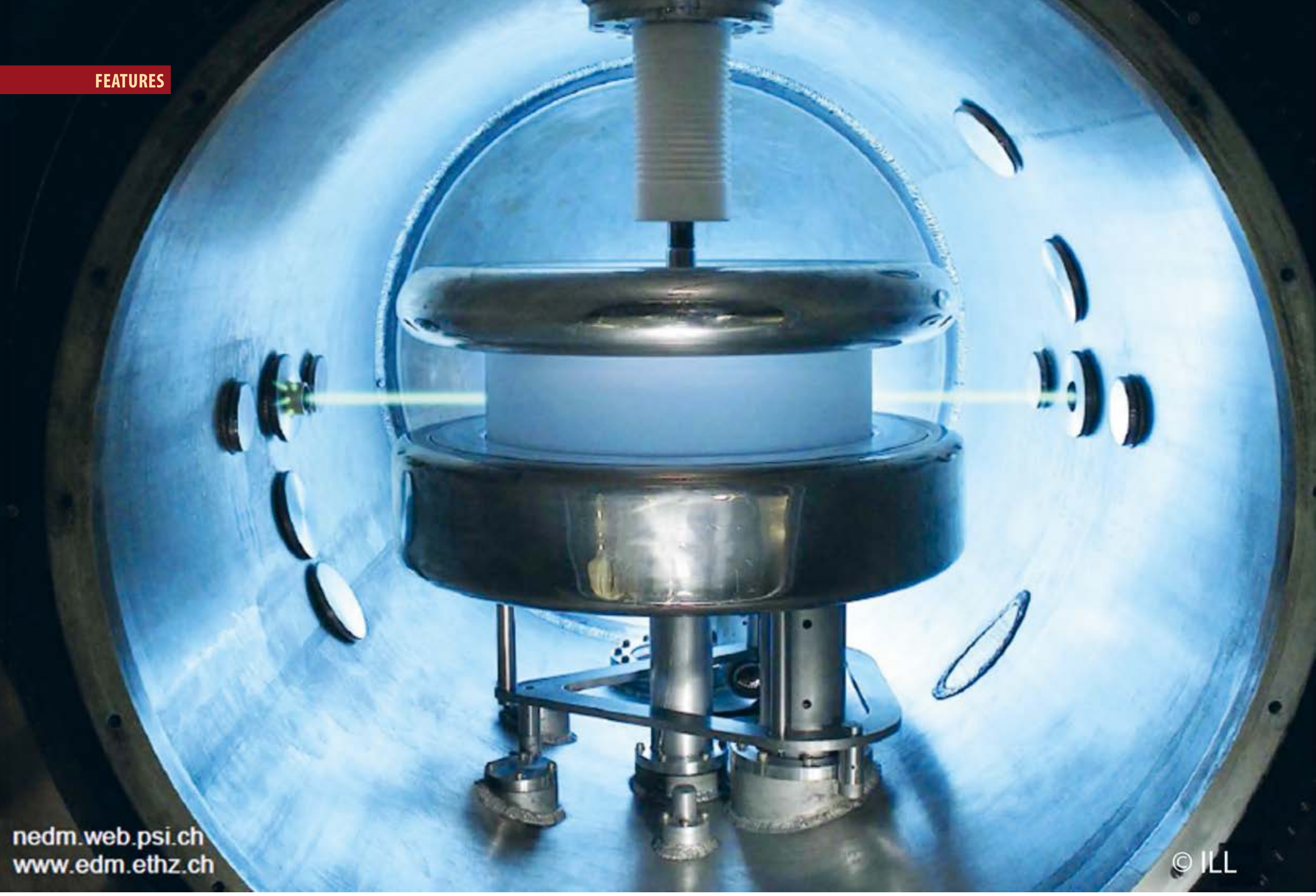

SEARCHES FOR NEW PHYSICS WITH FREE NEUTRONS AND RADIOACTIVE ATOMIC NUCLEI

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The Standard Model of Particle Physics is very successful but does not explain several experimental observations. Extensions of it, invoking new particles or phenomena, could overcome this. Experiments in different energy domains allow testing these extensions and searching for new particles. Here focus is on low-energy experiments with neutrons and radioactive nuclei.

▲ nEDM inner view vacuum chamber. © ILL

The Standard Model of Particle Physics and beyond

The Standard Model of Particle Physics (SM) successfully describes the fundamental particles (quarks and leptons), and their interactions via the electromagnetic and the weak and strong nuclear forces by exchanging messenger particle 'gauge bosons' (the photon for electromagnetism). However, it does not explain a number of observed phenomena. Examples are the breaking of parity symmetry by the weak force (meaning that of a weak decay process and its three-dimensional mirror image only one effectively occurs in Nature), the precise nature of this force, and the difference between the amount of matter and antimatter in the Universe.

Extensions of the SM try explaining these phenomena by adding specific features or new gauge bosons. Experiments try to confirm or falsify these extensions, indicating the direction for future work. Best known are searches for new particles at high-energy colliders. A good example is the discovery of the Higgs-boson (related to the generation of the mass of all particles), at the Large Hadron Collider at CERN (Geneva). Here we focus on experiments at much lower energies, with free neutrons and radioactive atomic nuclei. Recent reviews of this field are found in *e.g.* [1-2].

The matter-antimatter mystery and electric dipole moments

A currently very active field of research is trying to shed light on the small difference between the amount of matter and antimatter that must have occurred in the very early universe. When all antimatter had disappeared in 'collisions' with matter particles, thereby generating the cosmic background radiation we observe today, a small excess of matter (about one particle in a billion) evolved to form the universe we observe today, and is the cause for us being here. Andrei Sakharov showed that such a difference can be explained by three conditions, one of these being a violation of the so-called CP symmetry. This is the combination of charge symmetry (C) and parity symmetry (P), which requires replacing in a physical process all particles by their antiparticles (C) and taking the (three-dimensional) mirror image of the process (P). If the resulting process is also observed in Nature, CP symmetry is said to hold, if not it is violated. Violation of CP-symmetry is observed in a certain class of particles (called K^0, B^0 and D^0 mesons), but this is too small to explain the observed matter-antimatter difference. Physicists therefore search for other, larger signals of CP violation.

A very popular observable violating CP symmetry is a permanent electric dipole moment (EDM), d, of a particle. First experiments started with the neutron in the 1950's (Fig. 1), and sensitivity has increased by about six orders of magnitude. The current best value was obtained in an experiment at the Paul Scherrer Institute (Switzerland). The result, $d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{sys}) \times 10^{-26}$ e.cm [3], is consistent with zero. The high sensitivity is illustrated by the fact that if one would enlarge the neutron to the size of the Earth, the difference between the time-averaged position of positive and negative charges inside it should be less than several micrometers.

Permanent EDMs are also searched for in other particles, in atoms and in molecules [4]. Indeed, as many extensions of the SM include different CP-violating sources, these can only be distinguished when a variety of systems is studied. The highest-precision EDM results to date were obtained with ^{199}Hg and ThO molecules. Recently, interest has grown in octupole deformed nuclei as this was shown to enhance a possible EDM. As such isotopes are found in elements like Rn, Ra, Th, and Pa, with only radioactive isotopes, experiments require radioactive beam facilities, *e.g.* ISOLDE at CERN, Geneva or TRIUMF at Vancouver.

> **"Experiments in beta decay have led Pauli to suggest the existence of the neutrino and uncovered several fundamental properties of the weak force, such as the violation of parity symmetry and the overall structure of the weak interaction."**

Studying the weak nuclear force in neutron and nuclear beta decay

The most elementary beta-decay process is that of the neutron, changing it into a proton via the creation of a W gauge boson (a weak force messenger particle), and causing emission of an electron •••

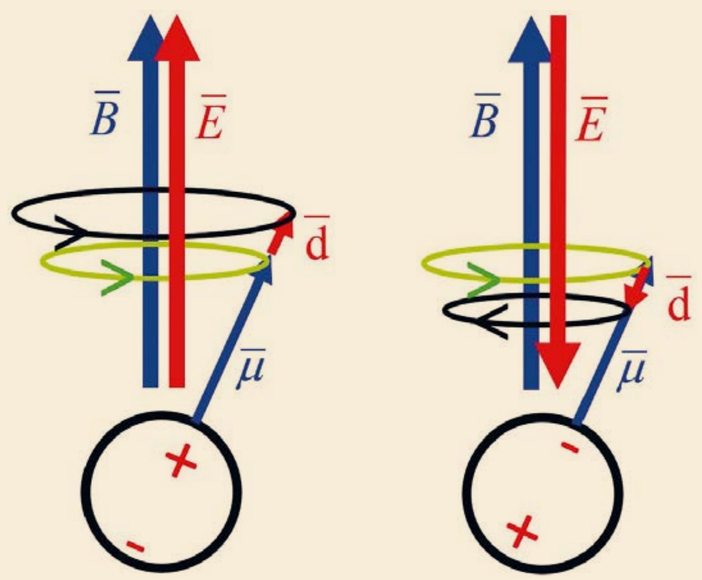

Fig. 1: a non-zero permanent EDM, ***d***, for the neutron would mean that the time-averaged position of positive and negative charges inside the (neutral) neutron would not coincide. This would cause a precession of the neutron spin when placed in an electric field, **E**. As the neutron has a magnetic moment, **μ**, which does not violate CP symmetry and causes a spin precession in a magnetic field, **B**, a non-zero EDM would cause a tiny difference in the neutron precession frequency when placed in alternatingly parallel (left) and anti-parallel (right) magnetic and electric fields.

••• and an electron-antineutrino (β^- decay). This occurs for a free neutron and for neutrons in radioactive nuclei with an excess of neutrons over protons. In radioactive nuclei with a proton excess, the inverse process (β^+ decay) can occur, changing a proton into a neutron with emission of a positron and electron-neutrino. Experiments in beta decay have led Pauli to suggest the existence of the neutrino and uncovered several fundamental properties of the weak force, such as the violation of parity symmetry and the overall structure of the weak interaction, *i.e.* the type of messenger particles that relate to it.

As the neutron (lifetime ~ 15 minutes) is a very simple system consisting of three quarks, it is an ideal probe for studying the weak force with few disturbing effects. In the beta decay of radioactive nuclei (with half-lives from a fraction of a second to billions of years), effects of the nuclear medium (*e.g.* virtual pion exchange) have to be included. However, the several thousand radioactive nuclei have very different properties, so that one can select the ones best suited for a given experiment. Important classes are those with an equal number of protons and neutrons, or a difference of just one (mirror nuclei).

One type of experiments determines the *ft*-value of a beta transition, which depends on its intensity and decay energy, and the half-life of the decaying state, corrected for percent-level effects. For so-called pure Fermi transitions this has provided a precise value for the *up-down* quark-mixing matrix element [4]. Similar measurements in neutron decay and for mirror nuclei are not yet competitive but are catching up [2]. The *up-down* matrix element is important for testing unitarity of the quark-mixing matrix, allowing to search for beyond-SM physics such as a fourth generation of quarks or new gauge bosons.

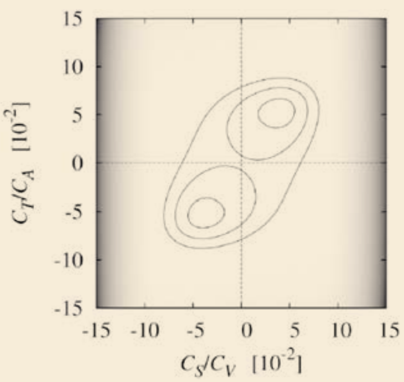

Fig. 2: result of the fit of nuclear and neutron decay data sensitive to scalar and tensor type weak interaction couplings (C_S and C_T) involving right-handed neutrinos, relative to the SM vector and axial-vector coupling constants C_V and C_A. The contours of constant χ2 correspond to iso-χ2 levels with values Δχ2 = 1, 4, and 9. Based on these limits, scalar and tensor type weak interactions with right-handed neutrinos could in principle occur in up to about 10% of the beta decays. From Ref. [1].

So-called correlation measurements observe the relative emission angle between the spins and momentum vectors of the initial neutron/radioactive nucleus and its decay particles, *i.e.* the electron or positron and the recoiling nucleus (the (anti-)neutrino from beta decay cannot be detected). Almost always the energies of the decay particles are also measured. One can further choose to polarize the spin of the neutron/nucleus in the direction of an applied magnetic field. The forward-backward asymmetry in the electron emission with respect to the polarized neutron spin provides the relative strength of the two types of weak force observed in Nature, the ratio g_A/g_V [1]. Further, precise tests of the parity or time reversal symmetries [5] can be performed, the latter testing whether a physical process and the 'in time backward running' process occur with the same probability. One can, finally, also search for possible new components of the weak force driven by as yet unobserved messenger bosons. The latter would induce a small change in the values of experimental observables with respect to their SM value (*e.g.* Fig. 2). Information obtained is complementary to that from colliders [1, 2].

Of course, instrumental (systematic) effects always have to be carefully considered. In this respect, the possibility to perform extensive simulations of the behaviour of the experimental apparatuses, is a big asset. Together with advances in detection technology and analysis tools, this has allowed reaching precisions at the per mil level. As this requires taking in account also small contributions to the value of observables induced by the strong force (*e.g.* [1]), new challenges and new research possibilities now open up for this field. ■

About the Author

Nathal Severijns is full professor of physics at KU Leuven University with a track record in low-energy weak interaction experiments with spin-polarized and unpolarized neutrons and exotic nuclei. He has written several review articles covering this research field.

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