Laboratory tests of the normal-mirror particle oscillations and the extended CKM matrix

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Abstract

The CKM matrix and its unitarity is analyzed by disentangling experimental information obtained from three different particle systems of neutrons, mesons, and nuclei. New physics beyond the Standard Model is supported under the new analysis. In particular, the newly proposed mirror-matter model (arXiv:1902.01837) can provide the missing physics and naturally extend the CKM matrix. Laboratory experiments with current technology for measuring neutron, meson, and nuclear decays under various scenarios are proposed. Such measurements can provide stringent tests of the new model and the extended CKM matrix.
INTRODUCTION

The Cabibbo–Kobayashi–Maskawa (CKM) matrix [1, 2] defines the strength of quark mixing in the standard model (SM). The CKM matrix for three families of quarks can be written as follows,

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$  \tag{1}

which, under the unitarity condition, is fully defined by four independent parameters including a phase allowing for the only CP-violation effect [3] confirmed in SM. More details can be found in a recent review [4].

The unitarity of the CKM matrix and its matrix elements, in particular, $V_{ud}$, have been studied with various experimental efforts. However, inconsistent results have been reported from the three different types of decay measurements:

1. neutron decay or lifetime,
2. $K/\pi$ meson decays,
3. nuclear transitions (superallowed $0^+ \rightarrow 0^+$ decays).

The discrepancies may lie in the different properties of new physics manifested in three different particle systems of neutrons, kaons/pions, and nuclei, as discussed later. In order to disentangle such effects, different experiments using different particle systems for determining the matrix elements are separated in the following discussions. In particular, $V_{ud}$ derived from the superallowed $0^+ \rightarrow 0^+$ decays [5] was often mixed with other measurements for evaluation of other matrix elements, which is avoided here.

ANALYSIS OF THE CKM MATRIX

The matrix element $|V_{ub}| = 0.00394(36)$ [6] is very small and therefore it contributes little in studies of the unitarity. The best direct constraint on $V_{us}$ is by measurements of the semileptonic $K_{l3}$ decays via $f_+(0)|V_{us}| = 0.21654(41)$ [7] where the form factor at zero momentum transfer $f_+(0)$ is calculated to be $0.9696(15)_{\text{stat}}(11)_{\text{sys}}$ by the lattice QCD
approach \[8\]. The best value for the matrix element \( V_{us} \) is then,

\[ |V_{us}| = 0.22333(60). \] \( \text{(2)} \)

Hadronic \( \tau \) decay experiments provide an independent measurement of \( V_{us} \) which, however, uses \( V_{ud}(0^+ \rightarrow 0^+) \) and has a larger uncertainty \[9\]. Therefore, it is not considered here.

The ratio of the radiative inclusive rates for \( K^\pm_{\mu^2} \) and \( \pi^\pm_{\mu^2} \) decays sets \( f_{K^\pm}/f_{\pi^\pm}|V_{us}/V_{ud}| = 0.27599(37) \] where the FLAG averaged lattice QCD calculations give the ratio of the isospin-broken decay constants \( f_{K^\pm}/f_{\pi^\pm} = 1.1932(19) \) \[10\]. The best value using the most recent updates is therefore,

\[ |V_{us}/V_{ud}| = 0.23130(48). \] \( \text{(3)} \)

The matrix element \( V_{ud} \) can then be obtained from measurements of meson decays using Eqs. \( \text{(2-3)} \),

\[ |V_{ud}| = 0.9655(33). \] \( \text{(4)} \)

For neutron \( \beta \) decays, the matrix element \( V_{ud} \) can be written as,

\[ |V_{ud}|^2 = \frac{2\pi^3}{G_F^2 m_e^5 f_n \tau_n (1 + 3\lambda^2)(1 + \delta'_R)(1 + \Delta Y_R)} = \frac{5024.46(30) \text{ sec}}{\tau_n (1 + 3\lambda^2)(1 + \Delta Y_R)} \] \( \text{(5)} \)

where the Fermi constant \( G_F = 1.1663787(6) \times 10^{-5} \) GeV\(^{-2}\), \( m_e \) is the electron mass, the neutron-specific radiative correction \( \delta'_R = 0.014902(2) \) \[11\], the phase space factor \( f_n \) is \( 1.6887(1) \) \[11, 12\], and natural units (\( \hbar = c = 1 \)) are used for simplicity. The 1\% difference in neutron \( \beta \)-decay lifetime \( \tau_n \) between measurements from “beam” and “bottle” experiments leads to the discrepant \( V_{ud} \) values according to Eq. \( \text{(5)} \). The neutron lifetime anomaly becomes more severe by more than 4\( \sigma \) from recent high-precision measurements \[13, 14\].

More recent measurements on the ratio of the axial-to-vector couplings \( \lambda = g_A/g_V \) especially after 2002 have provided more reliable values \[12\] and its current best value of \( \lambda = -1.27641(56) \) comes from the PERKEO III measurement \[15\]. One of the largest uncertainties other than the neutron lifetime in Eq. \( \text{(5)} \) is from the transition-independent radiative correction and its newly updated value is \( \Delta Y_R = 0.02467(22) \) \[16\]. Using the neutron \( \beta \)-decay lifetime of \( \tau_n = 888.0 \pm 2.0 \) s from the averaged “beam” values \[13, 17\], we can obtain the matrix element,

\[ |V_{ud}| = 0.9684(12). \] \( \text{(6)} \)
The “bottle” lifetime measurements using ultra-cold neutrons (UCN) are not consistent within themselves possibly due to the differences of the trap geometry [18]. For example, the two most recent measurements [14, 19] deviate from each other by 3.2σ. Using the average “bottle” lifetime of $\tau_n(\text{bottle}) = 879.4 \pm 0.6$ s, we can obtain $|V_{ud}(\text{bottle})| = 0.97317(50)$ from Eq. (5).

The matrix element determined from the superallowed $0^+ \to 0^+$ decays [5] using the updated $\Delta Y_R$ value [16] is $|V_{ud}(0^+ \to 0^+)| = 0.97370(14)$ [6], which exhibits a tension with $V_{ud}$ in Eq. (1) from the meson decay measurements by a deviation of 2.5σ. With the best known $V_{us}$ from Eq. (2), the unitarity of the CKM matrix is violated for any of the above-discussed $V_{ud}$ values as shown in Table I and especially the deviation is 5.3σ for the most trusted $V_{ud}(0^+ \to 0^+)$, indicating that new physics is needed.

The discrepancy of $V_{ud}$ values between meson and nuclear decay measurements has not drawn as much attention as the neutron lifetime anomaly, partly due to still larger uncertainties in meson decay studies. Another reason is that $V_{ud}(0^+ \to 0^+)$ is often treated as the gold standard for obtaining other matrix elements. $V_{ud}$ derived from the superallowed $0^+ \to 0^+$ decays is so trusted that exclusion of any exotic decay channels of neutrons was proposed [20]. Assuming that $V_{ud}(0^+ \to 0^+)$ is the true value, the apparent consistency between the neutron lifetime measured by the “bottle” approach and the axial-to-vector coupling ratio $\lambda$ derived from recent $\beta$-asymmetry measurements was studied in Ref [12] favoring the “bottle” method for the neutron $\beta$-decay lifetime. However, its tension with $V_{ud}$ inferred from measurements of meson decays ($K_{l3}$ and $K_{\mu2}/\pi_{\mu2}$) may reverse all these arguments, which will be discussed in the following.

TABLE I. Deviation in σ-level from unitarity of the CKM matrix for the first row of $|V_u|^2 = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ is shown based on $|V_{us}| = 0.22333(60)$ from Eq. (2), $|V_{ub}| = 0.00394(36)$, and different $V_{ud}$ values from different types of measurements.

| Measurement Type     | $|V_{ud}|$ | $|V_u|^2$ | σ  |
|----------------------|----------|----------|----|
| meson decays         | 0.9655(33) | 0.9822(63) | 2.8 |
| n-decay “beam”       | 0.9684(12) | 0.9878(22) | 5.4 |
| n-decay “bottle”     | 0.97317(50) | 0.9969(10) | 3.0 |
| nuclear $0^+ \to 0^+$| 0.97370(14) | 0.99798(38) | 5.3 |
MIRROR-MATTER MODEL AND THE EXTENDED CKM MATRIX

Various theoretic efforts [18, 21–23] have been devoted for solving the issues, in particular, the neutron lifetime anomaly. The idea of neutron dark decay in nuclei [24] based on the dark decay model of Fornal and Grinstein [22] pointed to clues of new physics from nuclear systems. A 4th quark in the mixing with the three known generations of quarks was recently suggested to solve the discrepancies in the CKM unitarity [25]. Most of the previous works focus on correcting the "beam" lifetime to agree with the "bottle" lifetime. Some of the more interesting models introduce $n - n'$ oscillations involving the mirror-matter theory [18, 21, 23].

There are several models on the mirror matter theory that have been proposed. Typically very weak interactions between particles of normal and mirror sectors are introduced. A photon-mirror photon kinetic mixing mechanism was suggested to couple the two sectors [26, 27]. The possibility of transition magnetic moments between the normal and mirror neutrons was studied as well [28]. Alternatively, a six-quark coupling was induced for the mixing of normal and mirror neutrons and explanation of the neutron lifetime anomaly [21].

Spontaneous symmetry breaking of the mirror symmetry was also used in various degrees. It was first used for an unsuccessful attempt of explanation of neutrino oscillations [29] by introducing a mirror symmetry breaking scale of a factor of 30. To reconcile the neutron lifetime discrepancies, a $n - n'$ oscillation model was proposed using a six-quark coupling and a small $n - n'$ mass splitting of $10^{-7}$ eV [30] where, like many other studies, the "bottle" lifetime is favored again.

Different models aim at different ways to solve the above discrepancies. In the following, we will introduce briefly the newly proposed mirror-matter model [18] and discuss various laboratory tests that can be carried out with current technology and distinguish this model from other proposed solutions.

In this new mirror matter model [18], no cross-sector interaction is introduced, unlike other models. It can explain various observations in the universe including the neutron lifetime puzzle and dark-to-baryon matter ratio [18], origin of baryon asymmetry [31], evolution and nucleosynthesis in stars [32], ultrahigh energy cosmic rays [33], and a requirement of strongly self-interacting dark matter to address numerous discrepancies on the galactic scale [34].
The critical assumption of this model is that the mirror symmetry is spontaneously broken by the uneven Higgs vacuum in the two sectors, i.e., $\langle \phi \rangle \neq \langle \phi' \rangle$, although very slightly (on the order of $10^{-15}$) [18]. When fermion particles obtain their mass from the Yukawa coupling, it automatically leads to the mirror mixing for neutral particles, i.e., the basis of mass eigenstates is not the same as that of mirror eigenstates, similar to the generation mixing of quarks and neutrinos. Further details of the model can be found in Ref. [18].

The immediate result of this model is the probability of normal-mirror neutral particle oscillations in vacuum [18],

$$P(t) = \sin^2(2\theta) \sin^2\left(\frac{1}{2}\Delta t\right)$$

(7)

where $\theta$ is the mixing angle, $\sin^2(2\theta)$ denotes the mixing strength of about $10^{-4}$ for $K^0 - K^{0'}$ and $2 \times 10^{-5}$ for $n - n'$, $t$ is the propagation time, and $\Delta$ is the small mass difference of the two mass eigenstates (on the order of $10^{-6}$ eV for both $K^0 - K^{0'}$ and $n - n'$) [18].

Under the new model, the symmetry breaking may occur in the same way [31] for the two discrete family ($Z_3$) and mirror ($Z_2$) symmetries resulting in one extended quark mixing matrix as follows,

$$V_{qmix} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} & V_{uu'}
V_{cd} & V_{cs} & V_{cb} & V_{cc'}
V_{td} & V_{ts} & V_{tb} & V_{tt'}
V_{dd'} & V_{ss'} & V_{bb'} & V'
\end{pmatrix}$$

(8)

where the quark-mirror quark mixing element $V_{qq'}$ could, as a naive estimate, be very similar to each other and for simplicity $V'$ is the $3 \times 3$ CKM matrix within the mirror sector. The unitarity for the first row of the matrix can then be written as $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{uu'}|^2 = 1$. This results in $|V_{uu'}| \simeq 0.11$ using the “beam” value of $V_{ud}$ from Eq. (6) and $V_{us}$ from Eq. (2). The same mixing mechanism for neutrinos has been applied for studies of the early universe and ultra-high energy cosmic rays [18, 31, 33] extending the corresponding mixing matrix of leptons similarly.

The mixing strength of neutral particles made of quarks can then be obtained from the mirror-mixing matrix elements for all constituent quarks,

$$\sin^2(2\theta) \simeq \prod_i |2V_{q,q'}|^2$$

(9)

where the mixing angle $\theta$ is assumed to be small and more mirror-mixing elements can be estimated with the known mixing strength. For example, the $n - n'$ mixing strength
\[ \sin^2(2\theta_{nn'}) = |2V_{uu'}|^2|2V_{dd'}|^4 \approx 2 \times 10^{-5} \] leads to \[ |V_{dd'}| \approx 0.071. \] The study of \( K_L^0 - K_{L'}^0 \) oscillations in the early universe for the origin of baryon asymmetry \([31]\) supports the mixing strength \( \sin^2(2\theta_{KK'}) = |2V_{dd'}|^2|2V_{ss'}|^2 \approx 10^{-4} \), resulting in \( |V_{ss'}| \approx 0.035. \)

\( V_{ud} \) values determined from meson decays and the “beam” lifetime are consistent and support the new mirror-matter model. The apparent consistency between the “bottle” lifetime and the superallowed \( 0^+ \rightarrow 0^+ \) decays is probably accidental. The additional mixing elements \( V_{uu'} \) and \( V_{dd'} \) may introduce additional radiative corrections (e.g., virtual \( n - n' \) process that does not affect neutron or meson systems) to the superallowed \( 0^+ \rightarrow 0^+ \) decays which will lower \( V_{ud}(0^+ \rightarrow 0^+) \) accordingly.

LABORATORY TESTS

As discussed above, \( V_{ud} \) and \( V_{us} \) determined from meson decays play a critical role. More accurate branching ratio measurements on the meson decays of \( K_{l3}, K_{\mu2}^\pm \) and \( \pi_{\mu2}^\pm \) are in need and meanwhile the corresponding hadronic constants \( f_+(0) \) and \( f_{K^\pm}/f_{\pi^\pm} \) need improvements in the lattice QCD calculations as their uncertainties are comparable with the experimental counterparts. This will provide an independent value of \( V_{ud} \) in comparison with the \( V_{ud} \) value from the neutron lifetime measurement of the “beam” approach. The agreement with much better uncertainties will provide very strong support for the new model. In addition, better \( V_{ud} \) and \( V_{us} \) values will define a better value of \( V_{uu'} \) and further reveal the mechanism of the mirror-particle oscillations by fulfilling self-consistent checks on the single-quark mixing strengths inferred from \( n - n' \) and \( K^0 - K_{L'}^0 \) oscillations.

Under the new \( n - n' \) oscillation model, the deviation of the neutron lifetime measured in the “bottle” approach from that in the “beam” method is due to the neutron loss by a fraction of \( \sin^2(2\theta)/2 \) in each collision with the walls even if the wall surface itself is perfect \([18]\). Such a \( n - n' \) oscillation mechanism results in a dependence of the measured lifetime on the geometry of a UCN trap. In particular, magnetic traps are better for such tests as imperfect wall surface conditions can be avoided. Experiments using traps with significantly different mean free flight times will provide one of the most stringent tests on the new model and distinguish it from other models. In particular, magnetic traps of a narrow cylindrical shape \([35, 36]\) could be re-run with better precision (e.g., close to that of the UCN\( \tau \) measurement \([14]\)) providing an immediate test of the model. Upon confirmation of the model, these
measurements will also nail down the mixing strength of \( n - n' \) oscillations and therefore provide a better estimate of the matrix elements \( V_{uu'} \) and \( V_{dd'} \).

The other parameter of the new model is the mass splitting \( \Delta \) between normal and mirror particles. Similar mass splitting values of the order of \( 10^{-6} \) eV for \( \Delta_{nn'} \) and \( \Delta_{KLK_S} \) that accounts for CP violation in SM indicate that all these phenomena may stem from the same mechanism of spontaneous symmetry breaking \([31]\) supporting the extended mixing matrix of Eq. (8). Under the consistent picture of the origin of both dark matter and baryon asymmetry \([31]\), we can obtain \( \Delta_{nn'} = 3 \times 10^{-6} \) eV with the \( n - n' \) mixing strength of \( \sin^2(2\theta) = 2 \times 10^{-5} \).

Laboratory tests of the mass splitting parameter can be done with a setup similar to the “beam” approach \([37]\) in neutron lifetime measurements. Neutrons in a magnetic field can be affected by an effective potential of \( \mu B \) where \( \mu = 6 \times 10^{-8} \) eV/T is the absolute neutron magnetic moment \([18]\). Such an effect is negligible for typical magnetic fields of \( B \lesssim 5 \) T since \( \mu B \ll \Delta_{nn'} \). Similar to the matter effect for neutrino oscillations and \( n - n' \) oscillations in stars \([32]\), however, the \( n - n' \) oscillations can become resonant in very strong magnetic fields when \( \mu B \sim \Delta_{nn'} \). For \( \Delta_{nn'} = 3 \times 10^{-6} \) eV, the resonant condition is \( B = 50 \) T. Direct-current high fields up to 45.5 T have recently been demonstrated in a very compact magnet setup with new conductor material and a novel design \([38]\). In a “beam” approach setup \([37]\), we could observe a significant neutron loss rate due to resonant \( n - n' \) oscillations when the magnetic field is slowly ramped up to about 50 T using the new technology. If it does confirm the new model, this laboratory test will help determine the mass splitting parameter more accurately.

The resonant condition of the matter effect for \( n - n' \) oscillations can be easily met at densities of \( 10^2 - 10^3 \) g/cm\(^3\) in stars \([32]\) while it is not feasible for a laboratory test on Earth. Nevertheless, we can conduct tests of cold/thermal neutrons traveling in a large detector made of dense and nearly absorption-free material. For example, cold neutron scattering occurs inside a liquid \(^4\)He detector at temperature of 4 K with the following properties: neutron velocity \( v = 2.5 \times 10^4 \) cm/s; liquid \(^4\)He density \( \rho = 0.125 \) g/cm\(^3\); scattering cross section \( \sigma = 1.34 \) b; and no absorption. From these parameters we can calculate a large ratio of the \( n - n' \) oscillation rate to the normal neutron \( \beta \)-decay rate: \( \lambda_{nn'}/\lambda_\beta \simeq 6 \) under the new model \([18]\). The neutron mean free path in liquid \(^4\)He is \( l = 40 \) cm. To keep the collisions inside the detector within the oscillation time scale of \( 1/\lambda_{nn'} \sim 160 \) s, unfortunately, the


detector size has to be as large as \( l/\sqrt{\sin^2(2\theta)/2} \sim 10^4 \) cm.

Another example is a heavy-water (D\(_2\)O) detector with neutrons at room temperature. We have the following parameters: scattering cross sections of \( \sigma(D) = 7.64 \) b and \( \sigma(O) = 4.232 \) b; absorption cross sections of \( \sigma_{abs}(D) = 5.19 \times 10^{-4} \) b and \( \sigma_{abs}(O) = 1.9 \times 10^{-4} \) b; density of \( \rho(D_2O) = 1.11 \) g/cm\(^3\); and neutron velocity of \( v = 2.2 \times 10^5 \) cm/s. The corresponding ratio of the \( n-n' \) oscillation rate to the absorption rate, \( \lambda_{nn'}/\lambda_{abs} \approx 0.16 \), is smaller than in the case of liquid \( ^4\)He. However, a much smaller mean free path of \( l = 1.5 \) cm results in a much smaller detector size of about 5 meters to contain neutrons within the oscillation time scale of one second.

Experiments measuring the branching fractions of \( K^0_L \) and \( K^0_S \) invisible decays can provide a different test (i.e., on \( V_{ss'} \)) of the new mirror-matter model \[18\]. Unfortunately, such branching fractions have not been constrained experimentally \[39\]. Under the new model assuming that the single quark mixing element \( V_{qq'} \sim 0.1 \), we can obtain an estimate of the branching fractions of \( K^0 \) invisible decays of about \( 10^{-6} \) for \( K^0_S \) and \( 10^{-4} \) for \( K^0_L \), which is reachable with current experimental capabilities. Measurements of the branching fractions at current kaon production facilities can determine the mixing element \( V_{ss'} \) more accurately. With future detector technology and accelerators, matrix elements of \( V_{cc'} \) and \( V_{bb'} \) could also be tested with similar measurements on the branching fractions of about \( 10^{-9} - 10^{-10} \) for \( D^0 \) and \( B^0 \) invisible decays \[18\].

The \( n-n' \) oscillation effects could also be studied in the quasi-free medium of a halo nucleus. The best example is \( ^{11}\)Be, a one-neutron halo nucleus. It has a 13.76 second \( \beta^- \)-decay half-life with a strong \( \beta^-\)-delayed particle decay (\( \beta\alpha \)) branch of 3.3% \[40\]. A rare decay branch of \( ^{11}\)Be \( \rightarrow ^{10}\)Be was measured with accelerator mass spectrometry (AMS) with an unexpectedly high branching ratio of \( 8.3 \pm 0.9 \times 10^{-6} \) \[41\]. Considering the neutron separation energy \( S_n = 501.64 \) keV for \( ^{11}\)Be, the neutron emission channel is not open while the \( \beta^-\)-delayed proton emission, i.e., the \( \beta p \) decay, is energetically possible and the only possible process without new physics for \( ^{11}\)Be \( \rightarrow ^{10}\)Be. A comparable branching ratio of \( \beta p \) \[42\] was also observed in a recent measurement of decaying protons from \( ^{11}\)Be stopped in the Active Target Time Projection Chamber (AT-TPC) \[43\]. However, various theoretical calculations \[44, 45\] have shown that such an \( \beta p \) decay branch can only contribute to the branching ratio of \( ^{11}\)Be \( \rightarrow ^{10}\)Be on the order of \( 10^{-8} \).

One possible explanation using the new \( n-n' \) oscillation model is to take into account
the quasi-free oscillation process in the halo, which can result in a branching ratio \[18\],

\[
BR = \sin^2(2\theta) \sin^2\left(\frac{\Delta_{nn'}}{2}\tau\right) \sim 10^{-5}
\]

(10)

where \(\tau\) is the \(^{11}\)Be lifetime. The result is in remarkable agreement with the AMS measurement. The virtual mirror neutron in the halo can undergo resonant oscillation near the edge of the nuclear potential well where \(\nabla_{\text{eff}} \sim \Delta_{nn'}\) and meanwhile overcome the barrier of the penetrability. The oscillatory \(n\) and \(n'\) can not escape freely due to energy conservation but will eventually decay via \(\beta p\) and \(\beta'p'\), respectively. The AMS approach measures the sum of \(\beta p\) and \(\beta'p'\) branching ratios while the AT-TPC detects only the \(\beta p\) branch. In a more sensitive TPC experiment, measurement of recoiled \(^{10}\)Be nuclei will give a summed branching ratio of both \(\beta p\) and \(\beta'p'\). At the same time detection of protons will provide the partial branching ratio of \(\beta p\) only. Any difference in the two ratios will indicate the existence of the \(\beta'p'\) decay supporting the idea of \(n - n'\) oscillations. Other possible candidates for similar decays are \(^{17}\)C, \(^{19}\)C, and \(^{31}\)Ne under the same criteria of one-neutron halo nuclei with \(S_n < 782\) keV.

CONCLUSION

The above-discussed experiments can test the mirror-matter theory in different systems of neutrons, mesons, and nuclei using the current technology. The underlying model parameters, i.e., the new mixing elements of \(V_{qq'}\) and mass splitting parameters can be further constrained and the consistency between them can be tested as well. Here we summarize the proposed laboratory experiments that can test the new model \[18\] and also distinguish it from other models:

1. UCN decays in magnetic traps with different geometries for different mean free flight times,

2. decays of cold neutrons through strong magnetic fields (e.g. \(B \sim 50\) T),

3. decays of cold neutrons in scintillation detectors made of liquid \(^4\)He, heavy water, or other nearly absorption-free dense materials,

4. branching fractions of \(K^0_L\) and \(K^0_S\) invisible decays,
5. better measurements of $K_{l3}$, $K_{\mu2}^\pm$ and $\pi_{\mu2}^\pm$ decays combined with better lattice QCD calculations,

6. branching ratios of $\beta p/\beta' p'$ decays of $^{11}$Be and other one-neutron halo nuclei like $^{17}$C, $^{19}$C, and $^{31}$Ne.

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