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SYMMETRY AND SYMMETRY-VIOLATION IN BETA DECAY; P, C AND A MYSTERIOUS T*

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Parity experiments with β decays were at the basis of the Standard Model for the electroweak interaction and continue to contribute, together with investigations of invariance for time reversal, to basic physics. In specific the essential role of β-ray polarimetry will be underlined with an extrapolation to a potential NdFe polarimeter for advanced studies of right-handed currents and time-reversal invariance at higher energies.

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1. Scope and introduction

In past years the symmetry breaking for mirror reflection (P), charge conjugation (C) and time reversal (T) in β decay has been under close scrutiny for any sign of deviation from maximality where the breaking seems to complete (as for P and C) and for any sign of actual breaking when this has not yet been observed (as for T). The origin of PC and (inferred) T violation is a deep issue and remains mysterious in many aspects despite enormous efforts in experimental and theoretical physics. We will first focus on the contribution of β-ray polarimetry to two main questions: are there deviations from maximal parity violation due to right-handed $V+A$ currents (Sect. 3), and: at what level can β decay violate time reversal invariance (TRI; Sect. 4)? A broader scope of parity experiments can be found in [1] and in references mentioned there. Some other lecturers of this school touch also P, C, and T aspects: Kullander on PC violation, Ejiri, Kozlowski, and Faessler on neutrino aspects, and Hardy on β shapes and lifetimes.

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The important polar and axial vectors in β decay are the momenta $\vec{p}$ and $\vec{q}$ of electron/positron and anti-neutrino/neutrino and the spins $\vec{J}$ and $\vec{\sigma}$ of decaying parent and $\beta^{\pm}$ particle, respectively. The *longitudinal* polarization P_β is related to the pseudoscalar $\vec{p}\cdot\vec{\sigma}$. The *transverse* electron polarization $(\vec{p}\times\vec{\sigma})$ is instrumental for TRI studies when combined with $\vec{J}$ or $\vec{q}$ to a triple set of orthogonal vectors. If any interaction shows a small but genuine preference for the left or for the right side of Fig. 1b (taking into account final state effects) this will imply TRI violation.

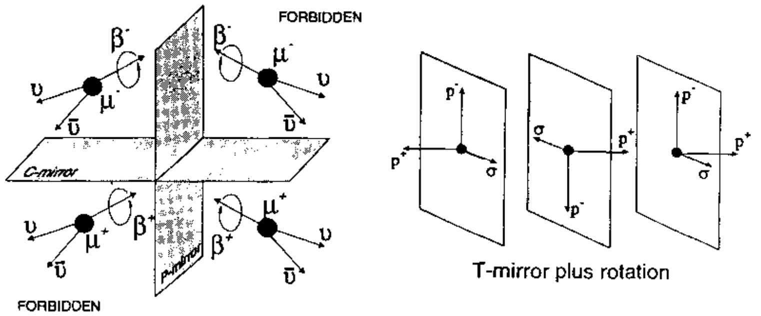

Fig. 1. Discrete transformations. a — P and C reflection, b — time reversal in case of pair creation with momenta p^- and p^+ and spin σ^- of the electron. Followed by a trivial rotation only one of the three vectors remains inverted. TRI assigns equal probability to both orthogonal combinations.

2. Framework for parity and *T*-reversal experiments

Immediately after "the fall of parity" in 1957 Jackson, Treiman and Wyld [2] were ready with a phenomenological description of the nuclear β decay without assumptions regarding P, C and T symmetry. They allowed P and C violation by using a Hamiltonian with a pseudoscalar part, and T violation by using complex coupling constants, assuming only that the neutrino ν will be sufficiently light to ignore its phase-space distortions. The probability for β decay of a nucleus became proportional to a sum of terms with correlations between $\vec{p}, \vec{q}, \vec{\sigma}$ and $\vec{J}$:

$$dW_\beta(E) \propto 1 + a\frac{\vec{p}\cdot\vec{q}}{EE_{nu}} \; + \; b\frac{\Gamma m_e}{E} + \vec{J}\cdot\left(A_\beta\frac{\vec{p}}{E} + B\frac{\vec{q}}{E} + D\frac{\vec{p}\times\vec{q}}{EE_\nu}\right) + \\ + \; \vec{\sigma}\cdot\left(G\frac{\vec{p}}{E} + Q\vec{J} + R\vec{J}\times\frac{\vec{p}}{E}\right)\,, \qquad (1)$$

where E and E_ν are the β and ν energy and $\Gamma = \sqrt{(1-(\alpha Z)^2)}$. The coefficients $a, b, \ldots, R$ are functions of complex coupling constants C_i and

C_i' ($i =$ *S*calar, *T*ensor, *V*ector, *A*xial Vector or *P*seudoscalar), but in the SM with only $V - A$ interaction $b, D, R, C_S, C_S', C_T, C_T', C_P$, and C_P' are zero. The term with coefficient a stands for $\beta - \nu$ correlations, the one with A_β for the β asymmetry (the textbook "Wu experiment"), the one with B for ν asymmetry and the one with Q for a polarization-asymmetry correlation. We pay in specific attention to the terms implying β polarimetry: the G-term related to P_β and the R-term representing T violation.

A possibly admixture of right-handed $V + A$ to dominant left-handed $V - A$ currents can be incorporated in the SM by a slight extension of its $\mathrm{SU(2)_L} \times \mathrm{U(1)}$ form to the gauge group $\mathrm{SU(2)_L} \times \mathrm{SU(2)_R} \times \mathrm{U(1)}$ with "manifest left-right symmetry". This requires two physical gauge bosons W_1 and W_2 having masses m_{W1} and m_{W2} and being mixtures of the weak eigenstates W_L and W_R:

$$W_1 = W_\mathrm{L} \cos\zeta - W_\mathrm{R} \sin\zeta\,, \tag{2a}$$

$$W_2 = W_\mathrm{L} \sin\zeta + W_\mathrm{R} \cos\zeta\,. \tag{2b}$$

$V + A$ admixtures can be treated in terms of the mass-squared ratio $\delta = (m_{W1}/m_{W2})^2$ and the mixing angle ζ. When small, ζ and δ can be expressed in C_i and C_i' by:

$$\zeta - \delta = (C_V' - C_V)/(C_V' + C_V) \text{ and } \zeta + \delta = (C_A' - C_A)/(C_A' + C_A)\,. \tag{3}$$

In the SM with maximum parity violation the scalar and pseudoscalar parts of the Hamiltonian occur with equal coupling constants C_i and C_i' and with $\delta = \zeta = 0$. Basic β-decay studies search for possible effects beyond the SM with non-zero values of δ and ζ. They are performed with a number of selected transitions:

- $^1\vec{n}$ (polarized neutrons [3]) to study terms with $a, A_\beta, B_\nu, D, (R)$.
- ^{3}H (tritium) for $P_{\beta,\mathrm{mixed}}$ and ν-mass studies (Refs. in [1]).
- $^8\vec{Li}$ to explore TRI and the R term [4].
- $^{19}\vec{Ne}$ (atomic beam) to measure A_β and to study TRI (Refs. in [1]).
- ^{26m}Al/^{30}P [5] and ^{14}O/^{10}C [6] for $R_1 = P_F/P_{GT}$.
- $^{107}\vec{In}$ [7] and $^{12}\vec{N}$ [8] for $R_2 = P^-/P^+$.
- ^{210}Bi (RaE) with high sensitivity for $V + A$ and T violation [9].
- $\vec{\mu}^+$ (polarized muons [10]) to search for $V + A$ and T violation.

The later Secs. 3 and 4 are devoted to a number of searches for $V + A$ currents and TRI violation.

2.1. The polarization of $\beta^\pm$ rays

emitted by unpolarized radio-active nuclei is described in the SM by $P_\beta^{V-A} = \pm G\cdot v/c$ with $G=1$ for GT *and for Fermi* decays, ignoring minor corrections for recoil and screening. With V+A, $_i \neq C_i'$ and beyond the minimal SM:

$$P_\beta^F/(v/c) = 1 - 2(\delta-\zeta)^2\,, \tag{4a}$$

$$P_\beta^{GT}/(v/c) = 1 - 2(\delta+\zeta)^2\,, \tag{4b}$$

$$\text{and the ratio :}\quad R_1 = P_\beta^F/P_\beta^{GT} = 1 + 8\delta\zeta\,. \tag{4c}$$

Verification of Eqs. (4a,b) requires *absolute* β polarimetry. This, however, is difficult and has been performed in the past only for β^- decays with Mott-polarimetry calibrated by double scattering of unpolarized electrons [11]. The *ratio* (4c) allows *relative* measurements without need for absolute P-calibration.

2.2. Polarized nuclei

emit *e.g.* positrons with preference in the direction of the initial spin $\vec{J}$. Quin and Girard [12] noticed that the ratio R_2 of the polarization of β rays emitted parallel or anti-parallel to $\vec{J}$ becomes a sensitive probe in case of right-handed $V+A$ admixtures. In the framework of manifest left-right symmetry:

$$R_2 = P_\beta^-/P_\beta^+ = R_2^0\left[1 - f(\delta+\zeta)^2\right] \tag{5}$$

with $f = 8\beta^2\cdot J\cdot A_\beta/\left(\beta^2-(J\cdot A_\beta)^2\right), \beta = v/c$ and R_2^0 the polarization ratio for a pure $V-A$ interaction. In simplified form

$$R_2^0 = (\beta - J\cdot A_\beta)\cdot(1+\beta J\cdot A_\beta)\,/\,(\beta+J\cdot A_\beta)\,(1-\beta J\cdot A_\beta)\,, \tag{6}$$

so that both f and R_2^0 require a separate determination of $J\cdot A_\beta$.

2.3. Forbidden β decays

deserve renewed interest. Earliest parity studies already recognized that destructive interference in forbidden β decays may lead to measurable deviations from the allowed β-shape and from $P_\beta = \pm v/$c. The deviations imply matrix elements of the type $C_V\int\gamma_5$ for $L=0$ Fermi and $C_A\int i\vec{\sigma}\cdot\vec{r}/R$ for $L=1$ *GT* decay, and in addition $C_V\int\vec{\alpha}, C_V\int i\vec{\boldsymbol{r}}/R$ and $C_A\int\vec{\sigma}\times\vec{\boldsymbol{r}}/R$ for $1^-\to 0^+$ transitions. Recently Sadler and Behrens [9] asked again attention for the $1^-\to 0^+$ decay of RaE (^{210}Bi; 5d, 1.2 MeV), the oldest studied β

decay and the one which happens to champion the largest deviations from the allowed shape and β polarization. They computed that V+A currents as well as T violation will cause very large cancellation effects, be it that they can be still overshadowed by nuclear structure effects. However, future computations may become sufficiently powerful to reduce the nuclear uncertainties so that the size of the $V + A$ and/or T-violation effects becomes visible. Fortunately, the parent nucleus $^{210}_{83}Bi_{127}$ has only one neutron and one proton outside closed shells with predominant $(1h_{9/2})_p(2g_{9/2})_n$ configurations. The daughter $^{210}_{84}Po_{126}$ has two $(1h_{9/2})_p$ protons. Starting with ten complex coupling constants Sadler and Behrens computed shape S(W) and polarization P_β(W) (Fig. 2) for cases, *(i) allowing V+A currents, but no violation, and (ii) allowing T violation with imaginary values of the coupling constants C_V and C_A, but no right handed currents.* The calculations

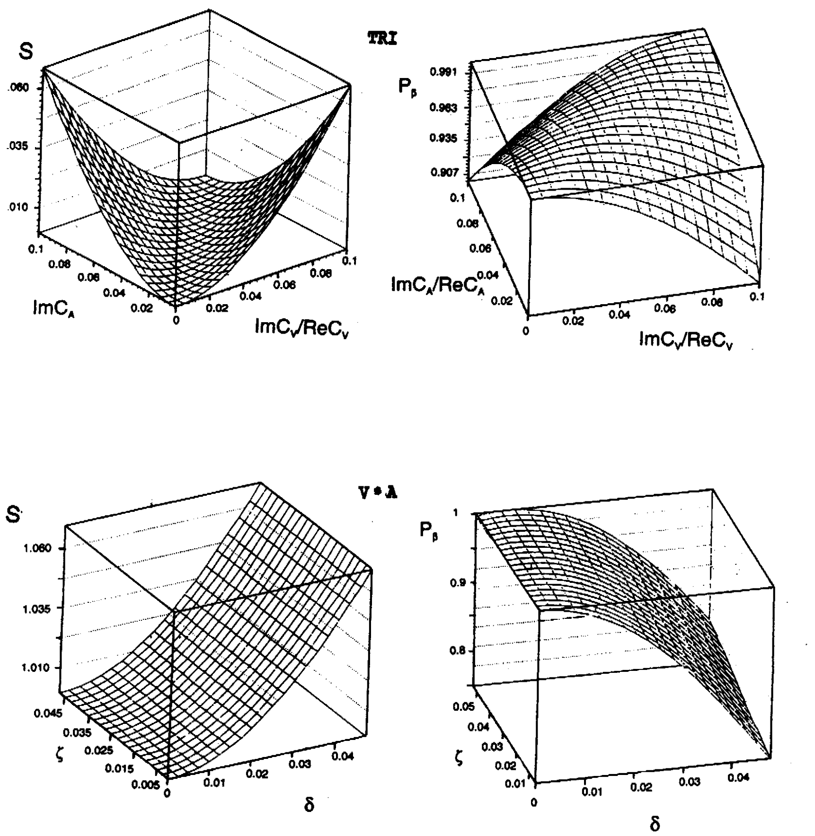

Fig. 2. Influence of right-handed V+A currents (bottom) and TRI-violation (top) on shape factor S (left) and polarization P_β (right) with RaE. Calculated values are normalized to $V - A$ and TRI values.

showed large sensitivity to δ ad *(i)* and to both δ and ζ ad *(ii)*. The deviations in shape and P_β are in relatively easy reach of modern experiments. Therefore RaE studies can becomes of renewed interest when combined with theoretical evaluation of nuclear effects.

2.4. Muonic beta decay

[10] is special because it is not disturbed by strong interactions, but forms energy- and production-wise a separate class with a challenge for β polarimetry at higher energies. The asymmetry of the β emission depends on ζ and δ via a term with $(2\delta^2 + 2\delta \cdot \zeta + \zeta^2)$ when measured near the endpoint energy of 52 MeV. It will also be important to observe P_β near this endpoint since there the muonic case becomes extremely sensitive for $V + A$ admixtures with a finite W_2 mass.

3. Searches for right-handed currents

The ratio $R_1 = P_\beta^F / P_\beta^{GT}$ has been measured with two different polarimeters; one developed in Groningen [5] based on Bhabha scattering and the other used in Louvain la Neuve [6] being based on the decay of positronium formed by β^+ rays in matter in an external magnetic field. This lecture selects the Møller/Bhabha polarimetry as an example because it serves at the same time as an introduction to conceivable polarimetry at higher energies.

3.1. Møller and Bhabha polarimetry

are based on scattering of β^- rays, respectively β^+ rays, by target electrons with alternating parallel (σ_p) and anti-parallel (σ_a) spins. The polarization asymmetry $\varepsilon = (\sigma_a - \sigma_p)/(\sigma_a + \sigma_p)$ approaches a maximum value 7/9 for symmetric scattering at higher energies with full incident and full target polarization. The polarimeter has been made in fourfold to reduce instrumental asymmetries, to enhance the statistical power, and to reduce the accelerator time for on-line target activation. In each polarimeter five plastic scintillators could register ten coincidence combinations between Bhabha-scattered positrons and recoiling target electrons. The polarization sensitivity S equals $2P_t \cdot \varepsilon\,(1 - \Delta)\cos\alpha$, with P_t the polarization of the target electrons, Δ a dilution factor and α the angle between the momentum of the incoming longitudinally polarized β^+ rays and the CoFe magnetization. Typically $S(\beta^+) \cong 0.058$.

The Groningen project used ^{26m}Al and ^{32}P sources produced in twofold target activation with a proton beam. Fast rotors (M_1 and M_2 in Fig. 3) transport the two short-lived sources periodically to their measurement positions between two times two polarimeters. The ratio R_1 has been measured

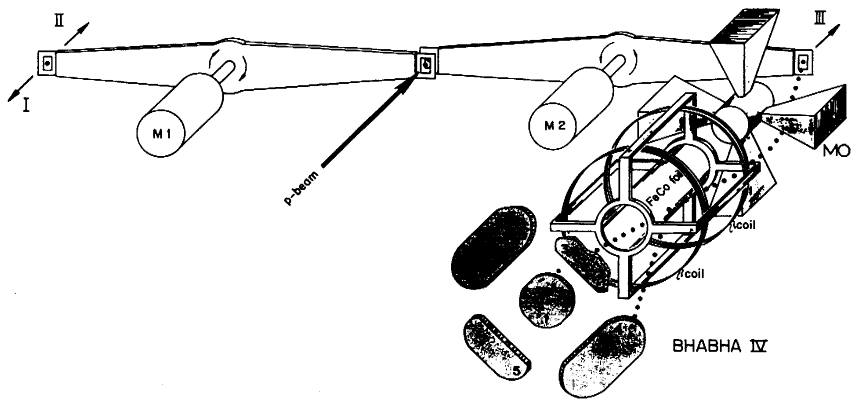

Fig. 3. Fourfold Bhabha polarimetry with fourth polarimeter in detail.

to a precision of $\sim 0.4\%$ with both this Bhabha polarimetry and the positronium method, giving:

$$R_1 = P_\beta^F / P_\beta^{GT}. = 1.0010 \pm 0.0027 \tag{7}$$

as a result when the Groningen and LLN data are taken together.

3.2. Mott polarimetry

has been performed in the past with shape-allowed β^- transitions. The measurements yielded long standing bounds [11]:

$$P_\beta^{GT}/(-v/c) = 1.001 \pm 0.008\,. \tag{8}$$

Without first-forbidden transitions the measurements gave the same value with less statistical accuracy ($\pm$ 0.012). A special case at low energies was offered by the decay of tritium with a known F/GT mixing parameter of 0.187, giving:

$$P_\beta^{GT+F}(^3H)/(-v/c) = 1.005 \pm 0.026\,. \tag{9}$$

The best value for Fermi decay is obtained by *comparative* β^+ polarimetry yielding a precise ratio R_1. Accepting P_β^{GT} as a 1% accurate calibrator [5] the $0^+ \to 0^+$ decay of ^{26m}Al gave:

$$P_\beta^F/(+v/c) = 0.99 \pm 0.01\,. \tag{10}$$

The results (7)–(10) yield bounds on δ and m_{W2} to be drawn in Fig. 5.

3.3. Experiments with nuclear polarization

are possible when parent nuclei with $\vec{J} \neq 0$ can be polarized along an axis of symmetry by asymmetric population of magnetic substates m = +J, $\ldots, -J$. The polarization can be achieved with: brute-force magnetization below 10 mK and B $\sim 10^5$ A/cm; crystalline fields of 10^5 to 10^7 A/cm between 10 and 100 mK; implantation in magnetized iron; reflection of slow neutrons against "supermirrors"; or with the decay of pions producing polarized muons.

Motivated by the paper of Quin and Girard [12] a Leuven-LLN-PSI-Zürich collaboration [7,8] measured P_β along the direction of the nuclear polarization to determine the ratio R_2. By implanting ^{107}In (32 min; 2.3 MeV) in magnetized iron a nuclear polarization of 57% resulted in $R_2/R_2^0(^{107}\mathrm{In})=$ 0.977(40). At PSI the collaboration produced polarized $^{12}\vec{\mathrm{N}}$(11ms; 16 MeV) through $^{12}\mathrm{C}(\vec{p}, n)$ and reached a nuclear polarization of 15%. This is less than with ^{107}In, but higher event rates allowed a better statistical accuracy: $R_2/R_2^0(^{12}\mathrm{N})= 0.9921(95)$. The findings correspond with pure $V - A$:

$$(\delta + \zeta)^2 = 0.0025 \pm 0.0046 \ (90\%\, cl), \tag{11}$$

being the result when the ^{107}In and ^{12}N data are combined.

3.4. Polarimetry of muonic β rays

is developed at PSI [10] with Bhabha scattering and annihilation in flight inside a CoFe layer with reversible magnetization (Fig. 4; $P_t \cong 7\%$). For longitudinal polarimetry a parallel or anti-parallel component of P_t is obtained by putting the scatterer at an oblique angle with the e$^+$ beam axis.

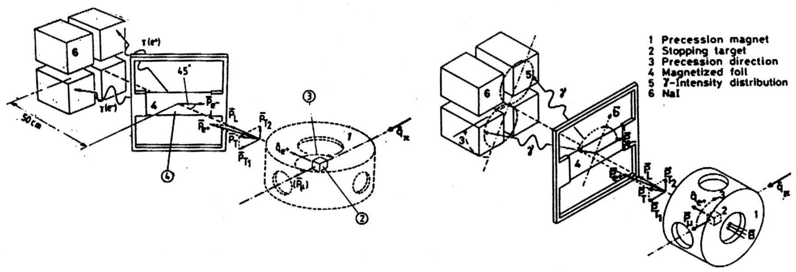

Fig. 4. Longitudinal (left) and transverse (right) polarimetry at PSI with β^+ rays from decaying polarized muons.

Polarized μ^+ particles from π^+ decays are brought to rest inside a precession magnet by which the μ^+ spin can be redirected. The muon data agree with the Standard Model with pure $V - A$ and with TRI. The instrumentation for muon experiments has been seminal to the development of concepts described in the later Sect. 5.

3.5. Bounds on the mass of the W_2 boson:

The β polarization and correlation yielded limits expressed in $\delta \cdot \zeta, (\delta + \zeta)^2$ or m_{W2} as presented in Fig. 5. This review figure is complemented by other experiments. In the course of time there has been some turbulence regarding a finite m_{W2} *value* suggested by combining data from neutron decay and atomic beams experiments. However, Schreckenbach *et al* [13] evaluated a ratio of coupling strengths $\lambda = g_A/g_V = -1.266$ (4) which encompasses the $V - A$ point, although with the remark that the bounds on m_{W2} are sensitive to the precise value of λ; *a* value $\lambda = -1.261$ already excludes this $V - A$ point.

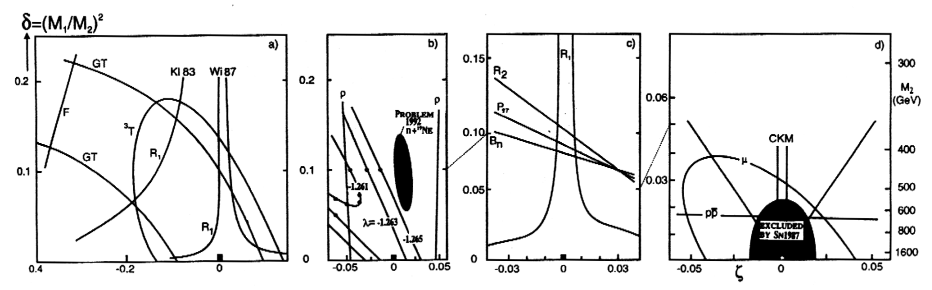

Fig. 5. Progressive bounds (90%cl; note the changing scales) in (δ, ζ) around the $V-A$ point (0,0) from: a — β polarimetry till 1990 with Fermi and GT transitions, with the mixed decay of tritium and with the ratios $R_1 = P^F/P^{GT}$; b — λ values and Michel parameter ρ ; c — $R_1 = P^F/P^{GT}, R_2 = P^-/P^+$, absolute GT polarimetry and ν asymmetry B_n; d — muonic, high-energy and astrophysical results.

A variety of studies [1] leads to m_{W2} bounds as implemented in Fig. 5d: direct searches at colliders, evaluation of the supernova SN87A data, deductions (300 to 1600 GeV) from the precisely known $K^0_{\mathrm{L}} - K^0_S$ mass difference of 3.521μeV. The very tight limit of 1600 GeV, suggested by a four-quark approximation, is softened when taking into account sensitivities as to Cabibbo-Kobayashi-Maskawa (CKM) angles and to the masses of the charm and top quarks. The constraint requires a light top quark and may have to be lowered to less than 300 GeV. Fig. 5d shows furthermore a limit deduced from $\vec{p}p$ collisions. From gauge considerations Masso [14] proposed the constraint $|\,\zeta\,| \leq \delta$.

4. Violation of time reversal invariance (TRI)

T violation has never been observed directly, but it has been inferred from observed PC violation and a general believe in PCT conservation. PC violation occurs in K^0 decay at the 0.23% level, while the empirical evidence for PCT symmetry is only at the 10% level. The SM incorporates the PC violation in kaonic decays by two small CKM elements (V_{ub} and V_{td}) with large phases. They involve the third generation so that the violation, already small in the K^0 system, will be still smaller by orders of magnitude for nuclear β decay. Thus any signal of a larger T violation implies physics beyond the SM. Searches for such a signal in β decay imply triple vectors (Fig. 1) combining the $\vec{p}$ with two out of the three vectors $\vec{J}, \vec{q}$ or $\vec{\sigma}$: $\vec{J}$ means nuclear polarization, $\vec{q}$ implies recoil measurements and $\vec{\sigma}$ requires electron polarimetry. TRI experiments concern two possibly non-zero terms in eq. (1): $D\vec{J}\cdot(\vec{p}\times\vec{q})$ via recoil experiments and $R\vec{J}\cdot(\vec{p}\times\vec{\sigma})$ via transverse electron polarimetry. Here, we restrict us to the R-term with its polarimetry aspects.

In the case of GT interactions the JTW theory [2] allows TRI violation when tensor interaction occurs with complex coupling constants:

$$R \propto \mathrm{Im}L_{TA} \mp (\alpha Z/p)\cdot \mathrm{Re}(L_{TT} - L_{AA}), \text{ with } L_{ij} = C_i' C_j^* + C_i C_j'^* \,. \quad (12)$$

TRI violation can be mimicked by final state effects through terms with αZ, becoming $\mathcal{O}(2\cdot 10^{-4})$ in case of heavier nuclei like ^{19}Ne, but reducing to $\mathcal{O}(10^{-6})$ in case of the decay of free neutrons. With negligible isospin impurities and final-state effects $R \cong \mathrm{Im}(C_T + C_T')/(3C_A)$. Herczeg [15] showed that an "exchange of spin-2 bosons or couplings to spin-0 leptoquarks" could generate such a charged weak tensor interaction. Experiments have been performed with $^8\vec{\mathrm{Li}}$ and $^{19}\vec{\mathrm{Ne}}$ and have been tried with the decay of free neutrons, using in all cases transverse Mott polarimetry to combine $\vec{J}$ with the vector product $\vec{p}\times\vec{\sigma}_e$.

In the ^{8}Li experiment by Sromicki *et al.* [4] the nuclear polarization (11%) has been obtained via $^7\mathrm{Li}(\vec{d},p)^8\vec{\mathrm{Li}}$. Their impressive Mott polarimeter featured rotational symmetry around $\vec{J}$ (Fig. 6). The β rays emitted in the horizontal plane were inspected upon their possible transverse polarization with Mott scattering by a lead belt (35 mg/cm^2) lead scatterer placed as a thin belt around the source. A left-right scattering asymmetry can be observed with two telescopes covering scattering angles from 120° to 155°. The telescopes with triple detection (δ, Δ and E) are subdivided into quadrants to provide four independent measurements of the R term.

Muonic β-decay has been studied via the product $\vec{\sigma}_\mu\cdot(\vec{p}\times\vec{\sigma})$ with β^+ energies between 15 and 45 MeV. After minor radiative corrections the results (Table I) agreed with the SM expectation of negligibly small effects.

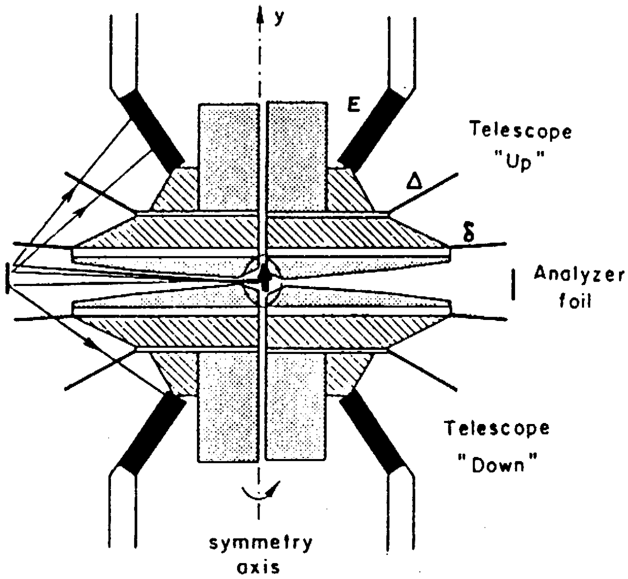

Fig. 6. Ring-shaped Mott polarimeter at ETH-Zurich around $^{8}\vec{\mathrm{Li}}$ (arrow at center) to test TRI via the R-term in Eq. (1).

The muonic experiments are more demanding than nuclear$-\beta$ decay investigations, as reflected by a larger uncertainty.

TABLE I

Searches for T-violation D and R terms in β-decay.

Decay of:	$D \cdot 10^3$	$R \cdot 10^3$
Neutron	-0.5 ± 1.4 [16]	
^{8}Li		0 ± 4 [5]
^{19}Ne	-0.1 ± 0.6 [17,18]	-79 ± 53 [19]
Muon		7 ± 23 [10]

5. Outlook to efficient electromagnetic polarimetry at higher energies

The polarimetry with nuclear β rays played an essential role in parity investigations with E_β up to one or two MeV. The muonic experiments shifted the interest in polarimetry already to higher energies. Thus far only a few attempts to photon and electron/positron polarimetry aimed at energies above 50 MeV. Yet, polarimeters with high efficiency and covering a regime from 5 to 100 MeV would be instrumental to a variety of objectives involving electron/positrons as well as photons:

TABLE II

Possibilities for polarimetry of electrons and positrons [20] (L = longitudinal, T = transverse), and γ rays (C = circular, L* = linear).

Method and typical energies	For: [Refs]	Short description [25]
Mott scattering $10 - 10^6$ eV	e^- [11] T (L)	Transverse sensitivity is based on spin-orbit coupling. Correction for finite thickness of high-Z scatterer can only be avoided by calibration via double scattering (*Absolute* polarimetry).
Positronium formation at energies below 100 eV	e^+ [6] L,T	The incident positron has to be slowed down to near thermal energies to form positronium in singlet and triplet state in MgO. In a magnetic field $\vec{B}$ the positronium decay depends on $\vec{P} \cdot \vec{B}$, offering excellent comparative polarimetry with periodic reversal of $\vec{B}$.
Compton scattering 0.1 - 100 MeV	γ C, L*	Circular polarimetry requires a scatterer with reversible polarization. Linear polarimetry can be performed with unpolarized scatterers.
Møller scattering > 0.5 MeV	e^- L,T	Mostly employed in L-polarimetry. Lower energies constrained by FeCo-scatterer thickness. Based on spin-spin interaction of scattered and scattering electron.
Bhabha scattering > 1 MeV	e^+ L,T	Similar to Møller scattering at energies > 5 MeV, but with smaller cross section. At lower energies the polarization sensitivity is less.
Annihilation in flight > 1 MeV	e^+ [10] L,T	Based on spin-spin interaction in a polarized target (e.g FeCo). At E ≥ 5 MeV ϕ-differentiation gives similar L- and T-sensitivity. Below 5 MeV: only L.
Compton back scattering > 100 MeV	$e^\pm$ L,T	High-energetic electrons or positrons are Compton scattered by a polarized laser beam. The photon polarization can be inverted periodically.
Pair production > 10 MeV	γ L$^*(C)$	L*-polarimetry via the azimuthal distribution of the plane in which the pairs are created. In principle C-sensitive if e^- and e^+ can be identified.
Triplet production > 100 MeV	γ L	Based on asymmetry in the azimuthal angular distribution of recoil electrons after pair production with atomic electrons.

- Parity and TRI experiments with the muon investigations.
- $\vec{p}p\gamma$ experiments as performed at present at KVI-Groningen with 200-MeV polarized protons and emission of 50- to 100-MeV photons with a thus far never measured degree of polarization.
- Beam polarimetry at $e^{\pm}$ linacs and storage rings.
- Photon polarimetry after radiative capture of polarized protons and neutrons from 2 to 6 MeV implying triple vector combinations.

Several interactions among those listed in Table II offer *in principle* and according to established QED theory polarization sensitivity at energies up to 100 MeV: Møller/Bhabha scattering, annihilation in flight, Compton scattering and pair creation with polarization transfer to the $e^{\pm}$. However, *practical* possibilities are limited by availability of suitable magnetic materials and suitable detection techniques.

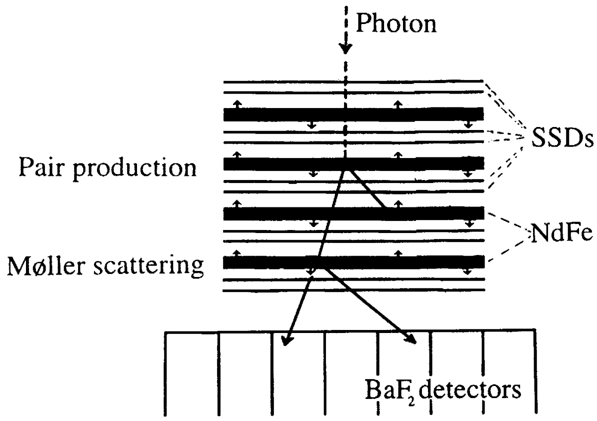

Fig. 7. A concept for polarimetry at energies up to 100 MeV using multiple NdFe + SSD layers. Arrows symbolize the magnetization of the NdFe layers (with chessboard pattern when seen from above). BaF_2 detectors are added to reconstruct the full energy of the incident photons or leptons.

We considered [20–23] the combination of modern magnetic materials with thin Silicium Strip Detectors [SSDs] for a new polarimetry concept: a multilayered calorimeter-type instrument with layers of magnetic $Nd_2Fe_{14}B$ (in short NdFe) sandwiched between SSDs with energy and location sensitivity. Such a detector (Fig. 7) can sample the polarization sensitive interactions occurring in the electromagnetic showers. The SSDs and following photon detectors can localize and recognize these interactions on an event by event basis. In case of incident photons, a typical Compton scattering can be characterized by (0011), the first two zeros referring to no signals in the two SSDs at the entrance and one signal in both SSDs at the exit side of the NdFe layer in which the event occurred. Similarly a Bhabha event would be (1122). The pair creation of an incident photon (0022) in the field of a nucleus does not depend on a degree of circular polarization of the photon. However, its eventual polarization will be transferred to the created e^+e^- pair in such a way that the e^+ or e^- with highest energy carries the largest part of the incident polarization. That e^+ or e^- offers a further chance to be polarimetrized. The NdFe layers can be subdivided in a chessboard patterns with alternating up and down magnetization and with different P-sensitive event rates in the up and the down squares.

This approach introduces novel aspects by using: *(i)* multilayers, *(ii)* NdFe with perpendicular magnetization, *(iii)* location-sensitive SSDs which are thin with respect to the NdFe layers. With *e.g.* ten layers of 10×10 cm^2 and a SSD-pitch of 1 mm one arrives at a 10^5-fold polarimeter as compared with a 4-fold one in Fig. 3. In principle the SSD wavers can accommodate Si architecture with integrated electronics. The residual energy of a shower can be detected by an array of BaF_2 crystals for e^+e^- and γ-ray detection.

For a feasibility study we constructed one element of NdFe sandwiched between four SSDs, two on either side. Tests with fully polarized $\beta^{\pm}$ rays with energies up to 16 MeV (^{12}N and ^{12}B [22]; ^{106}RuRh up to 3.5 MeV) demonstrated the proper function of the SSDs, but became at these relatively low energies not yet successful in showing P-sensitivity. Below 20 MeV suitable polarimetry is hindered by multiple scattering in the NdFe layers of 0.5 to 1 mm thickness. The promise of the method lies at higher energies.

For Monte Carlo simulations a GEANT code has been extended [20] with polarization and polarization-transfer parameters. The simulations provided information on the event-recognition and P-sensitivity capabilities. Initially we assumed for NdFe the single-crystal value $P_t = 5\%$, but in bulk material the actual value is unfortunately only 3.7%.

At present we can only stress the importance of searching for better high-remanence Rare Earth magnets: $Pr_2Fe_{14}B$ may be of some promise after refined metallurgy [23]. The above concept can also be used for transverse polarimetry with the P_t vector in the plane of scatterer. It allows soft-magnetic scatterers (CoFe, in future perhaps $Fe_{16}N_2$ [24]) with the advantage of a larger and easy to reverse target polarization ($P_t \cong 7\%$). The holding field can in principle be induced by external Helmholtz coils.

In conclusion: with continuing improvement of magnetic scatterers the above approach to electron, positron and photon polarimetry may become instrumental to future parity experiments and to further searches for the still mysterious role of TRI in β decays.

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