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β-Decay and the electric dipole moment: Searches for time-reversal violation in radioactive nuclei and atoms

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Abstract. One of the greatest successes of the Standard Model of particle physics is the explanation of time-reversal violation (TRV) in heavy mesons. It also implies that TRV is immeasurably small in normal nuclear matter. However, unifying models beyond the Standard Model predict TRV to be within reach of measurement in nuclei and atoms, thus opening an important window to search for new physics. We will discuss two complementary experiments sensitive to TRV: Correlations in the β-decay of ^{21}Na and the search for an electric dipole moment (EDM) in radium.

Keywords. β-decay; electric dipole moment; searches for new physics.

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1. Introduction

The current understanding of the mechanism leading to time-reversal violation (TRV) in particle physics is one of the greatest achievements of the Standard Model (SM). At the same time there is a strong push to move the theory beyond the SM, both to relate the parameters of the SM to an underlying larger framework and to address questions raised by cosmological observations. The search for TRV can play an important role in this respect. Theoretical models that try to provide a new framework nearly always predict additional sources of TRV that are not in the SM. Therefore, establishing new limits for non-SM TRV will constrain these new models. In this work we will discuss two approaches involving searches at low energy for TRV beyond the SM. The first approach is the measurement of β–ν correlations in β-decay, which has the potential for TRV searches but will also allow to obtain additional input on the already precise value of the CKM matrix element V_{ud}. The second approach concerns searches for a permanent electric dipole moment (EDM) of heavy nuclei.

The outline of this paper is as follows: We will first discuss the complementarity of the two methods and then discuss the current status of experiments for both approaches in general, and more specifically for the work undertaken at Kernfysisch Versneller Instituut (KVI), in the next two sections.

2. Complementarity of searches for TRV

The correlations in nuclear β-decay can be written schematically as

$$\frac{\mathrm{d}^2\Gamma}{\mathrm{d}\Omega_\mathrm{e}\mathrm{d}\Omega_\nu} \sim 1 + a\,\hat{p}\cdot\hat{q} + b\frac{m_\mathrm{e}}{E_\mathrm{e}} \tag{1}$$

$$+ \langle\vec{J}\rangle \cdot [A\hat{p} + B\hat{q} + D\hat{p}\times\hat{q}] \tag{2}$$

$$+ \langle\vec{\sigma}\rangle \cdot \left[G\hat{p} + N\langle\vec{J}\rangle + R\langle\vec{J}\rangle\times\hat{p}\right], \tag{3}$$

where $\hat{p} = \vec{p}/E_\mathrm{e}$ and $\hat{q} = \vec{q}/E_\nu$ are the velocity vectors of the β-particle and neutrino, respectively, $\vec{J}$ is the spin of the parent nucleus and $\vec{\sigma}$ is the spin of the β-particle. The first part (1) describes the β–ν correlation when the parent nucleus is not polarized and is characterized by the coefficients a and b. The second part (2) deals with correlations with respect to the direction of the spin of the parent nuclei. The coefficients A and B are the well-known β and neutrino decay-asymmetry coefficients, respectively. The fact that they are not zero expresses parity violation, i.e. $\hat{p}$ and $\hat{q}$ change sign under parity (P) while $\langle\vec{J}\,\rangle$ does not. For the coefficient D the correlation is even under P but is odd under time reversal (T) (all vectors change sign). The last part (3) requires measuring the polarization of the β-particle. Also for R the correlation is T-odd, but in addition it is P-odd.

Turning now to the EDM: Because its value can be understood as a displacement of charge on the one hand, i.e. $\vec{d} = \Delta q\vec{r}$ (P-odd) and proportional to the spin of the particle on the other hand, i.e. $\vec{d} = \eta\frac{e}{mc}\vec{s}$ (T-odd), it follows that $\vec{d}$ must be odd under both P and T [1].

Therefore, when searching for new sources of TRV the search for an EDM is in some way equivalent to searching for a finite triple correlation R. This has been reviewed by Herczeg [2] who finds that EDM limits are stronger in restricting the boundaries for new physics. In contrast, there might be new interactions (e.g. leptoquark exchanges) [3] that cannot be observed from a finite EDM but could be found from a finite value of the T-odd triple correlation D [2]. Therefore, in this respect, the search for the correlation coefficient D is complementary to search for a finite EDM.

Finally, we note that correlation coefficients in β-decay measure the mixing ratio ρ of the Gamow–Teller (GT) and Fermi (F) matrix elements.

$$\rho = \frac{C_\mathrm{A} M_\mathrm{GT}}{C_\mathrm{V} M_\mathrm{F}}, \tag{4}$$

where C_A and C_V are the axial-vector and vector coupling coefficients, respectively. Therefore, by measuring the correlation coefficients and the strength of the β-decay

(ft value) one can, in principle, obtain data of similar quality for mirror transitions as in superallowed Fermi transitions that serve as input in the determination of V_{ud} [4]. This point has recently been stressed by Naviliat-Cuncic and Severijns [5] and may give additional motivation to study correlations.

3. Correlations in β-decay

Presently the only measurements of the triple correlation coefficient D are for the neutron and ^{19}Ne. The neutron experiments have led to values of $D = [-0.6 \pm 1.2(\text{stat.}) \pm 0.5(\text{syst.})] \times 10^{-3}$ [6] and $= [-2.8 \pm 6.4(\text{stat.}) \pm 3.0(\text{syst.})] \times 10^{-4}$ [7] from the emiT experiment and the TRINE Collaboration, respectively. Measurements with ^{19}Ne have been pursued by the Calaprice group, and the combined value of four experiments was given as $D = (1 \pm 6) \times 10^{-4}$ [8] which is the most precise value to date. To push the limit further, final-state interactions (FSI) that mimic a non-zero D coefficient have to be taken into account. Recently, it was claimed that using effective field theory the effects of FSI can be calculated up to 10^{-7} [9] (the SM value is $D \leq 10^{-12}$ [10]). However, experiments need to become much more precise to reach a level of 10^{-7}.

A new technique is the trapping of a sample in an atom or ion trap and to observe the recoiling ion in coincidence with the β-particle. Such traps also allow to polarize the sample. Currently, experiments have been limited to measuring the β–ν correlation coefficient a of the unpolarized sample. These efforts have resulted in precise values of a that can compete with the various indirect techniques that do not allow triple correlation measurements. In particular results have been obtained for ^{38m}K [11] and ^{21}Na [12]. The values $a_{\text{exp}}/a_{\text{SM}} = 0.9981 \pm 0.0030^{+0.0032}_{-0.0037}$ for ^{38m}K and $0.9949 \pm 0.0069 \pm 0.0091$ for ^{21}Na are to be compared with the value $0.9989 \pm 0.0052 \pm 0.0039$ obtained indirectly for ^{32}Ar [13,14]. Note that for the case of ^{21}Na the systematic error includes the uncertainty in the SM prediction, because it is a mixed transition. Only mixed transitions can be used for determining the D coefficient, i.e. $D \propto \delta_{JJ'} M_{\text{F}} M_{\text{GT}}$.

Measurements involving polarization of the trapped sample have also been reported, particularly on ^{82}Rb [15,16], ^{37}K [17] and ^{80}Rb [18]. These measurements can already address issues concerning the β- and ν-asymmetry coefficients A and B. The development of this technique is an important step towards measuring D.

At KVI we are developing a set-up to measure the correlation coefficient D. We have set up the TRIμP Facility for these and other studies of fundamental symmetries and interactions and to produce radioactive nuclei and to trap these in atom and ion traps. In a magnetic separator [19], projectiles are separated from products produced in inverse kinematics [20]. The particles are stopped in a thermal ionizer [21]. Such a device is well suited to ionize alkali and alkaline-earth elements, which are the elements that can be laser cooled and trapped the easiest. From the thermal ionizer the radioactive particles can be transported as a secondary low-energy ion beam. This beam enters a set-up [22] consisting of two chambers configured for a magneto-optical trap (MOT) as shown in figure 1.

In the first small chamber the ions are collected on a foil that can be heated to release atoms. The atoms can then be trapped. We have chosen to work with the mirror nucleus ^{21}Na as for this element most of the laser infrastructure was

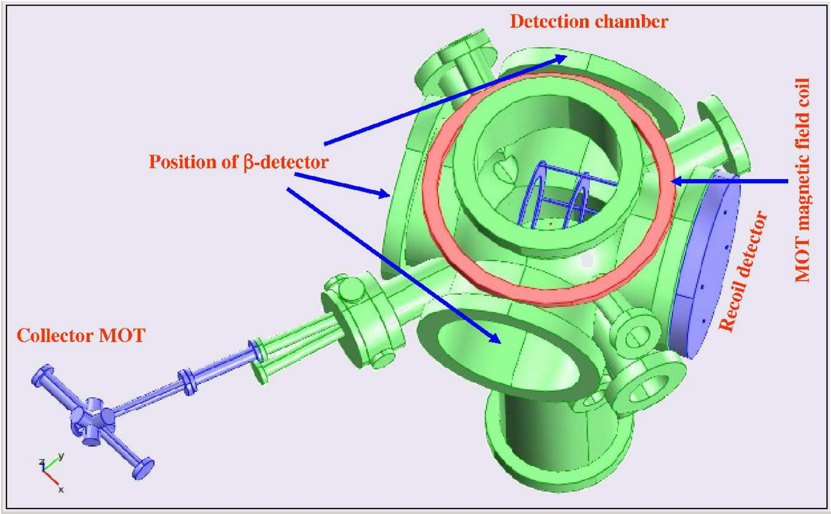

Figure 1. Schematic drawing of the collector and detection trap configuration.

available. We have observed the fluorescence of ^{21}Na but it is not yet sufficient to start measurements. Currently we are installing a transfer line by which the trapped atoms can be pushed towards the second MOT chamber. The second large chamber contains a position-sensitive β-detector and a reaction microscope. The latter is a device to observe ionized recoils from β-decay and measure their momentum with 4π efficiency. This instrument has been developed for atomic physics experiments [23]. It can be used in the energy range suitable for our work ($E_{\text{recoil}} \approx 100$ eV).

We recently studied [24] the response of the reaction microscope by ionizing the trapped ^{23}Na using a UV laser. Atoms in the excited state of the cooling cycle ($^2P_{3/2}$) can be probed in this way. In figure 2 the ions hitting the 2D sensitive multichannel plate (MCP) of the microscope can be seen. The intense region near the centre of the spectrum is from particles initially in the MOT cloud. The region has a diameter less than 1 mm. It is surrounded by a larger region of several mm of atoms that are cooled but not yet trapped (molasses). The sparsely populated circular region corresponds approximately to the sensitive area of the MCP and is due to random ionization throughout the volume of the microscope and are mostly uncorrelated with the UV pulse. Whereas the fluorescence of the atoms in the MOT cloud is visible to the naked eye, the halo around is not. Further study is required to find if this halo affects correlation measurements. These and other studies characterizing the set-up are currently in progress using mostly stable ^{23}Na.

As a final remark we note that precise lifetimes, branching ratios and Q-values are necessary when interpreting correlation coefficients of nuclei with mixed transitions, in particular of mirror nuclei, i.e. nuclei relevant for measuring D. A recent evaluation [25] shows which measurements are most relevant. The relevance of mixed transitions for measuring V_{ud} was already mentioned in the previous section. A new measurement of the ^{19}Ne and ^{21}Na was recently made at KVI in collaboration with a group from TUNL [26].

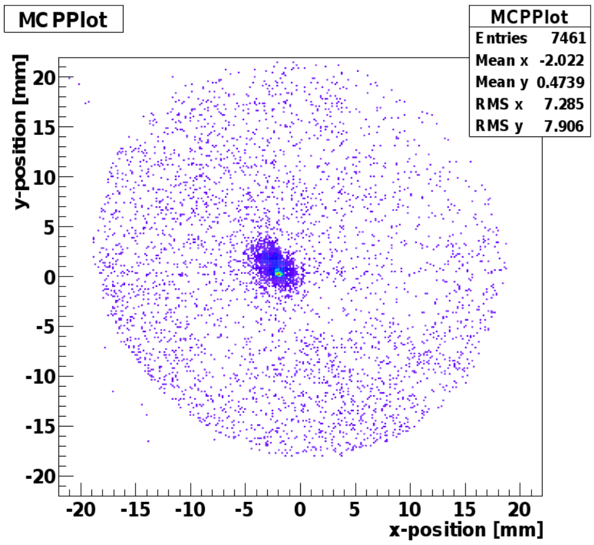

Figure 2. Two-dimensional position spectrum of ^{23}Na from the MOT following ionization with a UV laser. The UV laser probes all Na in the excited $^2P_{3/2}$ state.

4. Searches for a permanent electric dipole moment

Low-energy searches for EDMs are one of the main constraints on theories that are currently pursued in detail. For example the constraints on the minimal supersymmetric standard model (MSSM) obtained from EDM limits are already stringent, as recently reviewed in [27].

In table 1, an overview of some particles and their impact are given. Indeed, for the electron, neutron, and atoms new limits lead directly to new constraints, while the discovery potential, i.e., the range up to the SM value, remains large. Because a large electric field is desired to observe the precession due to an EDM, neutral particles are preferred for an EDM search. However, currently approaches

Table 1. Overview of some important experimental EDM limits (95% CL), the systems in which they were measured, the Standard Model values and the largest allowed predictions from various SM extensions.

Particle	Limit (e·cm)	System	SM	New physics	Ref.
Electron	1.9×10^{-27}	^{205}Tl atom	$\sim 10^{-38}$	10^{-27}	[28]
Muon	1.8×10^{-19}	Rest frame E field	$\sim 10^{-35}$	10^{-22}	[29]
Tau	2.5×10^{-17}	$(e^+e^- \to \tau^+\tau^-\gamma^*)$	$\sim 10^{-34}$	10^{-20}	[30]
Proton	7.9×10^{-25}	^{199}Hg atom	$\sim 10^{-31}$	5×10^{-26}	[31]
Neutron	7.4×10^{-26}	Ultra-cold neutrons	$\sim 10^{-31}$	5×10^{-26}	[32]
^{199}Hg	3.1×10^{-29}	^{199}Hg atom	$\sim 10^{-33}$	10^{-29}	[31]

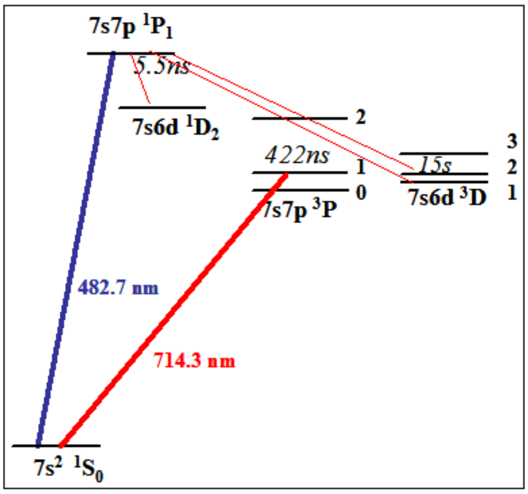

Figure 3. Atomic level scheme of low-lying states in Ra and some relevant transitions.

using storage rings [33,34] are being investigated, in particular for the proton and deuteron. The deuteron is of relevance because of its sensitivity to T-odd nuclear interactions [35]. Nonetheless, the strongest limits in the near future are expected to come from heavy atoms and molecules. Writing the dipole of a system schematically as a perturbation

$$d = \sum_i \frac{\langle \Psi_0 | D | \Psi_i \rangle \langle \Psi_i | H_{\mathrm{EDM}} | \Psi_0 \rangle}{E_0 - E_i} + \mathrm{c.c.}, \tag{5}$$

where D is the usual dipole operator, one observes that systems that are strongly polarizable (large $\langle \Psi_0 | D | \Psi_i \rangle$) and/or have nearly degenerate opposite parity states (small $E_0 - E_i$) will show the strongest effect given the strength of the P- and T-odd interaction H_{EDM} (for more details, see [1]). For our research we use both ^{225}Ra from a ^{229}Th source and Ra isotopes near ^{213}Ra, the latter is produced in our facility using the ^{206}Pb + ^{12}C reaction [36]. Ra has two possible enhancement factors apart from being a heavy atom.

The $7s7p\ ^3P_1$ and $7s6d\ ^3D_2$ (see figure 3) are nearly degenerate leading to the enhancement of a possible electron EDM in Ra of a factor 5000 [37]. In addition, for some Ra isotopes, enhancement of the order of 10^5 [37] of the EDM of nuclear origin arises due to octupole deformation and using the degeneracy of $7s7p\ ^3P_1$ and $7s6d\ ^3D_2$ states. Recently, ^{225,226}Ra was trapped [38] using the $^1S_0$–$^3P_1$ transition. This line is inefficient for cooling due to the long lifetime of the $^3P_1$ state. At KVI we are aiming to use the short-lived $^1P_1$ for the cooling cycle. A drawback is the strong leaking to the metastable D states. Recently, we demonstrated in the homologous Ba, which had not been trapped before, that employing suitable lasers for optical repumping can solve this problem and provide large capture efficiencies [39].

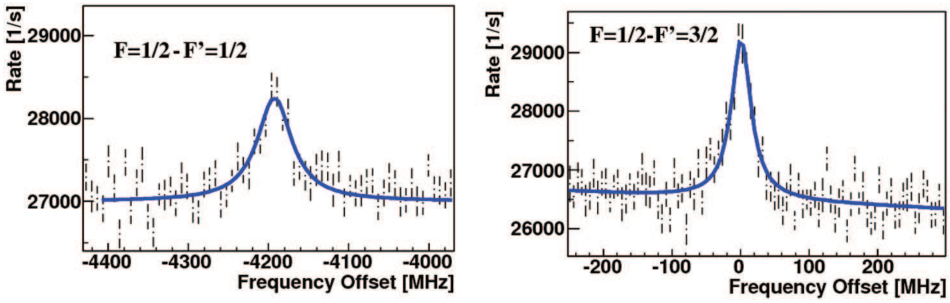

Figure 4. Laser-induced fluorescence signals from the two hyperfine components $F = 1/2 - F' = 1/2$ and $F = 1/2 - F' = 3/2$ of the $7s^2\ ^1S_0$–$7s7p\ ^1P_1$ transition.

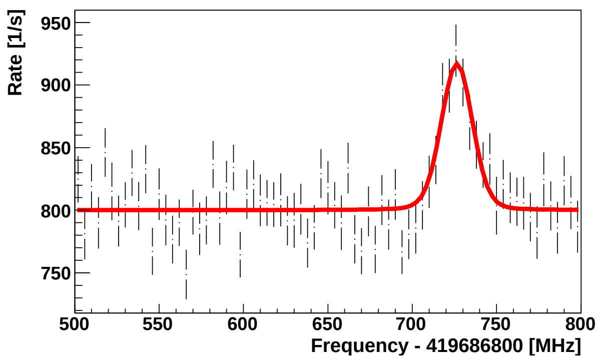

Figure 5. Laser-induced fluorescence signals from the $7s^2\ ^1S_0$–$7s7p\ ^3P_1$ transition.

We performed Doppler-free spectroscopy of the $7s^2\ ^1S_0$–$7s7p\ ^1P_1$ transition at 482.7 nm and the $7s^2\ ^1S_0$–$7s7p\ ^3P_1$ intercombination transition at 714.3 nm (figure 3). We used an atomic beam from an oven containing 10^{10} atoms of ^{225}Ra ($I = 1/2$) from ^{229}Th source. For the $^1S_0$–$^1P_1$ the hyperfine splitting was determined to be 4198(4) MHz (see figure 4) which is in good agreement with a previous determination [40]. The transition frequency is calibrated to a precision of 2 ppb against saturated absorption signals around 20715.75 cm^{-1} in molecular $^{130}Te_2$. The fluorescence observed from the weak $^1S_0$–$^3P_1$ transition is shown in figure 5. The data are measured relative to the 'a15' hyperfine component of the $R(116)$2-9 transition in molecular I_2. We have recently calibrated this line with an optical frequency comb. Further, atomic spectroscopy is required to provide also tests of the atomic theory which is a necessary input for the interpretation of the EDM measurement.

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