)$$

$$< p(p_2)|\bar{u}d|n(p_1) >= g_S(q^2)\bar{u}_p(p_2)u_n(p_1)$$

$$< p(p_2)|\bar{u}\gamma_5 d|n(p_1) >= g_P(q^2)\bar{u}_p(p_2)\gamma_5 u_n(p_1)$$

$$< p(p_2)|\bar{u}\sigma_{\mu\nu}d|n(p_1) >= \bar{u}_p(p_2)\left[g_T(q^2)\sigma_{\mu\nu}\right.$$

$$+g_T^1(q^2)\frac{1}{2M}(q_\mu\gamma_\nu - q_\nu\gamma_\mu)$$
$$+\, g_T^2(q^2)\frac{1}{4M^2}(q_\mu P_\nu - q_\nu P_\mu))$$
$$\left.+\, g_T^3(q^2)\frac{1}{2M}(\gamma_\mu \not{q}\gamma_\nu - \gamma_\nu \not{q}\gamma_\mu)\right] u_n(p_1)$$

and can be evaluated experimentally in the case of g_V, g_A, namely $g_V(0) = 1, g_A(0) \simeq 1.27$, and lattice in case of $g_S(0), g_T(0)$, which has determined $g_S = 0.8 \pm 0.4$ and $g_T = 1.05 \pm 0.35$.

If neglect recoil effects, which is good approximation since typically $\mathcal{O}(q/m_N) \sim 1\%$, there exist only leading Fermi and Gamow-Teller forms $a = g_V M_F$ and $c = g_A M_{GT}$, and many experiments are analyzed using only these two quantities. General expression describing differential decay rate for allowed beta decay:

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{(2\pi)^5} p_e E_e (E_0 - E_e)^2 \xi$$

$$\times \Bigg\{ 1 + a_{e\nu}(E_e) \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F \frac{m_e}{E_e}$$

$$+ F_{e\nu}(E_e) \left(\frac{\vec{p}_e \cdot \hat{\vec{n}} \vec{p}_\nu \cdot \hat{\vec{n}}}{E_e E_\nu} - \frac{1}{3} \frac{\vec{p} \cdot \vec{p}_\nu}{E_e E_\nu} \right)$$

$$\left. \frac{\times 3(< (\vec{J} \cdot \hat{\vec{n}})^2 > - J(J+1))}{J(2J-1)} \right)$$

$$+ \frac{< \vec{J} \cdot \hat{\vec{n}} >}{J} \hat{\vec{n}} \cdot \left(A_e(E_e) \frac{\vec{p}_e}{E_e} + B_\nu(E_e) \frac{\vec{p}_\nu}{E_\nu} \right.$$

$$\left. + D_{e\nu}(E_e) \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)$$

$$+ \vec{\sigma} \cdot \left[G_e(E_e) \frac{\vec{p}_e}{E_e} + H_\nu(E_e) \frac{\vec{p}_\nu}{E_\nu} \right.$$

$$+ K_{e\nu}(E_e) \frac{\vec{p}_e}{E_e + m_e} \left(\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} \right) + L_e(E_e) \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}$$

$$+ N_e(E_e) \hat{\vec{n}} \frac{< \vec{J} \cdot \hat{\vec{n}} >}{J}$$

$$+ Q_e(E_e) \frac{\vec{p}_e}{E_e + m_e} \left(\hat{\vec{n}} \cdot \frac{\vec{p}_e}{E_e} \frac{< \hat{\vec{n}} \cdot \vec{J} >}{J} \right)$$

$$\left. \left. + R_e(E_e) \frac{< \hat{\vec{n}} \cdot \vec{J} >}{J} \hat{\vec{n}} \times \frac{\vec{p}_e}{E_e} \right] \right\}$$

and leading-order results for the various correlation functions given by Jackson, Treiman, and Wyld.

Practical matter:

$$A_e^{ex}(E_e) = \frac{A_e(E_e)}{1 + b_F < \frac{m_e}{E_e} >}$$

where b_F, defined by

$$\zeta b_F = \pm 2\mathrm{Re}\left[|M_F|^2 (C_S C_V^* + C_S' C_V'^*) \right.$$

$$\left. + |M_{GT}|^2 (C_T C_A^* + C_T' C_A'^*) \right]$$

with

$$\zeta = |M_F|^2 (|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2)$$

$$+ |M_{GT}|^2 (|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2)$$

is Fierz interference parameter.

Now look at experiment: Start with $0^+ - 0^+$ analog decays, for which

$$M_F = I_- = \sqrt{(T - T_3)(T + T_3 + 1)} = \sqrt{2}$$

$$M_{GT} = 0$$

Test via measure

$$\mathcal{F}t \equiv f t_{\frac{1}{2}} (1 + \delta_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{G_\mu^2 V_{ud}^2}$$

with

$$K = \frac{2\pi^3 \log 2}{m_e^5} = 8120.2787(11) \times 10^{-10}\,\mathrm{GeV}^{-4}\,\mathrm{sec}$$

Nucleus	E_0(KeV)	$\mathcal{F}t$(sec)
^{10}C	885.87(11)	3076.7(4.6)
^{14}O	1809.24(23)	3071.5(3.3)
^{26m}Al	3210.66(06)	3072.4(1.4)
^{34}Cl	4469.64(23)	3070.2(2.1)
^{38m}K	5022.40(11)	3072.5(2.4)
^{42}Sc	5404.28(30)	3072.4(2.7)
^{46}V	6030.49(16)	3073.3(2.7)
^{50}Mn	6612.45(07)	3070.9(2.8)
^{54}Co	7222.37(28)	3069.9(3.2)

Since Fermi coupling G_F known from muon decay, allows the extraction of the CKM matrix element V_{ud}.

Yields

$$V_{ud} = 0.97425(22)$$

which, together with

$$V_{us} = 0.2256(9)$$

from $\Delta S = 1$ kaon decays, yields

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1.00008(56)$$

and thereby

$$\mathrm{Re}(\epsilon_L + \epsilon_R - \epsilon_\mu) < 5 \times 10^{-4}$$

Consistency also puts limit on Fierz term, yielding limit on Fierz term

$$-1 \times 10^{-3} < g_S \mathrm{Re}\epsilon_S < 3.2 \times 10^{-3}$$

Analysis depends on understanding of Coulomb. Can be avoided by using neutron but need two measurements since $Gamow - Teller$ is not known. Defining

$$\lambda = g_A/g_V$$

Using

$$f_n\tau_n \log 2(1+\delta_R)(1+3\lambda^2) = \frac{K}{G_F^2 V_{ud}^2}$$

and

$$A_e^n(0) = 2\frac{\lambda - \lambda^2}{1+3\lambda^2}$$

with measured values

Quantity	Value
$< \tau_n >_{PDG}$	885.7(0.8)
τ_n	888.4(3.2)sec
τ_n	886.3(3.4)sec
τ_n	878.5(0.8)sec
τ_n	889.2(4.8)sec
τ_n	882.6(2.7)sec
τ_n	887.6(3.0)sec
τ_n	891(9)sec
$< A_e^n >_{PDG}$	-0.1173(13)
A_e^n	-0.1189(7)
A_e^n	-0.1160(15)
A_e^n	-0.1135(14)
A_e^n	-0.1146(19)

find

$$\lambda = 1.2701(25) \quad \text{and} \quad V_{ud} = 0.9746(19)$$

in good agreement with Fermi decay number. To test Standard Model, need additional number.

To test Standard Model use correlations. Easiest is electron-neutrino correlation $a_{e\nu}$

$$a_{e\nu} = \frac{a^2 - \frac{1}{3}c^2}{a^2 + c^2}$$

Then for Fermi decay

$$a^F_{e\nu}(^{38m}\mathrm{K}) = 0.9981(45)\ \ \mathrm{TRIUMF}$$

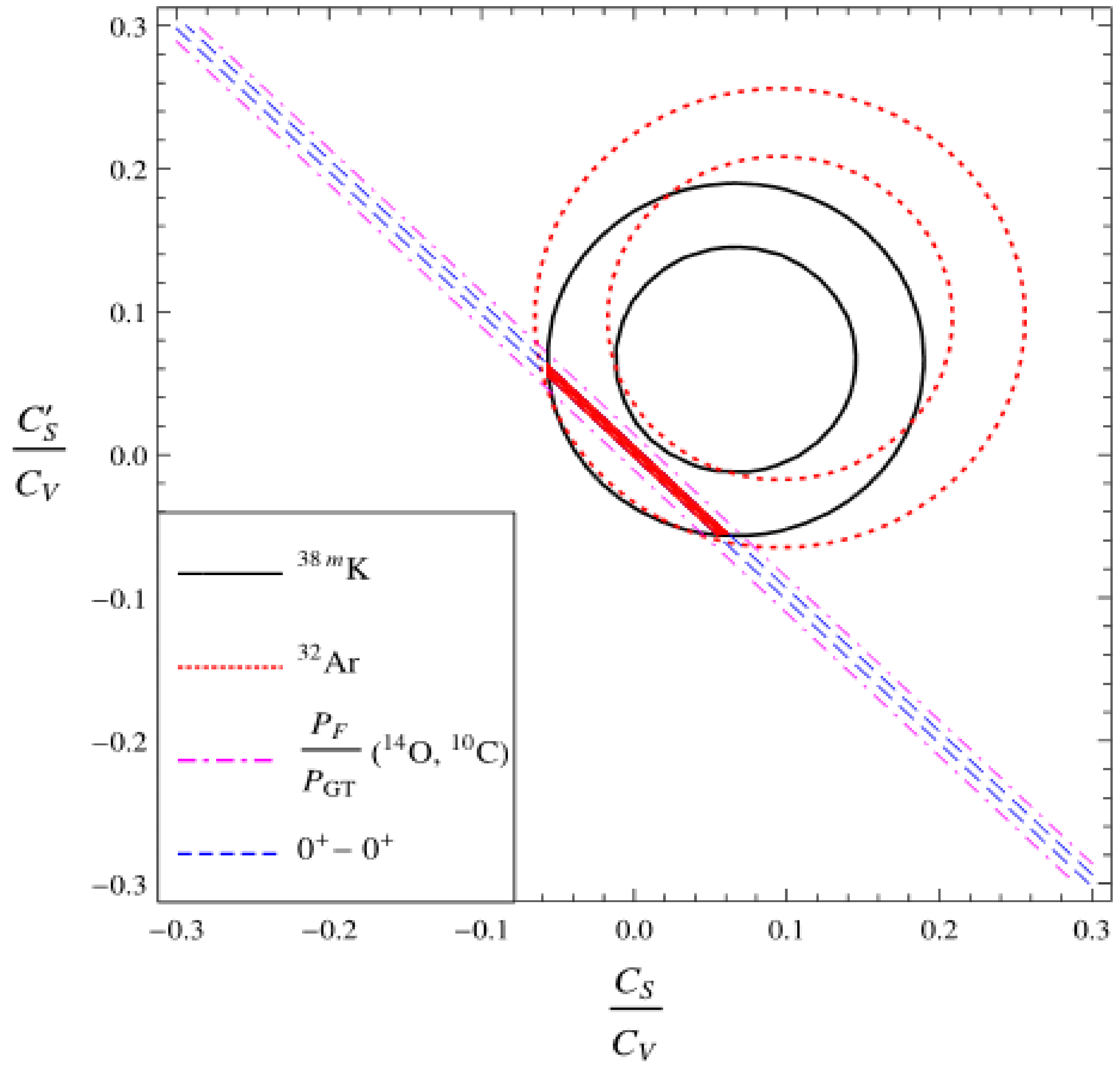
$$a^F_{e\nu}(^{32}\mathrm{Ar}) = 0.9989(65)\ \ \mathrm{ISOLDE}$$

Then

$$\left(\frac{C_S}{C_V} - \frac{1}{2}\zeta < \frac{m_e}{E_e} >\right)^2 + \left(\frac{C'_S}{C_V} - \frac{1}{2}\zeta < \frac{m_e}{E_e} >\right)^2$$

$$= \frac{1}{2}\zeta^2 < \frac{m_e}{E_e} >^2 + ^{SM}a^F_{e\nu} - ^{exp}a^F_{e\nu}$$

find limits on scalar couplings.



0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
$\frac{C'_S}{C_V}$
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
$\frac{C_S}{C_V}$
^{38m}K
^{32}Ar
$\frac{P_F}{P_{GT}}$ (^{14}O, ^{10}C)
$0^+ - 0^+$

For Gamow-Teller decays

$$a_{e\nu}^{GT}(^6\mathrm{He}) = -0.3308(30)\ \text{Oak Ridge}$$

Using

$$\left(\frac{C_T}{C_A} + \frac{1}{2}\zeta < \frac{m_e}{E_e} >\right)^2 + \left(\frac{C_T'}{C_A} + \frac{1}{2}\zeta < \frac{m_e}{E_e} >\right)^2$$

$$= \frac{1}{2}\zeta^2 < \frac{m_e}{E_e} >^2 - 3(^{SM}a_{e\nu}^{GT} - ^{exp}a_{e\nu}^{GT})$$

together with longitudinal polarization measurements on Fermi and Gamow-Teller decays

$$^{14}O,\, ^{10}C:\;\; P_F/P_{GT} = 0.9996(37)$$

$$^{26m}Al,\, ^{30}P:\;\; P_F/P_{GT} = 1.003(18)$$

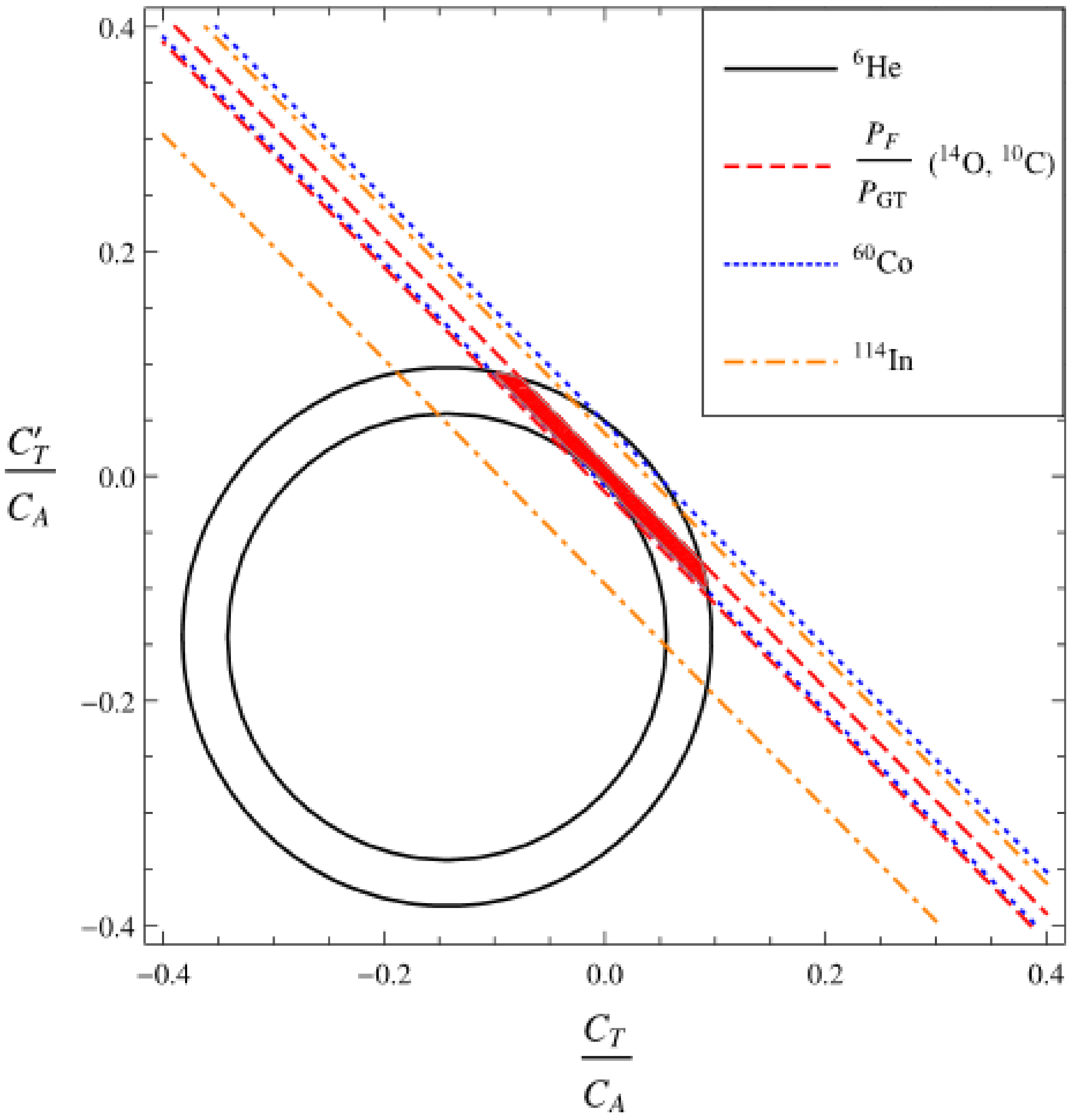
for which

$$P_F = \frac{p_e}{E_e}\frac{2\mathrm{Re}(C_S^* C_S' - C_V^* C_V')}{\left[|C_V|^2 + |C_V'|^2 + |C_S|^2 + |C_S'|^2\right](1 + b_F < \frac{m_e}{E_e} >)}$$

for Fermi decay and

$$P_{GT} = \frac{p_e}{E_e}\frac{2\mathrm{Re}(C_T^* C_T' - C_A^* C_A')}{\left[|C_A|^2 + |C_A'|^2 + |C_T|^2 + |C_T'|^2\right](1 + b_F < \frac{m_e}{E_e} >)}$$

for Gamow-Teller find limits shown.



^{6}He
$\frac{P_F}{P_{GT}}$ (^{14}O, ^{10}C)
^{60}Co
^{114}In
0.4
0.2
0.0
−0.2
−0.4
$\frac{C'_T}{C_A}$
$\frac{C_T}{C_A}$

Another tack is to look for possible deviations from simple $V-A$. Assume a heavy M_{W_R}, with

$$\tilde{\epsilon} = M^2_{W_1}/M^2_{W_2} << 1$$

and include mixing

$$W_L = W_1 \cos\zeta + W_2 \sin\zeta, \qquad W_R = -W_1 \sin\zeta + W_2 \cos\zeta$$

Writing basic interaction as

$$\mathcal{L} = \frac{g}{2\sqrt{2}} [W_L^{-\mu}(V_\mu^+ - A_\mu^+) + W_R^{-\mu}(V_\mu^+ + A_\mu^+) + h.c.]$$

effective low-energy weak Hamiltonian is

$$\mathcal{H}_{eff} = \frac{G_{eff}}{\sqrt{2}} [V_\mu^+ V^{-\mu} + \eta_{AA} A_\mu^+ A^{-\mu}$$

$$-\eta_{AV}(V_\mu^+ A^{-\mu} + A_\mu^+ V^{-\mu})]$$

where

$$\frac{G_{eff}}{\sqrt{2}} = \left[\frac{g^2}{8m_1^2}(\cos\zeta - \sin\zeta)^2 + \frac{g^2}{8m_2^2}(\cos\zeta + \sin\zeta)^2\right)\right]$$

$$\eta_{AA} = \frac{\lambda^2 m_2^2 + m_1^2}{\lambda^2 m_1^2 + m_2^2}$$

$$\eta_{VA} = \frac{\lambda(m_1^2 - m_2^2)}{\lambda^2 m_1^2 + m_2^2}$$

and

$$\lambda = \frac{1 + \tan\zeta}{1 - \tan\zeta}$$

Useful to define x, y via

$$x = \frac{1 + \eta_{VA}}{1 - \eta_{VA}} \qquad y = \frac{\eta_{AA} + \eta_{VA}}{\eta_{AA} - \eta_{VA}}$$

then for ratio of longitudinal polarization ratio for Fermi and Gamow-Teller decays find

$$-2.0 \times 10^{-3} < y^2 - x^2 < 1.7 \times 10^{-3}$$

from results from ^{14}O,^{10}C and

$$-0.8 \times 10^{-2} < y^2 - x^2 < 1.0 \times 10^{-2}$$

in case of ^{26m}Al,^{30}P results.

From Michel parameters in muon decay, ρ parameter gives

$$(x-y)^2 < 3 \times 10^{-4}$$

while ξ parameter yields

$$x^2 + y^2 < 2.8 \times 10^{-3}$$

Finally, in case of ^{19}Ne decay,

$$A_e^{^{19}\mathrm{Ne}} = \frac{2}{3}\frac{c^2 + \sqrt{3}ac - y^2c^2 - \sqrt{3}xyac}{a^2 + c^2 + x^2a^2 + y^2c^2}$$

$$\frac{(ft)^{0^+-0^+}}{ft^{^{19}Ne}} = \frac{a^2 + c^2 + x^2a^2 + y^2c^2}{2(1+x^2)a^2}$$

Using CVC value $a = 1$ and Gamow-Teller term $c = -1.5995(45)$ obtained from ^{19}Ne lifetime, Standard Model prediction for the beta-spin correlation is

$$^{SM}A_e^{^{19}\mathrm{Ne}} = -(3.97 \pm 0.14) \times 10^{-2}$$

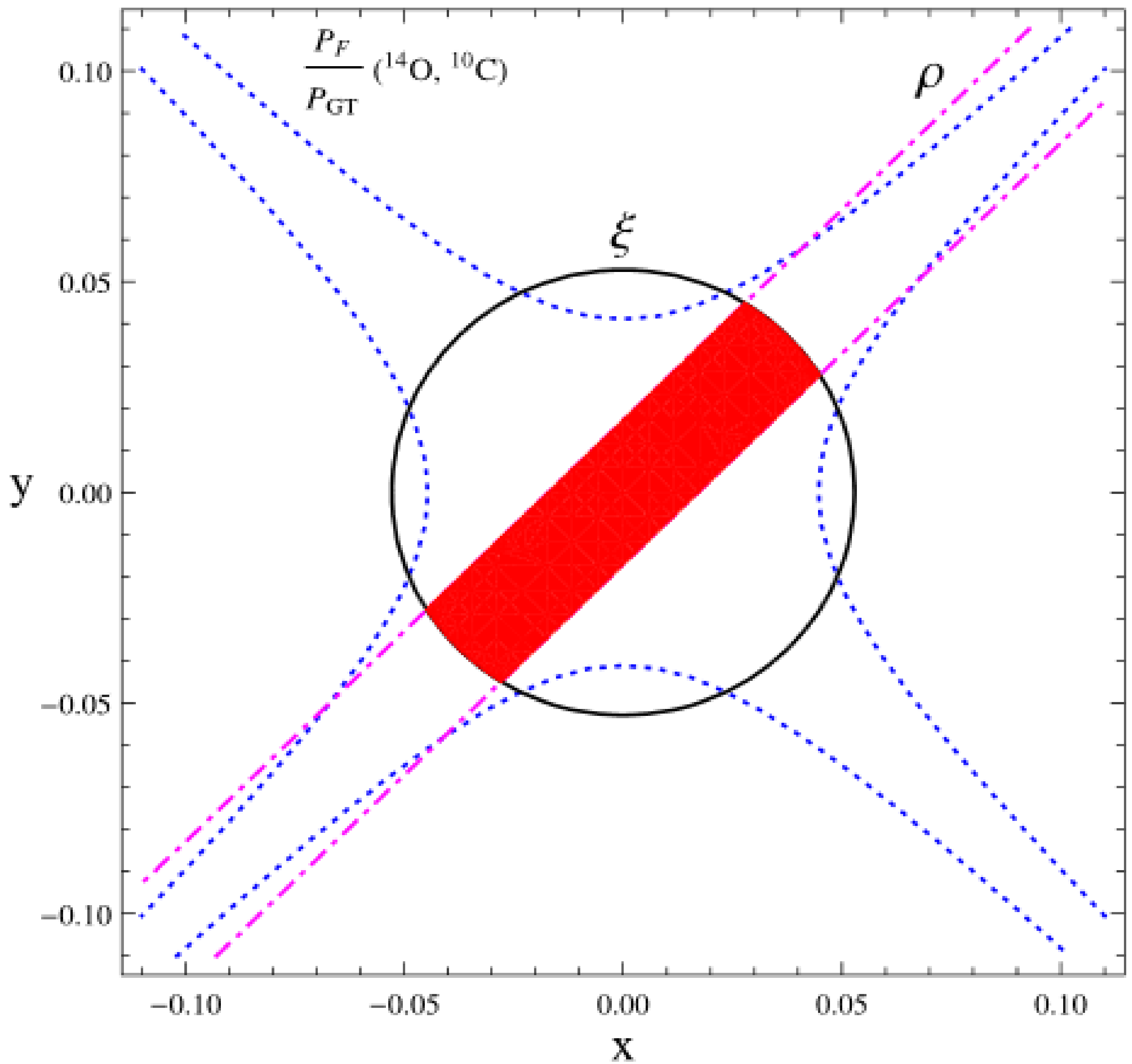
Comparing with experimental number

$$ {}^{exp}A_e^{^{19}\mathrm{Ne}} = -(3.91 \pm 0.14) \times 10^{-2} $$

have

$$ -0.45y^2 + 0.52xy + 0.01x^2 = (-0.6 \pm 2.0) \times 10^{-3} $$

Limits are as shown.



$\frac{P_F}{P_{GT}}$ (^{14}O, ^{10}C)
ρ
ξ
0.10
0.05
0.00
−0.05
−0.10
y
−0.10
−0.05
0.00
0.05
0.10
x

Future Beta Decay Efforts

i) $a_{e\nu}$ in ^{6}He decay at UW and GANIL

ii) N_{ab} at SNS

iii) $aBBA$ at SNS

iv) $UCNb$ at LANSCE

v) ^{35}Ar at ISOLDE

v) ^{35}Ar at ISOLDE

vi) $aSPECT$ at NIST

vii) $aCORN$ at NIST

viii) ^{8}Li at ANL

ix) ^{37}Ar at TRIUMF

x) $etc.$