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TRIμP — A NEW FACILITY TO INVESTIGATE FUNDAMENTAL INTERACTIONS WITH OPTICALLY TRAPPED RADIOACTIVE ATOMS*

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At the Kernfysisch Versneller Instituut (KVI) in Groningen, NL, a new facility (TRIμP) is under development. It aims for producing, slowing down and trapping of radioactive isotopes in order to perform accurate measurements on fundamental symmetries and interactions. A spectrum of radioactive nuclids will be produced in direct, inverse kinematics of fragmentation reactions using heavy ion beams from the superconducting AGOR cyclotron. The research programme pursued by the KVI group includes precision studies of nuclear β-decays through β–neutrino (recoil nucleus) momentum correlations in weak decays and searches for permanent electric dipole moments in heavy atomic systems. This offers a large potential for discovering new physics or to limit parameters in models beyond standard theory significantly. The scientific approach chosen in TRIμP can be regarded as complementary to such high energy physics. The facility in Groningen will be open for use by the worldwide community of scientists.

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1. Introduction — the standard theory

Atomic physics has played an important and crucial role in the development of modern physics. Precision measurements have lead quite often to unexpected discoveries such as the existence of several isotopes for one element or the discovery of anomalous magnetic moments. In these cases small and faint unexpected signals or tiny deviations from the standard theoretical treatment of atoms were observed. They have every time eventually lead to a new picture of fundamental physics.

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As an example, the manifestation of the deviation at the permille level of the electron g-factor from the value 2 predicted in the Dirac theory together with the observation of the Lamb shift in atoms have given rise to th best quantum field theory we know, Quantum Electrodynamics (QED) [2]. Today there is little serious doubt about the validity of QED in particular its underlying concepts. Only the sometimes very difficult calculations present mathematical problems and discussions on the best suited technical approaches occur. However, in all known cases agreement has been reached at an admirable level of precision between theory and experiments over 10 orders of magnitude in momentum transfer.

QED is the U(1) part of the so called electroweak Standard Model (SM) which has SU(2)×U(1) symmetry [3]. Together with the understood features of strong interaction — mainly known as Quantum Chromodynamics (QCD) — it forms the standard theory. This is a powerful theoretical reference framework which allows to describe all observations in particle physics until the turn of the millenium. Although the recently discovered, spectacular neutrino oscillations are not fully provided with standard theory, they can, however, be most probably incorporated in a straight forward way without any significant changes to the basic structure of this theory building. The model uses 12 fundamental fermions, which are the six quarks (u, d, s, c, b, t) and the six leptons (e, $\mu, \tau, \nu_e, \nu_\mu, \nu_\tau$), as building blocks of matter and 12 bosons (γ, W^+, W^-, Z^0, 8 gluons) as mediators of the forces. It should be mentioned that through the inclusion of QED in the electroweak Standard Model all atomic physics and its wide range of applications in various different branches of sciences is fully covered by the standard theory.

Despite its success, the Standard Model leaves many physical questions open. It provides an accurate description of all experimental observations in particle physics. However, often it also lacks any deep explanation for them. Among the open standing problems are the number of three particle generations, the masses of the fundamental fermions (quarks and leptons), the origin of parity violation in weak interactions or the dominance of matter over antimatter in the universe. In order to provide better explanations for some or all of these questions many speculative models have been invited. They carry names like Left-Right Symmetry, Technicolor, Supersymmetry and many more. String- and Brane- or even M-theory offer even a coherent description which includes gravitation and quantum mechanics under one umbrella. For testing the predictions of these models, there are in principle two different conceptual approaches. One searches directly for new processes and particles. This is typically done at high energy facilities. The alternative approach is to search for deviations in the behaviour of systems which can be described to very high precision within standard theory. This method, for example, can exploit the fact that properties of atomic systems can be well calculated in the framework of QED. Precision measurements could reveal small deviations which may originate from New Physics.

2. TRIμP — a new facility

At the Kernfysisch Versneller Insituut (KVI) in Groningen a new facility — TRIμP (**T**rapped **R**adioactive **I**sotopes: μicro laboratories for fundamental **P**hysics) is at present being set up [4]. It aims for producing radioactive nuclids, slowing them down and trapping them in atomic respective ion traps for precision experiments.

The isotopes are produced in direct, in inverse kinematics and in fragmentation reactions. Heavy ion beams, which were accelerated in the the superconducting AGOR cyclotron, are directed on fixed targets, the material of which are chosen for optimal production rates.

The created isotopes of interest need to be separated from the primary beam and other reaction products. This can be achieved in a combined fragment and (gas filled) recoil separator. This device consists of mass and momentum selective ion optical image system. The arrangement has two pairs of dipole magnets for the primary particle selection and quadrupoles for accurate imaging (see figure 1). The whole device foresees two possible target positions, one at its very entrance for fragmentation reactions and

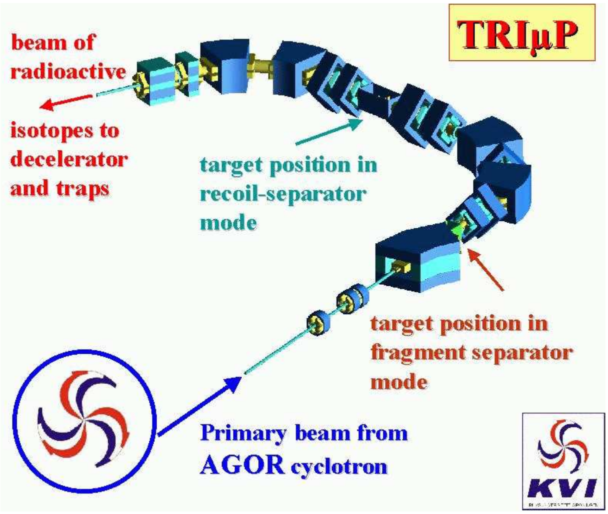

Fig. 1. The TRIμP combined fragment and recoil separator. It is designed to access a large variety of proton-rich isotopes.

another one between the two dipole pairs for inverse kinematics reactions. Since the reaction products appear in a distribution of charge states, gas filling of the separator is essential for good imaging. The gas densities can be chosen such that electron capture and stripping result in an effective charge for the ions, which determines their trajectory in the ion optical system [5].

After the separator the nuclids of interest which typically have 1 MeV/c momentum are slowed down in a (gas) moderator to energies in the eV range. They are further cooled by a buffer gas while being guided and radially confined by a radio frequency quadrupolar field in to a Paul Trap. The latter acts as a beam buncher. After neutralization the atoms can be stored in atoms traps, *e.g.* a magneto-optical trap.

A user facility is created which is open to the worldwide scientific community. TRIμP is jointly funded by FOM [1] and the Rijksuniversiteit Groningen in the framework of a managed programme. The time planning foresees that the facility is set up by 2004 followed by an exploitation phase until 2013. First physics experiments are expected in 2005.

3. Research at TRIμP

Research using trapped radioactive atoms and ions covers a wide range of physics topics in atomic, nuclear and particle physics [6] (see figure 2). The local group of researchers concentrates on two groups of experiments- precision measurements of nuclear β-decays and searches for permanent electric dipole moments in atoms.

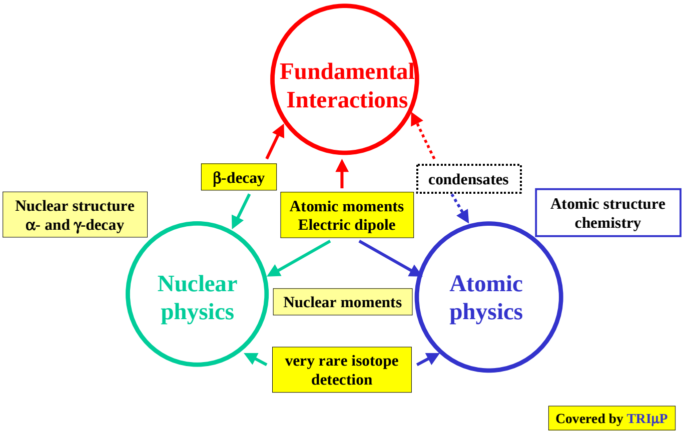

Fig. 2. Atom and ion traps are employed in experiments with their main goal in different fields of physics and particularly in interdisciplinary research.

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3.1. Precision measurements of nuclear β-decays

In standard theory the structure of weak interactions is V–A, which means there are vector (V) and axial-vector (A) currents with opposite relative sign causing a left handed structure of the interaction and parity violation [7]. Other possibilities like scalar, pseudo-scalar and tensor type interactions which might be possible would be clear signatures of new physics. So far they have been searched for without positive result. However, the bounds on parameters are not very tight and leave room for various speculative possibilities. The double differential decay probability $d^2W/d\Omega_e d\Omega_\nu$for a β-radioactive nucleus is related to the electron and neutrino momenta $\vec{p}$ and $\vec{q}$ through

$$\begin{aligned}\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 \quad & + a\frac{\vec{p}\cdot\vec{q}}{E} + b\sqrt{1-(Z\alpha)^2}\frac{m_e}{E} \\ & + \langle\vec{J}\rangle \cdot \left[A\frac{\vec{p}}{E} + B\vec{q} + D\frac{\vec{p}\times\vec{q}}{E}\right] \\ & + \langle\vec{\sigma}\rangle \cdot \left[G\frac{\vec{p}}{E} + Q\vec{J} + R\langle\vec{J}\rangle \times \frac{\vec{q}}{E}\right] ,\end{aligned} \tag{1}$$

where m_e is the β-particle mass, E its energy, $\vec{\sigma}$ its spin, and $\vec{J}$ is the spin of the decaying nucleus. Among the coefficients D is of particular interest for further restricting model parameters. It describes the correlation between the neutrino and β-particle momentum vectors for spin polarized nuclei and is parity violating in nature.

The coefficient R violates parity and time reversal. However, it relates to parameters in speculative models which are already well constraint by searches for electric dipole moments (see below). A direct measurement of the neutrino momentum is not efficiently possible. Instead the recoiling nucleus can be detected instead and the neutrino momentum can be reconstructed using the kinematics of the process. Since the recoil nuclei have typical energies in the few 10 eV range, precise measurements can only be performed, if the decaying isotopes are suspended using extreme shallow potential wells. Such exist, for example, in magneto-optical traps, where many atomic species can be stored at temperatures below 1 mK. Since one needs to be able to trap the atoms optically and also the nuclear properties must be such that one has a rather clean transition, the isotopes of primary interest for KVI experiments are ^{20}Na, ^{21}Na, ^{18}Ne and ^{19}Ne. Optical trapping of both atomic Na and Ne is possible, although, in the latter case trapping of metastable atoms is required [8]. In the case of Na successful recoil spectroscopy experiments has been carried out in the framework of atomic charge transfer reactions [9]. For example, right-handed currents could give rise to deviations from standard theory predictions, which are searched for. Such observations would be expected to shine light into the mysteries behind parity violation in weak interactions.

3.2. Permanent electric dipole moments in atoms

A permanent electric dipole moment of any fundamental particle violates both parity and time reversal symmetries [10]. With the assumption of CPT invariance the permanent dipole moment also violates CP. The CP violation as it is known from the Kaon systems causes through higher order loops permanent electric dipole moments for all particles which are at least 4 orders of magnitude below the present experimentally established limits. It should be noted that the known sources of CP violation are not sufficient in Sakharov's model for the baryon asymmetry, *i.e.* the dominance of matter over antimatter in the universe [11]. New sources of CP violation would need to be discovered. Indeed, a large number of speculative models foresees permanent electric dipole moments which could be as large as the present experimental limits just allow. Historically the non-observation of permanent electric dipole moments has ruled out more speculative models than any other experimental approach in all of particle physics [12].

Permanent electric dipole moments have been searched for in various systems with different sensitivities (see Table I). In composed systems such as molecules or atoms fundamental particle dipole moments can be enhanced

TABLE I

Limits on permanent electric dipole moments d for electrons (e) [13], muons (μ) [14], tauons (τ) [15], protons (p) [16], neutrons (n) [17], and the mercury atom (^{1}99Hg) [18].

	Present limit on $\lvert d\rvert$ $[10^{-27}\mathrm{e\,cm}]$		Standard model prediction $[10^{-27}\mathrm{e\,cm}]$	New physics limits $[10^{-27}\mathrm{e\,cm}]$
e	< 1.6	(90% C.L.)	$\lesssim 10^{-11}$	$\lesssim 1$
μ	$< 1.05 \cdot 10^{9}$	(95% C.L.)	$\lesssim 10^{-8}$	$\lesssim 200$
τ	$< 3.1 \cdot 10^{11}$	(95% C.L.)	$\lesssim 10^{-7}$	$\lesssim 1700$
p	$-3.7\,(6.3) \cdot 10^{4}$	$\sim 10^{-4}$	$\lesssim 60$	
n	< 63	(90% C.L.)	$\sim 10^{-4}$	$\lesssim 60$
^{199}Hg	< 0.21	(90% C.L.)	$\sim 10^{-6}$	$\lesssim 0.2$

significantly [19]. Particularly in polarizable systems there can exist large internal fields. Radium atoms in excited states are very interesting for electric dipole moment searches. Because of the rather close lying $7s7p^3P_1$ and $7s6d_2^3$ states the a significant enhancement has been predicted [20] which gives an significant advantage over the mercury atom, the system which has given the best limits so far [18]. From a technological point of view they well accessible spectroscopically and a variety of isotopes can be produced in fusion and evaporation or in fission reactions. The advantage of an accelerator based radium experiment is apparent, because electric dipole moments require isotopes with spin and all Ra isotopes with finite nuclear spin are relatively short-lived.

3.3. Parity violation in atoms

Precise measurements of weak charges in atomic parity violation experiments and the precise electroweak parameter measurements at the LEP storage ring facility at CERN demonstrate together that the electroweak Standard Model covers interactions over 10 orders of magnitude in momentum transfer to very high precision. At present atomic parity experiments [21] may have found hints to nuclear anapole moments. A severe limitation in the interpretation of the experiments arises from atomic structure calculations which are possible at present to about 1% accuracy. Weak interactions in atoms scale with Z^3. The Francium atom offers 18 times stronger weak interaction effects and one expects calculations of the atomic structure at the same level of accuracy as for the so far best system, the Cesium atom. Since there are only rather short lived Francium isotopes, such experiments are well suited to be carried out at accelerator sites. Efforts exist at Legnaro, Italy, Stony Brook, USA, and Los Alamos, USA. A second important issue is the distribution of neutrons in the nuclei to which weak interactions are very sensitive. For Cesium a variation of the neutron number means that radioactive isotopes will be involved.

3.4. Applications

For cold radioactive isotopes also a large variety of possibilities exists in research connecting to applied sciences. For example one can imagine to use cold polarized β-emitters which can be softly deposited on condensed matter surfaces. This will allow to extend the method of β-NMR, which is very successful in bulk material [22], to condensed matter surfaces.

4. Conclusions

The new facility TRIμP at KVI is expected to offer new possibilities to study with high precision fundamental interactions in physics and fundamental symmetries in nature. The approach combines nuclear physics, atomic physics and particle physics in experimental techniques as well as in the conceptual approaches. The intense interaction between theory and experiment will be necessary for an optimal exploitation of the facility. Photons, Atoms and all That will occupy an essential and central part in this activity. Without the groundwork and the development of state of the art spectroscopy and atom manipulation techniques in the recent past it would never be possible to achieve the desired precision, which is necessary to arrive at relevant scientific conclusions.

This article is dedicated to Tomasz Dohnalik on the occasion of his 60th birthday. The author feels privileged to know Tomasz as a scientist and as a friend. In periods when free communication and travel in Europe was not the usual normality, as it naturally should be, our scientific relationship had important and unforgettable special human components as well. I am very grateful for Tomasz' friendship. The organizers of the PAAT2002 conference deserve thanks for providing a relaxed and stimulating atmosphere.

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