

Precision experiments with cold and ultra-cold neutrons

Neutron β -decay and gravity resonance spectroscopy

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Abstract We present selected results from the first round of the Priority Programme SPP 1491. This programme gets funding from the German DFG and the Austrian FWF funding agencies. The aim of this programme is to address basic open questions in particle and astrophysics using a specific tool: the neutron, which allows the search for new physics becoming manifest itself as small deviations from expectations.

Keywords Standard model neutron β -decay · The quantum bouncing ball qBOUNCE

1 Introduction

New high intensity sources for ultra-cold neutrons and neutron decay products are coming into operation. The priority programme 1491 exploits new technologies and addresses some questions of modern science: the nature of the fundamental forces and underlying symmetries, as well as the nature of the gravitational force at very small distances. New facilities and technological developments now open the window for significant improvement in precision by 1-2 orders of magnitude. This allows to probe these questions in a complementary way to LHC-based experiments or even constitutes a unique way.

The 6th International Symposium on Symmetries in Subatomic Physics (SSP2015), 08 - 12 Jun 2015, Victoria, Canada, was related to the following four priority 20 areas A - D:

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- **Priority Area A** CP-symmetry violation and particle physics in the early universe (addressed mainly by the search for the neutron electric dipole moment)
- **Priority Area B** The structure and nature of weak interaction and possible extensions of the Standard Model (addressed mainly by precise studies of the neutron β -decay)
- **Priority Area C** Relation between gravitation and quantum theory (probed by investigations of low-energy bound states in the gravitational field)
- **Priority Area D** Charge quantization and the electric neutrality of the neutron (probed by a precision test of the neutron's electric charge)

The intended improvement in experimental precision has to go in parallel with the development of new or improved measurement techniques which are often at the extreme border of feasibility.

- **Priority Area E** New techniques: 1) particle detection, 2) magnetometry, 3) neutron optics

This article addresses a few points of this programme presented at the symposium.

2 Neutron β -decay within priority area B

Neutron β -decay provides insights into the Standard Model and beyond. A main issue is the question concerning a hypothetical unification of all forces shortly after the Big Bang. This grand unification is not part of the Standard Model, and new symmetry concepts are needed like left-right symmetry, fundamental fermion compositeness, new particles, leptiquarks, supersymmetry, and many more. In the search for new symmetries, we see experiments with cold and ultra-cold neutrons as a high-precision frontier in the domain of low-energy studies. These experiments fit in a greater field of precision measurements comprising cold or ultra-cold neutrons, cold or ultra-cold ions or atoms, protons, electrons, and their antiparticles. A second frontier in the domain of high-energy physics is certainly the Large Hadron Collider (LHC). Low-energy experimentation allows to probe these questions in a complementary way to LHC-based experiments or even constitutes a unique way.

Neutron decay offers a number of independent observables, considerably larger than the small number of parameters describing this decay in the Standard Model. The first element V_{ud} of the quark mixing CKM matrix is one of the two parameters describing neutron decay within the Standard Model, the other being the ratio $\lambda = g_A/g_V$ of axial-vector to vector coupling constants including their relative phase.

Observables in free neutron decay are abundant: besides the lifetime τ_n [1–4], (older references can be found in [5]), angular correlations involving the neutron spin as well as momenta and spins of the emitted particles are characterized by individual coefficients, which can be related to the underlying coupling strengths of the weak interaction, including yet unobserved ones. Examples are the electron-antineutrino correlation coefficient a [6–8], the beta asymmetry parameter A [9–13], the neutrino asymmetry parameter B [14, 15] (reconstructed from proton and electron momenta), the proton asymmetry parameter C [16], the triple correlation coefficient D [17, 18], the Fierz interference term b , and various correlation coefficients involving the electron spin [19, 20]. Each coefficient in turn relates to an underlying broken symmetry. A method of loss-free spectroscopy is presented in Ref. [21]. So far, the measurement of Schumann et al. [16] is the only precision measurement of C (see also Ref. [22]), with a 1.1 % error: 0.4 % statistics and 1 % systematics but new measurements [23] are underway at beam position PF1B [24] at Institut Laue Langevin.

Precise symmetry tests of various kinds are coming within reach with the proposed facilities *Nab* [25] and PERC [26, 27]. The spectra and angular distributions of the emerging decay particles will be distortion-free on the level of 10^{-4} , more than 10 times better than achieved today [28]. PERC is a joint project of the Universities of Heidelberg and Mainz, Institut Laue-Langevin (ILL), Technische Universität München, and the Technische Universität Wien. We have designed a new type of momentum spectrometer for PERC, which uses the $\mathbf{R} \times \mathbf{B}$ drift effect to disperse the charged particles [29].

2.1 Theoretical considerations

In order for Neutron Beta-Decay to become a Laboratory for Standard Model tests, a theoretical analysis of the lifetime, the energy spectra and angular distributions must be carried out with relativ precision of order 10^{-4} . This was done in [30] within the standard quantum field theory at the rest frame of the neutron and in the non-relativistic approximation for the proton by taking into account the radiative corrections to order α , the proton recoil correction and the weak magnetism to order $1/M$, where M is the average mass [31]. The authors showed that the account for the contributions of the proton photon correlations in the radiative corrections to the neutron beta decay does not contradict the description of the radiative corrections to the lifetime of the neutron and the proton recoil spectrum in terms of the standard radiative corrections but makes the proton recoil asymmetry C symmetric with respect to change of correlation coefficients $A - B$. They showed that the Standard Model describes well the lifetime of the neutron $\tau = 880.1(1.1)\text{s}$ with the theoretical value $\tau = 879.6(1.1)\text{s}$, for the axial coupling constant ratio $\lambda = -1.2750(9)$ and CKM matrix elements V_{ud} obtained from the $0^+ \rightarrow 0^+$ transitions and the unitarity condition, respectively [30].

Above the theoretical background calculated in the SM, they investigated the contributions of new physics in terms of Herzeg coupling constants at the hadronic level. They also showed that after renormalization of the axial coupling constant λ and V_{ud} the contributions of physics to linear order perturbation theory can be expressed in terms of the scalar and tensor weak lepton-baryon interactions, which can be measured from the asymmetries of the energy spectra and angular distributions of the neutron beta decay [30, 31].

For the bound β -decay, they showed that angular distributions of the production of hydrogen in the ground hyperfine state with $F = 0$ can be used for the measurements of the contributions of new physics by measuring the left-handed polarization state of the antineutrinos [32].

These theoretical studies of order 10^{-4} pave the way for the following searches for physics beyond the Standard Model on the same level of accuracy:

- A search for right-handed admixtures to the left-handed feature of the Standard Model. As a natural consequence of symmetry breaking in the early universe, they should be found in neutron β -decay. Signatures are a W_R mass with mixing angle ζ .
- A search for scalar and tensor admixtures g_S and g_T to the electroweak interaction. g_S and g_T are also forbidden in the Standard Model but supersymmetry contributions to correlation coefficients can approach the 10^{-3} level, a factor of five away from the current sensitivity limit [15, 33].
- A first search in neutron β -decay for the Fierz interference term b , which is forbidden in the Standard Model but can approach the 10^{-3} level from supersymmetry contributions.
- A search for supersymmetry in the LHC era: one could expect small deviations in the low-energy tests, such as deviations from CKM unitarity, but no effect at the LHC.

3 Priority area C

This section focuses on the control and understanding of a gravitationally interacting elementary quantum system using the techniques of resonance spectroscopy. It offers a new way of looking at gravitation at short distances based on quantum interference [34]. The neutron gives access to all parameters related to gravity: distance, mass, curvature, energy-momentum tensor, and torsion. It reflects from a mirror in well-defined quantum states in the gravity potential of the earth. In 2002 the lowest stationary quantum state of neutrons in the gravitational field was clearly identified [35–37] by us in a collaboration with V. Nesvizhevsky and coworkers. Here, the quantum states have pico-eV energy, compared with the typical energy scale for bound electron in an atom (eV). This proof of principle triggered new experiments and activity in this direction [5], namely the setting up of the GRANIT [38] and the *q*BOUNCE [39] collaboration.

The key technique for gravity experiments is a newly-developed Gravity Resonance Spectroscopy (GRS) method [34, 40, 41]. It is named in that way, because the energy difference between quantum states in the gravity potential has a one-to-one correspondence to the frequency of a modulator, in analogy to the Nuclear Magnetic Resonance technique, where the zeeman energy splitting of a magnetic moment in an outer magnetic field is related to the frequency of a radio-frequency field. Phase measurements in gravity potentials can now be related to frequency measurements with unprecedented accuracy. We expect a similar statistical sensitivity for small energy changes as measurements of the electric dipole moment [42] since the same neutrons are used. The precision of our method relies on the fact that frequency measurements can be performed with incredibly high precision. At this level of precision, we are able to provide constraints on any possible gravitylike interaction. In particular, a dark energy chameleon field is excluded for values of the coupling constant $\beta > 6.9 \times 10^6$ at 95 % confidence level (C.L.), and an attractive (repulsive) dark matter axion-like spin-mass coupling is excluded for the coupling strength $g_s g_p > 3.7 \times 10^{-16}$ (5.3×10^{-16}) at a Yukawa length of $\lambda = 20 \mu\text{m}$ (95 % (C.L.) [41]. Other limits on chameleon fields stem from neutron interferometer measurements [45, 46] and atom interferometry [47], see also [49].

The authors of [43] analysed the Dirac equation for slow fermions coupled to linearised massive gravity above the Minkowski background and derived the effective lowenergy gravitational potential. The obtained results can be used in terrestrial laboratories for the detection of gravitational waves and fluxes of massive gravitons emitted by cosmological objects. In addition the neutron spin precession within linearised massive gravity has been calculated, which in principle can be measured by neutron interferometers.

Another observable is the spatial density distribution of a free falling neutron above a reflecting mirror. A newly developed position dependent neutron detectors makes it possible to visualize the square of the Schrödinger wave function [39, 44]. We have now at hand a high-precision gravitational neutron spectrometer with available spatial resolution of $1.5 \mu\text{m}$. Neutrons are detected in CR39 track detectors after neutron capture in a coated $^{10}\text{Boron}$ layer of 100 nm thickness. An etching technique makes the tracks visible with a length of about $3 \mu\text{m}$ to $6 \mu\text{m}$ [48].

An application possibility for GRS is a search for a hypothetical charge of the neutron [50]. The method makes use of a Ramsey-technique although until now it was considered to be impossible to use this technique for charge measurements, because a phase accumulation cancels by inverting the electrical field. But in the presence of an electric field E_z , the energy of quantum states in the gravity potential changes due to an additional electrostatic potential if a neutron carries a non-vanishing charge q_n . Important for this

method is the fact that the energy shift differs from state to state due to the properties of a Schrödinger wave packet in a linear potential of the gravity acceleration of the earth. It is of great advantage that the break down voltage and therefore the electric field available scales with the reciprocal square root of the distance. With the already realized $E_z = 50$ kV/mm, the discovery potential reads $\delta q_n = 3 \cdot 10^{-20} \frac{e}{\sqrt{\text{day}}}$. Further improvements should increase the sensitivity.

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