

Study of Fundamental Symmetries in Nuclei

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Weak interactions in nuclei, with beta decays and muon capture reactions in particular, have been used, over the last forty years, as the unique laboratory for studying fundamental symmetries. Upon surveying briefly my past research efforts in relation to the hypothesis of conserved vector currents (CVC), partially conserved axial currents (PCAC), and the absence of second-class currents, I wish to identify some unique roles that weak interactions in nuclei are yet to play as we venture into the twenty-first century.

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I. Introduction

It is my great honour to be able to dedicate this contribution to Dr. Ta-You Wu on the occasion of his ninetieth birthday. My encounter with Dr. Wu did not actually begin until about ten years ago, shortly after I returned to Taiwan on a permanent basis and Dr. Edward Yen at Tsing Hua University brought me to pay him a brief visit. Since then, Dr. Wu has gradually assumed the role of being a teacher, a fatherly figure, as well as an intimate friend (when frustrations or feelings can be expressed without hesitation, nor reservation) – a role grown out of my frequent contacts with him, first through preparation of the manuscript on the textbook “Relativistic Quantum Mechanics and Quantum Fields” (World Scientific, Singapore, 1991), then on the arrangements of his regular classes at Taida, and lately even on regular visits whenever I could find time to do so. I truly admire Dr. Wu when he says that people respects him because he poses no threats to anyone else – his state of mind is way beyond what Confucius says about “knowing and feeling the Heaven’s will” (知天命).

There are only a very small number of people who, through many years of hard work and tough thinking, luckily reach the state of truly understanding and deeply enjoying a certain subject. One day near the end of the last year, Dr. Wu showed me [1], during my say-hello visit at his residence, his note on the Lorentz invariance of Ldt in Hamilton’s principle. He sort of entertained himself with the notion that for so many years of teaching on the subject he did not pinpoint the specific aspect now published in [1]. Over the last decade, I have learned from Dr. Wu quite a few aspects of similar nature. In his seventy

years both as a physicist and as a teacher, Dr. Wu has recognized and accumulated a wealth of knowledge regarding subtleties in different areas of physics and revealed many of these points to me primarily through informal conversations. To this date, Dr. Wu often entertains himself and his visitors by discussing the subtle aspects of a specific physics subject with little concern whether the subject is currently fashionable or not. This is why he has kept me as one of his sincere admirers.

In a 1957 letter to Dr. Ta-You Wu immediately after he was awarded the Nobel prize, Professor Yang acknowledged Dr. Wu for initiating him "into the field of symmetry laws and group theory in the Spring of 1942". To my knowledge, Dr. Wu's keen interest in symmetry concepts remains strong as of today. It might therefore be appropriate for me to add to this celebration some of my work making use of nuclei as the laboratory to study fundamental symmetries.

An $A = (Z, N)$ nucleus is a system of Z protons and N neutrons stacking up closely in a volume with a radius of a few fm. Stable nuclei ranging from the deuteron ($A = 2$) to nuclei of more than 200 nucleons are found in nature. Admittedly, nuclei are unique systems consisting of strongly interacting elementary particles and account for the diverse variety of objects in our visual world. As most of the known elementary particles do not live long enough, experimentations with nuclei offer an important avenue for further understanding how the laws of nature work or testing if the perceived conjecture is indeed acceptable. For instance, the theory for weak interactions involving charged currents, including Fermi's current-current interactions and discovery of parity violation, began with observations associated with β decays in nuclei.

Therefore, it should not be a surprise that many of the underlying ideas or fundamental symmetries associated with the standard model may be tested in nuclei. The subject itself has grown to the point that it is no longer possible to attempt an overview of the field, which include many subject matters, methodologies, and occasionally variations in the choice of specific models for nuclei or currents. Instead, we wish in this contribution to describe a very specific example and methodology to demonstrate the theme that nuclei offers a unique laboratory for testing the validity of fundamental symmetries.

II. General aspects: theory versus experiment

We wish to use the famous $A = 12$ triad as our illustrative example. The ground states of the ^{12}B and ^{12}N nuclei and the 15.110 MeV excited state of the ^{12}C nucleus constitute an $J = 1^+$ isospin triplet. There are many electroweak reactions involving the $A = 12$ triad, including:

$$\begin{aligned}
&\text{Beta decays: } {}^{12}B \rightarrow {}^{12}C(g.s.) + e^- + \bar{\nu}_e, \\
&{}^{12}N \rightarrow {}^{12}C(g.s.) + e^+ + \nu_e, \\
&\text{Muon Capture: } \mu + {}^{12}C(g.s.) \rightarrow \nu_\mu + {}^{12}B, \\
&\text{Gamma decay: } {}^{12}C^* (15.110) \rightarrow {}^{12}C(g.s.) + \gamma, \\
&e^- + {}^{12}C(g.s.) \rightarrow e^- + {}^{12}C^* (15.110), \\
&\text{Neutrino excitations: } \nu_e + {}^{12}C(g.s.) \rightarrow e^- + {}^{12}N, \\
&\bar{\nu}_e + {}^{12}C(g.s.) \rightarrow e^+ + {}^{12}B, \\
&\nu(\bar{\nu}) + {}^{12}C(g.s.) \rightarrow \nu(Y) + {}^{12}c^* (15.110).
\end{aligned}$$

With $V_\lambda(x)$ and $A_\lambda(x)$ the hadronic weak polar and axial vector currents, Lorentz invariance allows us to introduce the following covariant nuclear form factors:

$$\begin{aligned}
&\langle {}^{12}B(p', \xi') | V_\lambda(0) | {}^{12}C(p) \rangle \\
&= -\sqrt{2} \epsilon_{\lambda\kappa\rho\eta} \xi_\kappa^{\prime*} \frac{q_\rho}{2m_p} \frac{Q_\eta}{2M} F_M(q^2),
\end{aligned} \tag{1a}$$

$$\begin{aligned}
&\langle {}^{12}B(p', \xi') | A_\lambda(0) | {}^{12}C(p) \rangle \\
&= \sqrt{2} \left\{ \xi_\lambda^{\prime*} F_A(q^2) + q_\lambda \frac{q \cdot \xi^{\prime*}}{m_\pi^2} F_P(q^2) - \frac{Q_\lambda}{2M} \frac{q \cdot \xi^{\prime*}}{2m_p} F_E(q^2) \right\}
\end{aligned} \tag{1b}$$

where

$$\begin{aligned}
q_\lambda &\equiv (p' - p)_\lambda, \quad Q_\lambda \equiv (p' + p)_\lambda, \\
M &= \frac{1}{2}(M_i + M_f) = \frac{1}{2}[M({}^{12}C) + M({}^{12}B)], \\
\xi^{\prime*} &\equiv (\vec{\xi}^{\prime*}, i\xi_0^{\prime*}), \\
\xi^{\prime*} \cdot \xi' &\equiv \vec{\xi}^{\prime*} \cdot \vec{\xi}' - \xi_0^{\prime*} \xi_0' = 1, \\
\xi^{\prime*} \cdot p' &= 0.
\end{aligned}$$

Here $F_{M,A,P,E}(q^2)$ are referred to as the "weak magnetism", "axial", "pseudoscalar", and "weak electricity" form factors. In terms of these form factors, the transition amplitude T for the muon capture reaction from ${}^{12}C(g.s.)$ to the ground state of ${}^{12}B$:

$$\mu^-(p^{(\mu)}, s^{(\mu)}) + {}^{12}C(p) \rightarrow \nu_\mu(p^{(\nu)}, s^{(\nu)}) + {}^{12}B(p', \xi') \tag{2}$$

is given by

$$T = \frac{G}{\sqrt{2}} \langle {}^{12}B(p', \xi') | [V_\lambda(0) \mp A_\lambda(0)] | {}^{12}C(p) \rangle \cdot i\bar{u}^{(\nu)}(p^{(\nu)}, s^{(\nu)}) \gamma_\lambda (1 + \gamma_5) u^{(\mu)}(p^{(\mu)}, s^{(\mu)}). \quad (3)$$

We introduce the following combinations of the covariant form factors [2],

$$G_V = -F_M(q^2) \frac{E^{(\nu)}}{2m_p}. \quad (4a)$$

$$G_A = -F_A(q^2) - F_M(q^2) \frac{E^{(\nu)}}{2m_p}, \quad (4b)$$

$$G_P = F_P(q^2) \frac{m_\mu E^{(\nu)}}{m_\pi^2} - F_E(q^2) \frac{E^{(\nu)}}{2m_p} - F_M(q^2) \frac{E^{(\nu)}}{2m_p}, \quad (4c)$$

with

$$q^2 = (p' - p)^2 = (p^{(\mu)} - p^{(\nu)})^2 = -m_\mu^2 + 2m_\mu E^{(\nu)} = 0.740m_\mu^2,$$

$$E^{(\nu)} = (m_\mu - \Delta) - \frac{(m_\mu - \Delta)^2}{2M({}^{12}B)} = 91.41 \text{ MeV},$$

$$\Delta = M({}^{12}B) - M({}^{12}C) = 13.881 \text{ MeV}. \quad (4d)$$

Denoting the direction of the muon spin by \hat{n} , we have

$$G^{-2} \int \frac{d^2\Omega^{(\nu)}}{4\pi} \sum_{s^{(\nu)}} |T(s^{(\mu)}, s^{(\nu)}, \xi'^*)|^2 = \frac{1}{3}(3G_A^2 - 2G_A G_P + G_P^2) + i\vec{\xi}' \times \vec{\xi}'^* \cdot \hat{n} \frac{1}{3}(3G_A^2 - 2G_A G_P), \quad (5a)$$

$$G^{-2} \int \frac{d^2\Omega^{(\nu)}}{4\pi} \frac{1}{2} \sum_{s^{(\mu)}} \sum_{s^{(\nu)}} \sum_{\xi'} |T(s^{(\mu)}, s^{(\nu)}, \xi'^*)|^2 = 3G_A^2 - 2G_A G_P + G_P^2. \quad (5b)$$

Taking into account the effect of the initial-state Coulomb interaction factorized in a way analogous to the role of Fermi functions in beta decays, we cast the capture rate in the form:

$$\Gamma(\mu^{-12}C(g.s.) \rightarrow \nu_\mu {}^{12}B(g.s.)) = \Gamma_0(3G_A^2 - 2G_A G_P + G_P^2),$$

$$\Gamma_0 \equiv \left(\frac{GE^{(\nu)}}{\pi}\right)^2 \left(1 + \frac{E^{(\nu)}}{m_\mu + M_f}\right)^{-1} C({}^{12}C) \left(\frac{Z({}^{12}C)}{137} \frac{m_\mu M_i}{m_\mu + M_i}\right)^3, \quad (6)$$

$$Z({}^{12}C) = 6, \quad C({}^{12}C) = 0.841.$$

To obtain observables for the capture reaction with initially polarized muons, we choose the \hat{z} axis for the quantization of the spin of the recoil ^{12}B so that $\vec{\xi}'(\pm) = (\mp 1/\sqrt{2})(\hat{x} \pm i\hat{y})$ and $\vec{\xi}'(0) = \hat{z}$ (with $\hat{x}, \hat{y}, \hat{z}$ three orthogonal unit vectors) may be used in connection with Eq. (5a). In this way, we obtain the average polarization P_{av} and the average alignment A_{av} , as below [2]:

$$P_{av} \equiv \frac{h_{+1} - h_{-1}}{h_{+1} + h_{-1} + h_0} = \frac{2}{3} \left(1 - \frac{G_P^2}{3G_A^2 - 2G_A G_P + G_P^2} \right), \quad (7a)$$

$$A_{av} \equiv \frac{h_{+1} + h_{-1} - 2h_0}{h_{+1} + h_{-1} + h_0} = 0 \quad (7b)$$

In the case of unpolarized muon capture, we can also choose $\hat{z} = \hat{\nu}$ in Eqs. (4) (with all the \hat{n} terms dropped out) and calculate the longitudinal polarization P_L and the longitudinal alignment A_L [2]:

$$P_L = \frac{2(2G_A G_V - G_V^2)}{3G_A^2 - 2G_A G_P + G_P^2}, \quad (8a)$$

$$A_L = \frac{2(2G_A G_P - G_P^2)}{3G_A^2 - 2G_A G_P + G_P^2}. \quad (8b)$$

We see that all physical observables associated with the muon capture reaction (2) can be expressed in terms of G_V, G_A , and G_P , or in terms of the covariant form factors $F_{M,A,P,E}(q^2)$.

Along the same line, the transition amplitudes for beta decays are given by

$$\begin{aligned} & \mathcal{T}(^{12}B \rightarrow ^{12}C + e^- + \bar{\nu}_e) \\ &= \frac{G}{2} \langle ^{12}C(p_1) | [V_\lambda^\dagger(0) + A_\lambda(O)] | ^{12}B(p_2, \xi) \rangle \cdot i\bar{u}_e(p_e) \gamma_\lambda (1 + \gamma_5) v_\nu(p_\nu), \end{aligned} \quad (9a)$$

$$\begin{aligned} & \mathcal{T}(^{12}N \rightarrow ^{12}C + e^+ + \nu_e) \\ &= \frac{G}{2} \langle ^{12}C(p_1) | [V_\lambda(0) + A_\lambda(O)] | ^{12}N(p_2, \xi) \rangle \cdot i\bar{\nu}_e(p_e) \gamma_\lambda (1 + \gamma_5) u_\nu(p_\nu), \end{aligned} \quad (9b)$$

Accordingly, the e^\mp decay energy and angular distributions and the corresponding asymmetry coefficients α_\pm are given by [3]:

$$\begin{aligned} & d^3\Gamma(e^\mp) \\ &= \frac{G^2}{8\pi^4} |\sqrt{2}F_A^\mp(0)|^2 F_\mp(Z, E_e) p_e E_e (\Delta^\mp - E_e)^2 (1 \mp \eta_\mp + a_\mp E_e) dE_e d\Omega_e \\ & \times \left\{ 1 \mp (h_1 - h_{-1})(1 \mp \alpha_\mp E_e) \cos \vartheta_e + (1 - 3h_0)\alpha_\mp E_e \left(\frac{3}{2} \cos^2 \vartheta_e - \frac{1}{2} \right) \right\}, \end{aligned} \quad (10)$$

where

$F_{\mp}(Z, E_e) \equiv$ Fermi function for the e^{\mp} decays,

$h_1, h_{-1}, h_0 \equiv$ populations of the $J_z = 1, -1, 0$ states of ^{12}B or ^{12}N ,

$$h_1 + h_{-1} + h_0 = 1,$$

$$\cos \vartheta_e \equiv \hat{p}_e \cdot \hat{z},$$

$$a_{\mp} = \pm \frac{4}{3m_p} \frac{F_M^{\mp}(0)}{F_A^{\mp}(0)}, \quad (11)$$

$$\alpha_{\mp} = \frac{1}{3m_p} \left(\pm \frac{F_M^{\mp}(0)}{F_A^{\mp}(0)} - \frac{F_E^{\mp}(0)}{F_A^{\mp}(0)} \right),$$

$$\eta_{\mp} \equiv \frac{\Delta^{\mp}}{3m_p} \left(\mp 2 \frac{F_M^{\mp}(0)}{F_A^{\mp}(0)} + \frac{F_E^{\mp}(0)}{F_A^{\mp}(0)} \right),$$

$$\Delta^{\mp} \equiv M(^{12}C, ^{12}N) - M(^{12}C).$$

The form factors $F_{A,M,E}^{\mp}(q^2)$ are defined in the sense of Eqs. (1). They are all related since suitable isospin rotations allow us to transform from one triad member to the other. Again, we see that all physical observables associated with beta decays can be expressed in terms of the same set of covariant form factors $F_{M,A,P,E}(q^2)$.

We may also introduce, along the same line as Eqs. (1),

$$\begin{aligned} & \langle ^{12}C^*(p', \xi') | J_{\lambda}^{e.m.}(0) | ^{12}C(p) \rangle \\ &= -\epsilon_{\lambda\kappa\rho\eta} \xi_{\kappa}^{\prime*} \frac{q_{\rho}}{2m_p} \frac{Q_{\eta}}{2M} \mu(q^2), \end{aligned} \quad (12)$$

with $\mu(q^2)$ the M1 (magnetic) transition form factor which can be measured via the electron scattering $e^- + ^{12}C \rightarrow e^- + ^{12}C^*(15.110)$. The γ decay rate is given by

$$\Gamma(^{12}C^* \rightarrow ^{12}C \gamma) = \frac{\alpha}{3} \frac{E_{\gamma}^3}{m_p^2} |\mu(0)|^2. \quad (13a)$$

Using the experimental value of 37.0 ± 1.1 eV, we obtain

$$\mu(0) = 1.97 \pm 0.02. \quad (13b)$$

follows,

$$J_{\lambda}^{e.m.}(x) = \frac{1}{2} I_{\lambda}^{(3)}(x) + Y_{\lambda}(x), \quad (14)$$

with $I_\lambda^{(3)}(x)$ and $Y_\lambda(x)$ the third component of the isovector current and the hypercharge current, respectively. The conserved vector current (CVC) hypothesis identifies $I_\lambda^{(3)}(x)$ of Eq. (14), the charge-lowering and charge-raising weak currents $V_\lambda(x)$ and $V_\lambda^\dagger(x)$ as the members of the same conserved isovector currents $\vec{I}_\lambda(x)$. CVC leads to

$$F_M^\mp(0) = \mu(0) = 1.97 \pm 0.02. \quad (15)$$

It also leads to the prediction that $F_M(q^2)$ and $\mu(q^2)$ have the same q^2 dependence.

Now we turn our attention back to beta decays. With the appropriately calculated f values [4], Eq. (10) may be integrated to yield [3]:

$$\Gamma(e^-) = 124.51 \text{ sec}^{-1} [F_A^-(0)]^2 \left(1 + 0.005 \frac{F_E^-(0)}{F_A^-(0)} \right), \quad (16a)$$

$$\Gamma(e^+) = 251.28 \text{ sec}^{-1} [F_A^+(0)]^2 \left(1 + 0.006 \frac{F_E^+(0)}{F_A^+(0)} \right), \quad (16b)$$

which are to be compared with the experimental values:

$$\Gamma(e^-) = 32.98 \pm 0.10 \text{ sec}^{-1}, \quad (17a)$$

$$\Gamma(e^+) = 59.60 \pm 0.20 \text{ sec}^{-1}. \quad (17b)$$

In late 1970's, several beautiful experiments were performed to measure the variation with energy of the asymmetry coefficients α_\pm on the nuclear β decays: $^{12}\text{B} \rightarrow ^{12}\text{C} e^- \nu_e$ and $^{12}\text{N} \rightarrow ^{12}\text{C} e^+ \nu_e$. These measurements yield

$$\begin{aligned} \alpha_- &= -(0.07 \pm 0.20)/\text{GeV} \text{ (Lebrun et al. [5])}, \\ &= +(0.24 \pm 0.44)/\text{GeV} \text{ (Brandle et al. [6])}, \\ &= +(0.25 \pm 0.34)/\text{GeV} \text{ (Masuda et al. [7])}, \\ \alpha_+ &= -(2.77 \pm 0.52)/\text{GeV} \text{ (Masuda et al. [7])} \\ &\quad -(2.73 \pm 0.39)/\text{GeV} \text{ (Brandle et al. [8])}. \end{aligned} \quad (18a)$$

The standard picture, consisting of CVC, the absence of second-class currents (SCC), and the hypothesis of partially conserved axial currents (PCAC), leads to the prediction [3, 9]:

$$\begin{aligned} \alpha_- &= (0.88 \pm 0.03)/\text{GeV}, \\ \alpha_+ &= -(2.75 \pm 0.03)/\text{GeV}. \end{aligned} \quad (18b)$$

The remarkable agreement between experiment and theory has constituted the basis for our confidence towards the standard picture. Note that, in the discussion so far, there is little sensitivity toward the validity of PCAC, which relates the divergence of the charged

weak axial currents to the pion source currents (thus resulting in the pion pole dominance for the pseudoscalar form factor).

Finally, we return to the muon capture reaction (2). In principle, P_{av} , A_{\parallel} , P_L , and A_L can be measured by detecting the angular distribution of the electrons from the subsequent β decay of the recoil $^{12}\text{B}(g.s.)$ (with respect to the \hat{z} axis defined by \hat{n} or $\hat{\nu}$). In practice, the nonzero value of A_L enters the angular distribution by a multiplication factor of $\alpha_- E_e (\frac{3}{2} \cos^2 \vartheta_e - \frac{1}{2})$ and so might be too small to be of any interest. Nonetheless, the experimental determination of the capture rate [Eq.(6)], average polarization P_{av} [Eq. (7a)], and longitudinal polarization P_L [Eq.(8a)] already allow us to solve $G_{V,A,P}$; the solution is unique if the standard signs of $G_{V,A,P}$ are adopted.

Experimentally, we have [10]:

$$\left[\Gamma(\mu^{-12}\text{C} \rightarrow \nu_{\mu} \text{ } ^{12}\text{B}) \right]_{\text{exp}} = (6.2 \pm 0.3) \times 10^{-3} \text{sec}^{-1}. \quad (19)$$

On the other hand, Possoz et al. [II] measured the "apparent" average polarization of the recoil $^{12}\text{B}(g.s.)$ from polarized-muon capture by $^{12}\text{C}(g.s.)$ and subtracted the contribution due to those recoil $^{12}\text{B}(g.s.)$ which were produced indirectly, e.g. $\mu^{-12}\text{C}(g.s.) \rightarrow \nu_{\mu} \text{ } ^{12}\text{B}^* \rightarrow \nu \text{ } ^{12}\text{B}(g.s.)\gamma$. More careful analysis on the subtraction of the background in their experiment were performed by Kobayashi *et al.* [12] and by Hwang [2]. The final model-independent result for the average polarization of $^{12}\text{B}(g.s.)$ produced directly from $\mu^{-12}(g.s.) \rightarrow \nu_{\mu} \text{ } ^{12}\text{B}(g.s.)$ is given by

$$(P_{av})_{\text{exp}} = 0.47 \pm 0.05. \quad (20)$$

We note that, making use of the formulae (6) and (7a), we may extract G_A and G_P numerically from the data (19) and (20). The value of G_A in turn gives the ratio $F_M^-(q^2)/F_A^-(q^2)$ at $q^2 = 0.740m_{\mu}^2$. Taking, with justification, the assumption of similar q^2 dependence for $F_{M,A,E}(q^2)$, viz.:

$$\frac{F_M(q^2)}{F_M(0)} \approx \frac{F_A(q^2)}{F_A(0)} \approx \frac{F_E(q^2)}{F_E(0)}, \quad (21)$$

we obtain

$$F_M^-(0)/F_A^-(0) = 4.73 \pm 1.16. \quad (22a)$$

As indicated earlier, we have, granting validity of CVC,

$$F_M(0)/F_A(0) = 3.86 \pm 0.12. \quad (22b)$$

The agreement between (22a) and (22b) constitutes an impressive test of CVC.

Meanwhile, the asymmetry measurements [5, 6, 7, 8] yields

$$F_E(0)/F_A(0) = 3.67 \pm 0.44, \quad (23)$$

a value which can be understood in the nucleon-only impulse approximation (NOIA) [12] (without the presence of second-class currents). Thus, we deduce from the value of G_P at $q^2 = 0.740m_\mu^2$

$$F_P(q^2)/F_A(q^2) = -(1.08 \pm 0.24). \quad (24a)$$

On the other hand, assuming PCAC for the nucleon pseudoscalar form factor and using the Cohen-Kurath wave functions of $^{12}C(g.s.)$ in the NOIA calculation, we obtain [2]:

$$\begin{aligned} [F_P(q^2)/F_A(q^2)]_{NOIA} &= -1.02(1 + q^2/m_\pi^2)^{-1} + \delta \\ &= -0.99. \end{aligned} \quad (24b)$$

The excellent agreement between Eqs. (24a) and (24b) constitutes a test of PCAC, another important ingredient in the standard picture [namely, CVC, PCAC, and the absence of second-class axial vector currents].

To sum up, we have seen in a model-independent fashion that, even without the CVC test by extracting the shape factors from the observed e^\mp energy spectra [13] in the β decays of ^{12}B and ^{12}N , the basic ingredients of the standard picture, namely, CVC, PCAC, and the absence of second-class axial vector currents, can be individually tested and confirmed by the combination of the muon capture data [10,11] and the results of the asymmetry measurements [5-8].

III. Discussion and summary

The standard picture, namely, CVC, PCAC, and the absence of second-class currents, is an overall statement of the various symmetries including chiral symmetry. It is of utmost importance to ask if the existing data have verified individually the basic ingredients of the standard picture. The analysis presented in the previous section demonstrates that there is a completely model-independent positive answer to the question, making use of the $A = 12$ nuclei as the laboratory for testing fundamental symmetries.

There are other nuclei which also deserve serious attention. For instance, the case with $A = 8$ looks quite promising [14,15]. The $A = 6$ [16] and $A = 3$ [17] nuclei are another noteworthy places. Nevertheless, it remains difficult to arrive at a completely model-independent result regarding the validity of the standard picture.

What may be of much interest is that, by going from beta decays ($q^2 \approx 0$) to the muon capture reaction ($q^2 \approx m_\mu^2$), we are able to better determine the weak magnetism form factor so as to test CVC in a decisive manner and we also begin to have a real chance to determine the pseudoscalar form factor in order to compare with the PCAC prediction. It is clear that we should attempt to employ reactions such as (μ, ν_μ) or (ν_μ, μ) at even larger q^2 so as to test the various symmetries to higher precision.

Furthermore, the recent measurement [17] of the muon capture reaction has reached a remarkable experimental accuracy:

$$\Gamma(\mu^- + {}^3\text{He} \rightarrow \nu_\mu + {}^3\text{H}) = (1496 \pm 4) \text{ sec}^{-1}. \quad (25)$$

With the data of such precision, one may begin to use it to test specific symmetry to high precision, or equivalently, to constrain physics beyond the standard model [18]. Should the experimental error cited for Eq. (19) [of about 5 %] could be improved to a similar level [of about 0.3 % in Eq. (25)], the various conclusions drawn in the previous section would become highly precise. We could be heading for another era of precision physics using nuclei as the laboratory for studying physics beyond the standard model.

In summary, we have used $A = 12$ triad to show in a model-independent fashion that, even without the CVC test by extracting the shape factors from the observed e^\mp energy spectra [13] in the β decays of ^{12}B and ^{12}N , the basic ingredients of the standard picture, namely, CVC, PCAC, and the absence of second-class axial vector currents, can be individually tested by the combination of the muon capture data [10,11] and the results of the asymmetry measurements [5-8]. The opportunity to employ nuclei to perform high-precision symmetry studies is genuine and should not be overlooked.

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