High Precision Experiments with Cold and Ultra-Cold Neutrons

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In this talk I will present precision experimentation of the Neutron and Quantum Physics Group at TU Wien using thermal, cold and ultra-cold neutrons. The neutrons are investigated both in-beam, or confined in traps, with the aim to test fundamental interactions and symmetries. The following topics are discussed:

a) Neutron Experiment on Quantum States at the pico-Scale

Since the 19th century, interferometry has become a key measurement tool in science as well as applied technologies. Use cases are various: from the investigation of light properties to waver positioning in semiconductor industry, from g-sensors for gravitometry to the most recent discovery of gravitational waves. In 1974 matter wave interferometry was introduced by Rauch et al. at Atominstitut (ATI) of TU Wien. The quantum wave function of each single particle is split and superpositioned forming a unique measurement tool to probe fundamental quantum (wave-) properties of the neutron giving deep insight into the quantum nature of matter and of Quantum Mechanics in general.

Here we present an innovative approach to thermal neutron interferometry. We are realising within the same device simultaneous interferometry of optical light, X-rays and thermal neutrons. Using the complementary sensitivity of all three waves we obtain enhanced sensitivity for various quantum phenomena of matter waves. We propose an infrastructure with "external" metrology via optical interferences while measuring the "internal" degrees of freedom via X-ray and neutron interferometry. The combination of optical, X-ray and neutron interferometry allows to realise a so-called split crystal neutron interferometer. Beam splitter and -combiner are at large distance while their alignment is controlled with subnano-metre and -radian accuracy. It will allow new types of experiments providing strongly improved sensitivity to quantum phenomena of matter waves such as quantum causality and contextuality. The enlarged spacing between the components allows to use the device as a quantum sensor for research for dark matter or for gravitational interaction of fermions.

Interferometry with very cold neutrons (VCNs) has been less successful in the past. Crystals could not serve as natural optical elements, artificially produced grating structures resulted in very small diffraction angles or unwanted diffraction orders and neutron loss. As a second pillar our colleagues from University of Vienna install a new VCN infrastructure with an innovative approach to VCN-interferometry based on holographically formed nanodiamond-composite gratings as optical elements.

Ultracold neutrons (UCNs) with energies less than 300 neV and macroscopic wavefunctions can be used as quantum probes for gravity at micrometre to millimetre scales. Using the respective superposition of gravitational eigenstates in the Earth's gravitational field, the *q*BOUNCE collaboration has developed gravity resonance spectroscopy (GRS). As a third pillar, we build an innovative design with the aim to extend the interaction time by 3 orders of magnitude, resulting in the same increase in precision. This is achieved by a new setup that stores UCNs quasi loss-less in so-called whispering gallery states in a micro-machined storage ring. The setup has multiple possible configurations that serve as a facility to apply any electromagnetic, mechanical, or gravitational excitation, thereby enabling measurements of the structure of space-time and gravitation or any hypothetical (dark) interactions.

b) β-decay of free polarized neutrons

Today, all semileptonic charged-current weak interaction cross sections needed in cosmology, astrophysics, and particle physics must be calculated from neutron decay parameters determined by our working group. In particular $\lambda = g_A/g_V$, the ratio of the axial-vector to vector coupling, enters in the prediction for the energy consumption in the sun via the primary reaction in the pp-chain and the solar neutrino flux, the light elements in the primordial nucleosynthesis, and the neutron star formation. λ is also used for the calibration of neutrino detectors, and an input for the unitarity check of the quark-mixing CKM matrix. Of further concern is the Standard Model unitarity requirement of the CKM matrix. This matrix relates the quarks in the weak interaction basis and the quarks in their mass eigenstates.

The reason is that the neutron is the only particle whose weak decay gives precise information on the weak interactions of first particle generation. Observables in free neutron decay are abundant: besides the lifetime τ_n, 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 underlying coupling strengths of the weak interaction. As a personal preference, our working group concentrates on correlations between neutron spin and electron, neutrino and proton momenta, and measures the coefficients *A* (*β*-asymmetry parameter), *B* (neutrino-asymmetry parameter) and first time measurement of *C* (proton-asymmetry parameter) with increasing accuracy. The *A* coefficient is most sensitive on λ, and since 1997, we have provided precise and most reliable value for λ further reducing the sources of error typical for correlation coefficient experiments using magnetic fields, such as a magnetic mirror effect, edge effects, beam related background, and degree of polarization, while vastly increasing statistical accuracy. We think that these results are more favourable than earlier experiments, where large corrections had to be made for neutron polarization, electron-magnetic mirror effects or background, which were all in the 15% to 30% range. The main corrections in our neutron decay asymmetry experiments are due to neutron beam polarization (0.3%) and background (0.1%). As a consequence, the uncertainties in reducing the total correction on A_0 are less than 0.3% with an error of 0.33%. In the meantime, a dissertation at TU Wien has reduced the error on polarization measurements below 10^{-4}. The result of our PERKEO III collaboration instrument gives $\lambda = -1.27641(45)_{stat}(33)_{sys}$. The UCNA collaboration confirms the value of λ of our group although with larger error bars.

The situation here is significantly different from neutron lifetime τ_n measurements; we still do not know the neutron lifetime with sufficient accuracy today. There is a very substantial disagreement of 6.6 σ standard deviation between storage ($\tau_n = 878.5 \pm 0.8$ s) and beam results ($\tau_n = 888.0 \pm 2.1$ s). See for example the discussion in the particle data group for the years 1990 - 2022. In a recent publication, Fornal and Grinstein proposed that the puzzle could be solved if the neutron would decay on the one percent level via a dark decay mode, one possible branch being $n \rightarrow \chi + e^+ + e^-$. With data from the PERKEO II experiment we set limits on the branching fraction and exclude a one percent contribution for 95% of the allowed mass range for the dark matter particle.

New symmetry tests of various kinds are coming within reach with the neutron decay facility PERC at Munich research reactor FRM2 or at ESS, the European Spallation Source.

c) **Astrophysics & Quantum Technology: Gravity Resonance Spectroscopy constrains Dark Energy and Dark Matter scenarios**

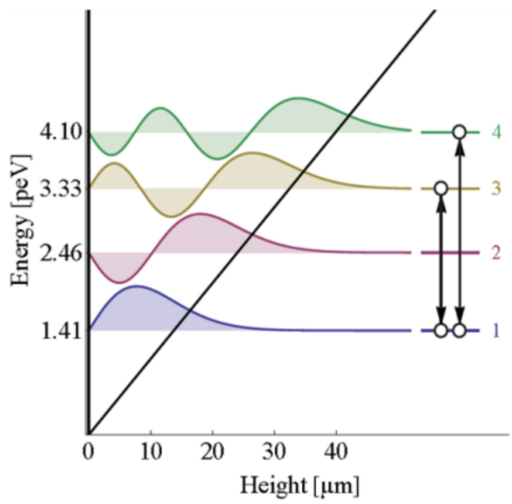

***Fig. 3:** Pico-eV energy eigenstates E_1- E_4 and Airy-function solutions of the Schrödinger equation for bound ultra-cold neutrons in the linear gravity potential of the earth.*

Quantum technologies provide highest precision through quantum interference. They are utilized in a variety of fields; from natural science to medicine. In particular resonance spectroscopy methods have opened up the field of low energy particle physics for the study of fundamental interactions. However, up to now, gravity and astro-particle physics is mostly out of scope for resonance spectroscopy. One reason is that there is so far no known quantum theory of gravitation. The other is that our knowledge is based on astronomical observations or pendulum experiments. Often, the studied objects are taken as point-like test masses, which are certainly not considered as typical quantum tools.

We present a novel resonant spectroscopy technique devoted to the study of gravitation and the related cosmological problems of Dark Matter and Dark Energy. The object is a quantum mechanical wavepacket of an ultra-cold neutron, and the new method extends the techniques of Purcel, Rabi and Ramsey to neutron quantum states in the gravity potential of the Earth. The new technique is named Gravity Resonance Spectroscopy (GRS) in close analogy to Magnetic Resonance Spectroscopy (MRS). Here a neutron in the gravity potential of the Earth is placed on a reflecting mirror, and transitions between the gravitational quantum states are performed by applying mechanical oscillations of the mirror with the proper transition frequency, whereas in MRS technique, an atom, a molecule or a nucleus with a magnetic moment is placed in an outer magnetic field and transitions between the magnetic Zeeman splitting are performed by applying proper oscillations of radiofrequency fields. Resonant transitions between several of the lowest quantum states are observed for the first time. Similarly to the 5-region Ramsey setup for atoms, we have established a 5-region GRS experiment.

The strength of GRS is that it does not rely on electromagnetic interactions. The use of neutrons as test particles bypasses the electromagnetic background induced by van der Waals forces and other polarizability effects providing the key to a sensitivity of several orders of magnitude below the sensitivity of atoms.

The measurements deliver severe restrictions on cosmology and any gravity-like interaction within the level of sensitivity of 1.4×10^{-15} eV. If some yet undiscovered particles of Dark Matter or Dark Energy interact with a neutron, the result is a measurable energy shift in the observed quantum states, devoid of electromagnetic perturbations. These measurements together with neutron interferometer measurements allow to restrict the parameter space for a chameleon field, hypothetically being responsible for the accelerated expansion of the universe, by seven orders of magnitude, and, makes it possible to find or exclude this field in full parameter space. Another example is the pseudo-scalar interaction of an axion field, a prominent candidate for the unknown Dark Matter, which would provide a force between the spin of the neutron and the neutron mirror. Limits on axion fields are improved by a factor of 30.

We present recent results on the following topics:

First, we analyze the dynamics of ultracold neutrons caused by interactions violating Lorentz invariance within the Standard Model Extension (SME). We use the effective non–relativistic potential for interactions violating Lorentz invariance derived by Kostelecký and Lane (1999) and probe contributions of these interactions to the transition frequencies of transitions between quantum gravitational states of UCNs bouncing in the gravitational field of the Earth.

Second, we analyze a possibility to probe beyond-Riemann gravity by GRS. We improve by order of magnitude some constraints obtained by Kostelecký and Li (2021).

Third Erik Verlinde's theory of entropic gravity, postulating that gravity is not a fundamental force but rather emerges thermodynamically, has gathered much attention as a possible resolution to the quantum gravity problem. We address some criticism by modelling linear gravity acting on small objects as an open quantum system and show full compatibility with the *q*BOUNCE experiment.