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Physics beyond the standard model with trapped atoms in the LHC era

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Summary. — Experiments carried out with the TRINAT trap system are described. These lead to limits on scalar interactions and on right-handed currents in the weak interaction process of β decay that are beyond the standard model of weak interactions. An upgraded experimental system and its improved capabilities are described.

1. – Introduction

In the standard model of weak interaction, the spin 1 of the exchanged boson implies that the interaction of the boson with the fermions must be of vector (V) and/or axial-vector (A) nature. The experimental observation of maximal parity violation means that V and A appear in equal strength. The further observation that neutrinos are left-handed means that these two interactions have opposite signs. Hence the "V-A" description of the weak interaction. However, this is put in the standard model "by hand", to accommodate the experimental observations. There is no first-principle reason why other interactions, that conserve quantum numbers, may not be present at some level. This level, however minute, may indicate the existence of interactions beyond the standard model. Such interactions can be scalar (S) or tensor (T) interactions and perhaps vector bosons that interact with right-handed neutrinos. The existence of such

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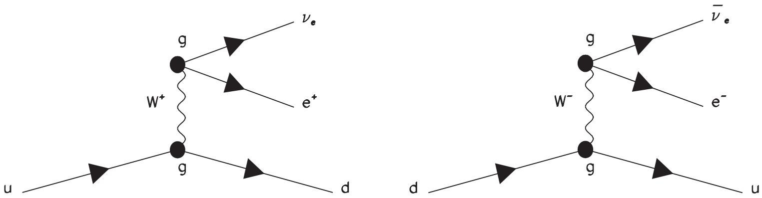

Fig. 1. – Left: Feynman diagram for β^+ decay. Right: Feynman diagram for β^- decay.

other, weaker interactions, implies the existence of bosons much heavier than the W and Z bosons.

In nuclear β decay at the nucleon level there are two processes: $n \to p\beta^-\bar{\nu_e}$ and $p \to n\beta^+ \ \nu_e$, where the latter can happen only for bound protons while the former can happen also for a free neutron. At the quark level these involve the u, d quarks, the $e^\pm$ and ν_e, $\bar{\nu_e}$ leptons and are described by the Feynman diagrams shown in fig. 1. A general formulation of the β decay transition probability (when β polarization is not measured), without requiring the standard model assumptions regarding invariance with respect to parity, charge conjugation and time reversal and allowing, in addition to vector and axial-vector interactions, also for scalar and tensor interactions is [1]

$$\begin{aligned} \mathrm{d}W = \mathrm{d}W_o\xi \Bigg(1 + \frac{\vec{p_\beta}\cdot\vec{p_\nu}}{EE_\nu}a_{\beta\nu} + \frac{\Gamma m_e}{E}b + \frac{\vec{J}}{J}\cdot\left[\frac{\vec{p_\beta}}{E}A_\beta + \frac{\vec{p_\nu}}{E_\nu}B_\nu + \frac{\vec{p_\beta}\times\vec{p_\nu}}{EE_\nu}D\right] \\ + c\left[\frac{\vec{p_\beta}\cdot\vec{p_\nu}}{3EE_\nu} - \frac{(\vec{p_\beta}\cdot\vec{j})(\vec{p_\nu}\cdot\vec{j})}{EE_\nu}\right]\left[\frac{J(J+1)-3\langle(\vec{J}\cdot\vec{j})^2\rangle}{J(2J-1)}\right]\Bigg). \end{aligned} \tag{1}$$

Here p_β, E and p_ν, E_ν are the β and ν momenta and energies, respectively. $\langle J\rangle$ is the nuclear vector polarization of the initial state, $\vec{j}$ is a unit vector in the direction of $\vec{J}$ and $\Gamma = \sqrt{1-(\alpha Z)^2}$ is the Coulomb factor. The measurement of the coefficients $a_{\beta\nu}, b, c, A_\beta, B_\nu$ and D is feasible using atom traps as will be discussed below. Their values and the normalization factor ξ are related to the (complex) interaction amplitudes C_i (i = S, V, A, T: Scalar, Vector, Axial-vector and Tensor interactions, respectively) [2]. The interaction amplitudes are in turn related to the chirality coupling constants a_{ij}, j, k for the neutrino and quark respectively [2].

In the standard model with V-A interaction and left-handed neutrinos

$$\begin{aligned} & g_V = 1, g_A = -1.27 \text{ (measured in neutron decay)}, \\ & a_{LL} = V_{ud}\frac{g^2}{8M_W^2} \cong 8\cdot 10^{-6}\,\mathrm{GeV}^{-2}, \quad a_{ij} = 0 \ i,j \neq L,L, \\ & a_{\beta\nu} = \frac{y^2-\frac{1}{3}}{y^2+1},\ y = \frac{C_V M_F}{C_A M_{GT}}, \\ & b = 0,\ c = \frac{-\Lambda_{JJ'}}{1+y^2},\ A_\beta = \frac{\mp\lambda_{JJ'} - 2\delta_{JJ'}y\sqrt{J/(J+1)}}{y^2+1}, \\ & B_\nu = \frac{\pm\lambda_{JJ'} - 2\delta_{JJ'}y\sqrt{J/(J+1)}}{y^2+1}, D = 0. \end{aligned}$$

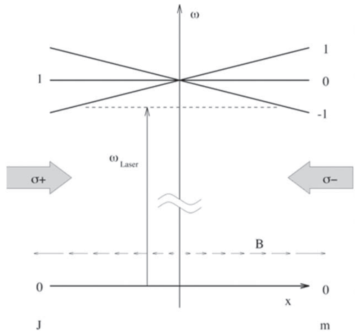

Fig. 2. – Simple, 1-D model of a MOT.

$|M_F|$ and $|M_{GT}|$ are the Fermi and Gamow-Teller matrix elements, respectively, and g_i are hadronic form factors.

Transition	$\lambda_{J'J}$	$\Lambda_{J'J}$
$J \to J' = J - 1$	1	1
$J \to J' = J$	$\frac{1}{J+1}$	$-\frac{2J-1}{J+1}$
$J \to J' = J + 1$	$-\frac{J}{J+1}$	$\frac{J(2J-1)}{(2J+3)(J+1)}$.

The measurement of these coefficients can show deviations from the values predicted by the standard model. By judiciously chosing the β decay transition it is possible to be selectively sensitive to the interactions that cause such a deviation.

2. – Magneto Optical Traps (MOTs)

These traps are intended to trap neutral atoms, utilizing combinations of laser beams tuned according to the atomic properties of the trapped atoms. A simplified one-dimensional model, shown in fig. 2, explains the principle of the trapping scheme in a MOT [3]. It assumes atoms with a $J = 0$ ground state and a $J = 1$ excited state. Two counterpropagating, circularly polarized beams of opposite helicity are detuned to the red of the transition. In addition there is a magnetic field gradient, splitting the $J = 1$ excited state into three magnetic sublevels. If an atom is located to the left of the center, defined by zero magnetic field, and is moving to the left, its $J = 0 \to J = 1$, $m = 1$ transition is closer to the laser frequency than the transitions to the other m-levels. As $\Delta m = +1$ transitions are driven by σ^+ light, atoms on the left are more in resonance with the beam coming from the left, they absorb the σ^+ light and the momentum $\hbar k$ of the absorbed quantum is pushing them towards the center. This creates a net restoring force. The same argument holds for atoms on the right side. The atoms then reemit the absorbed light in random directions, causing them to slow down and move to the center where no external force exists. Also, moving atoms see light opposing their motion Doppler shifted closer to the resonance which cools the atoms and temperatures in the milikelvin range can be achieved. In reality the trap is three-dimensional so the magnetic field, the optics, frequency and polarization are more complex. Also, in many atoms the useful optical transitions are not necessarily $J = 0 \to J = 1$. It is therefore necessary to develop the traps in a way that they can be adapted to a variety of conditions.

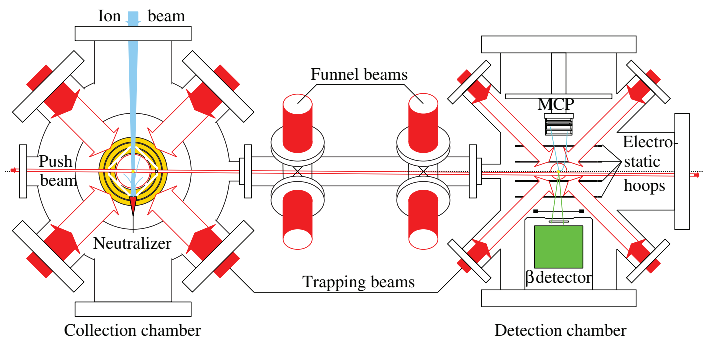

Fig. 3. – The TRINAT double-MOT system.

2˙1. *The TRIUMF Neutral Atom Traps (TRINATs).* – The TRIUMF double-MOT system was developed for use in conjunction with the ISAC radioactive beam. A general layout is shown in fig. 3. The $\sim 30\,\mathrm{keV}$ radioactive ion beam is delivered to the first ("collection") trap. The mass-separated ion beam is converted to neutral atoms by stopping in a hot Zr conical foil. The MOT traps a fraction of the atoms from the low-velocity tail of the thermal Maxwell-Boltzmann distribution. The radiation level in the collection trap is high, therefore, using a laser "push-beam", the trapped atoms are transferred to a second, clean ("detection") trap with 75% efficiency.

3. – Limits on scalar boson interaction

Sensitivity to contributions from scalar interaction is obtained by studying a pure Fermi $0^+ \rightarrow 0^+$ decay β-ν angular correlation. Under these conditions (eq. (1))

$$\mathrm{d}W(\theta) = 1 + b\frac{\mathrm{m}_\beta}{\mathrm{E}_\beta} + a_{\beta\nu}\frac{\mathrm{v}_\beta}{\mathrm{c}}\cos(\theta),$$

with $a_{\beta\nu} = 1 - 4\frac{g_S^2}{g_V^2}(|a_L^S|^2 + |a_R^S|^2)$ and $b = \pm\frac{g_S}{g_V}\frac{\mathcal{R}e(a_{LL}a_R^S)}{|a_{LL}|^2}$. a_L^S and a_R^S are the scalar left- and right-handed chirality coupling constants (sect. **1**). In the SM $b = 0$, $a_{\beta\nu} = 1.0$. Beyond the SM there are predictions in MSSM for $C_S + C_S^{'} \leq 0.001$ [4].

The trapping light beams were tuned to the atomic transitions of ^{38m}K leaving the ^{38}K atoms untrapped. We maintained a constant population of about 2000 atoms, 100% ^{38m}K with a size of 0.75 mm FWHM. We studied the β-ν angular correlation in $^{38m}\mathrm{K} \xrightarrow{\beta^+} {}^{38}\mathrm{Ar}$ pure Fermi decay. The detection sytem is shown in fig. 4. We detected the β^+ particles with the plastic scintillator coupled to a silicon microstrip detector, yielding energy and position information. The recoiling ^{38}Ar ions were accelerated by an electric field and detected with the MCP yielding momentum (through time-of-flight) and position information. From these β^+ and recoil momenta the neutrino momentum was reconstructed thus fully reconstructing the β-ν angular correlation, from which the coefficient $a_{\beta\nu}$ was deduced. The results are shown in fig. 5: $\tilde{a} = a_{\beta\nu}/(1+bm_\beta/\langle E_\beta\rangle) = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$. The corresponding lower limit on a scalar boson mass with $g_S = 1.02 \pm 0.1$ [5] is $M_S > 250\,\mathrm{GeV}/c^2$. This is the best limit set so far on this quantity [6]. The results

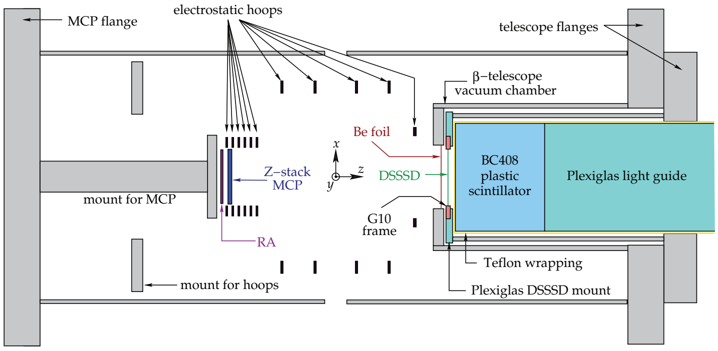

Fig. 4. – The detector system for the measurement of the ^{38m}K β decay.

in terms of the chirality coupling constants $|a_L^S|$ and $|a_R^S|$ are shown in fig. 6 (green). The results expected with the upgraded experimental system (sect. **4**˙3) are shown in red and further improvement is planned. Recently a relation was formulated between the continuous spectrum of the $pp \to e + m_T + X$ data (m_T is the transverse mass) taken at the LHC and possible limits on scalar interaction [7]. The relation depends on the interaction: $\sigma(m_T > \overline{m_T}) = f(\sigma_i, a_{i,j})$, $i, j =$ V, A, S, T, L, R. Using it the authors deduce limits of $|a_L^S|, |a_R^S| < 1.3 \cdot 10^{-2}$. There are issues of model dependence

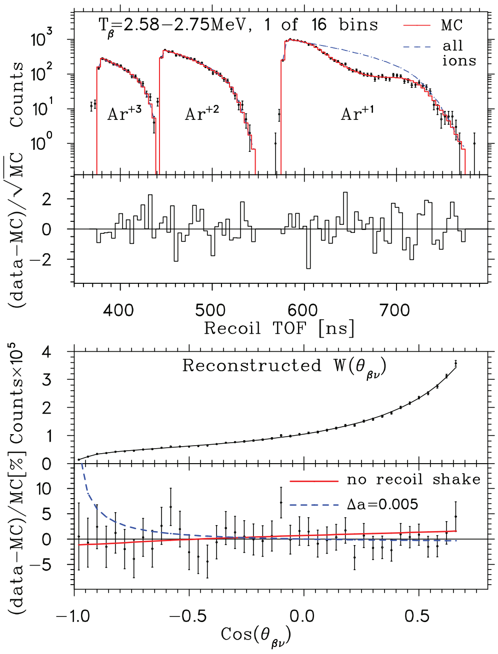

Fig. 5. – Top: time-of-flight of the recoiling ions fitted by Monte Carlo simulation. Bottom: the reconstructed β-ν angular correlation fitted by Monte Carlo simulations. Below each plot is the residual yield, [6].

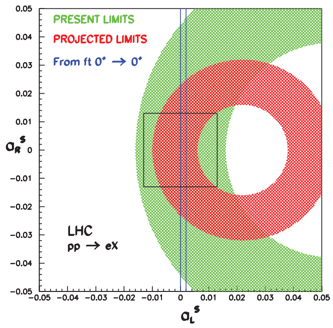

Fig. 6. – Limits on scalar interactions.

and of mass scale but nevertheless these limits are shown in fig. 6. This demonstrates the complementarity of the present work and that done in high-energy accelerators.

4. – Limit on right-handed currents

When we use polarized trapped atoms we have access to the coefficients A_β, B_ν, D and c (eq. (1)). The experimental observable in this case is the asymmetry defined as

$$\text{Asymmetry} = \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}.$$

$\sigma(\uparrow)$ and $\sigma(\downarrow)$ are the yields with positive and negative polarizations, respectively. Further observation of eq. (1) reveals that if the β particles are detected in the same direction as the radioactive nucleus is polarized, the asymmetry will yield, to first order, the coefficient A_β. If the β particles are detected perpendicular to the polarization direction then substituting

$$\vec{P_\nu} = -\vec{P_R} - \vec{P_\beta} \implies \mathrm{d}W \propto -\frac{\vec{J}}{J} \cdot \left[\frac{B_\nu \vec{P_R}}{E_\nu} + D \frac{(\vec{P_\beta} \times \vec{P_R})}{E_\beta E_\nu} \right].$$

By measuring the angular correlation between the recoiling ions and the polarization direction in the same plane we obtain the value of B_ν. By measuring this angular correlation in the plane orthogonal to the polarization direction we obtain the value of D. Measurements of A_β and B_ν provide information on possible right-handed currents [2]. D is the coefficient of a triple vector product that reverses sign when reversing the polarization direction, equivalent to reversing time and should be zero under the SM.

4˙1. *Polarization of the trapped atoms.* – This is done by the method of optical pumping described here for ^{37}K. Trapping of ^{37}K is done using the $S_{1/2} \to P_{3/2}$ (D2) transition while for polarization we use the $S_{1/2} \to P_{1/2}$ (D1) transition. Using a right-circularly polarized (σ^+) light in the D1 wave length all the ground state m_F substates except for the substate $F = m_F = 2$ are de-populated. The $F = m_F = 2$ state cannot absorb σ^+ light (hence "dark state"), becomes the most (only) populated state and the system is polarized, fig. 7 (left). Because the trapping D2 light can de-populate this state it has to be turned off during the optical pumping. We developed a scheme in which the atoms

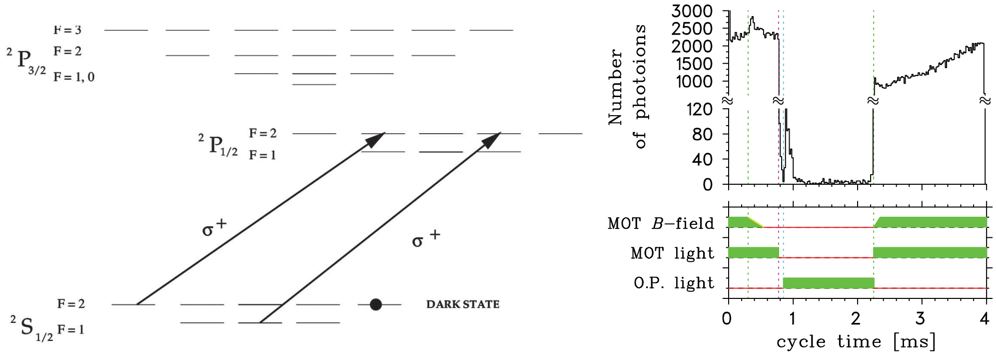

Fig. 7. – Left: atomic levels and transitions used to polarize ^{37}K. Right: photoions yield in the trapping-polarizing cycle.

are trapped, then the trapping B-field and laser light are turned off and the polarization B-field and laser light are turned on. By switching between one process and the other we maintain trapped polarized atoms. To measure the polarization we used a 355 nm laser beam that can ionize only atoms in the excited state. The ions were accelerated by the electric field and detected by the MCP. When the atoms are completely polarized no atoms can be excited since the $m_F = 2$ state cannot absorb light. In fig. 7 (right) we show the yield of photoions as a function of time in the polarization cycle. It shows a very low yield during the optical pumping period indicating close to 100% polarization.

4·2. *Measurement of the B_ν coefficient.* – The detection system described above was used for the measurement of B_ν We trapped and polarized ^{37}K using the general scheme described in sect. **4·1**. Using the photoions yield we found $\langle P_{\sigma^+}\rangle = (+97.7 \pm 0.4^{+0.2}_{-0.5})\%$ and $\langle P_{\sigma^-}\rangle = (-95.8 \pm 1.0^{-0.4}_{+1.3})\%$. We measured the asymmetry of the recoiling atoms as a function of position on the MCP, *i.e.* the angle with respect to the polarization axis, fig. 8 (left). The result is: $B = -0.755 \pm 0.020(\mathrm{stat}) \pm 0.013(\mathrm{syst})$, in agreement with the SM prediction of $B^{\mathrm{SM}} = -0.7692(15)$ assuming $\lambda \equiv g_A M_{GT}/g_V M_F = +0.5754(16)$; if λ was negative B^{SM} would be $+0.5702$, so our results determine the sign of λ to be positive [8]. This was the first search for new physics using trapped polarized radioactive nuclei.

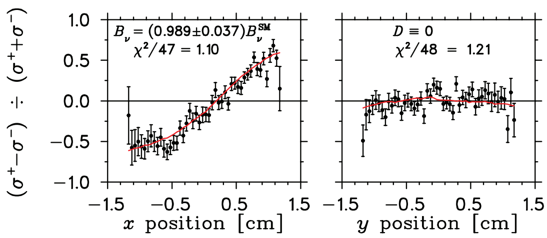

Fig. 8. – Asymmetries measured in the polarization-β plane (left) and in the orthogonal plane (right), [8].

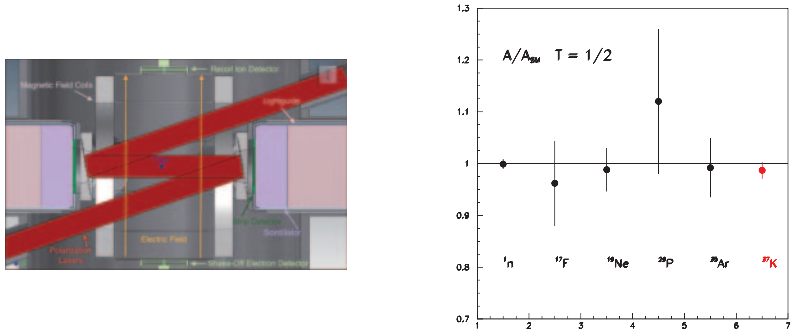

Fig. 9. – Left: the upgraded experimental system for measurements with polarized ^{37}K. The red lines represent the polarization laser beam. Right: preliminary results of A_β for ^{37}K in terms of the SM value, compared with other measurements [10].

4˙3. *Measurement of the A_β coefficient.* – Our experimental system underwent a very extensive upgrade in order to significantly improve the sensitivity. It has larger detectors, capability to detect the shakeoff electrons following the β^+ decay and two additional β detectors placed on the polarization axis (sect. **4**). A trapping scheme known as AC MOT [9] was implemented to improve the efficiency of the polarization cycle. In addition, the proton beam producing the radioactive isotopes was increased by over an order of magnitude.

The new system was commissioned by carrying out the measurement of the A_β parameter (sect. **1**). The system is shown in fig. 9 (left). ^{37}K atoms were trapped and their decay β's were detected by two plastic scintillators (left and right in fig. 9 (left)). The shakeoff electrons were detected in coincidence by a MCP detector significantly reducing the background. The trapped atoms were polarized by laser beams in the direction of the detected β particles. The result deduced from the asymmetry measurement is: $A_\beta = -0.563 \pm 0.009$ [10]. It is shown in fig. 9 (right) in terms of the SM value and is already the best result for nuclear β decay. The polarization in that measurement was 0.99 ± 0.01. A followup experiment was carried out and the polarization was determined to be 0.9913 ± 0.0008 [11]. Analysis of the data is underway and the statistical uncertainty is expected to be better than 1%.

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