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Perspectives for mass spectrometry at the DESIR facility of SPIRAL2

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ABSTRACT

DESIR (Desintégration, excitation et stockage des ions radioactifs, i.e. decay, excitation and storage of radioactive ions) will form the experimental area exploiting low-energy beams of the next-generation radioactive beam facility SPIRAL2 at GANIL, presently under construction. In addition to beams from the SPIRAL2 production building, DESIR will also receive beams from the separator-spectrometer S^3 and from the SPIRAL1 facility. In the following, the DESIR facility and its instrumentation related to Penning trap based mass spectrometry and trap-assisted decay spectroscopy are introduced. The related envisaged experimental program is outlined.

1. The DESIR facility at SPIRAL2

The DESIR facility [1] at GANIL will be one of the new large installations exploiting radioactive beams. DESIR, constructed in the framework of the SPIRAL2 facility [2] of GANIL (see Fig. 1), will receive low-energy beams (10–60 keV) from (i) the existing SPIRAL1 facility, which will soon improve its capabilities by producing a much larger panel of elements using the $1^+/n^+$ scheme with a 1^+ ion source and a charge breeder and by including target fragmentation, (ii) the SPIRAL2 production building using fission, deep-inelastic and fusion–evaporation reactions, and (iii) the separator-spectrometer S^3 by means of fusion–evaporation reactions. Therefore, an extremely large variety of exotic isotopes with unprecedented intensities will be available for experiments in nuclear structure physics, for fundamental interaction studies, for investigations in nuclear astrophysics, but also for interdisciplinary work ranging from industrial applications to isotope production and much more.

This wide range of isotopes will be complemented with state-of-the-art equipment for decay spectroscopy, laser spectroscopy, and trapping experiments, the three pillars of the DESIR scientific program (Fig. 2). For decay-spectroscopy studies, the PIPERADE device presented below will allow to provide ultra-pure samples for devices like a total-absorption spectrometer, neutron-multiplicity and neutron time-of-flight setups, a 4π charged-particle detector, and $\beta\gamma$ decay stations. The LUMIERE facility, the laser spectroscopy installation of DESIR, will measure static properties of exotic nuclei like their electric quadrupole and magnetic dipole moment as well as their spin and parity. LUMIERE will also allow for a highly efficient separation of close-lying states based on their different spins and thus their different hyperfine structure. The laser installation will also provide polarised and oriented beams for decay spectroscopy. Finally, Paul, Penning and magneto-optical traps will allow the manipulation, storage, and study of exotic species to address questions in different areas of scientific research. These investigations will range from mass measurements to fundamental interaction studies via $\beta-\nu$ correlations.

The DESIR facility has recently been funded to a large extent and construction will begin in 2015 for a start of the DESIR scientific program in 2017. Two setups, related to mass spectrometry with a high-precision Penning trap and to a Penning-trap based mass separator and storage device, will be described in more detail in the following paragraphs.

2. Mass measurements at DESIR

2.1. The MLLTRAP Penning trap facility

High-precision mass measurements at DESIR will be performed using the MLLTRAP setup, which is a cylindrical double Penning-trap system, based on a 7 T superconducting magnet, providing the trapping field with two highly homogeneous magnetic field regions

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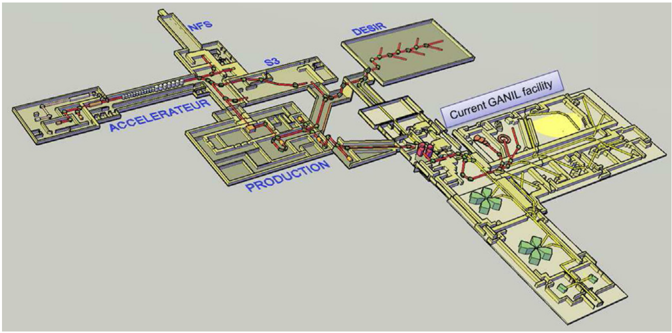

Fig. 1. The GANIL facility including the new SPIRAL2 part with neutrons-for-science (NFS), the separator-spectrometer S^3 and the DESIR facility.

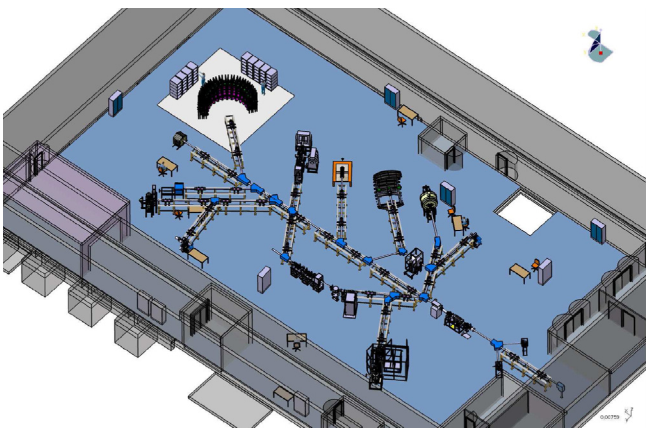

Fig. 2. Schematic installation of the different setups in the DESIR building, a 1500 m^2 large experimental hall.

($\Delta B/B \leq 0.3$ ppm in a volume of 1 cm^3). Technical details about the trap design can be found in [3].

MLLTRAP has been set up and commissioned at the Maier-Leibnitz Laboratory (MLL) in Garching, using stable ions from an offline source, reaching a mass resolving power of about 10^5 in the first (purification) trap and a precision of $\delta m/m = 2.9 \times 10^{-8}$ for ^{87}Rb (statistical uncertainty) measured in the second (precision) trap. Fig. 3 shows the MLLTRAP setup as presently installed in Garching.

Systematic uncertainties due to magnetic field fluctuations have been characterized. These magnetic field fluctuations, as part of the systematic error, were investigated using $^{85}Rb^+$ ions. The long-term fluctuations due to the flux-creep effect were measured to be $\delta B/\delta t \cdot 1/B = -1.3(3) \times 10^{-9}$/h. The systematic uncertainty contribution of the magnetic field fluctuations was determined to be $\sigma_B(\nu_{ref})/\nu_{ref} = 7.36(38) \times 10^{-9}$/h [4]. In order to further increase the accuracy of the trap system, temperature and pressure stabilization systems have been developed and implemented in order to minimize systematic effects on the magnetic field. Temperature fluctuations can now be stabilized to peak-to-peak variations of temperature of $\Delta T_{pp} = \pm 6$ mK and pressure variations in the liquid helium reservoir of the magnet to about $\Delta p_{pp} = \pm 0.2$ hPa [5]. The MLLTRAP setup will be integrated into the DESIR facility, once the required infrastructure in the DESIR experimental hall becomes available.

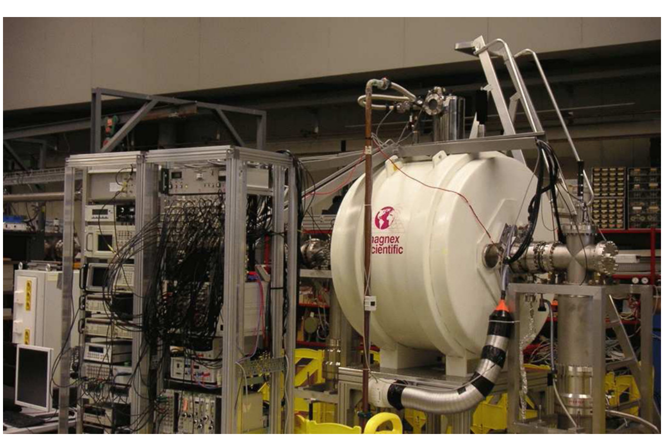

Fig. 3. Double Penning-trap system MLLTRAP, presently installed at the Maier-Leibnitz-Laboratory (MLL) in Garching.

2.2. Perspectives for precision mass measurements at DESIR with MLLTRAP

Mass measurements of radionuclides help to test nuclear models and allow to investigate nuclear structure effects such as shell closures, pairing, deformation or halo nuclei [6,7]. The investigation of exotic nuclei at the limits of nuclear existence, both at the drip lines and in the region of super-heavy elements, is of particular interest and has been at the forefront of nuclear physics studies already for a long time. In the following paragraphs, the experimental program related to mass-spectrometric investigations at the DESIR facility is outlined, based on existing letters of intent [8]. Here the unique features provided by the combination of intense beams (primary as well as exotic) and a suite of complementary instrumentation will be exploited.

2.2.1. Superallowed and mirror β-decay Q-value measurements

The precise determination of partial half-lives, comprising $T_{1/2}$ and the branching ratios, as well as atomic mass values with relative uncertainties well below 1×10^{-8} is required for precision measurements in β-decaying isotopes that can provide stringent tests of the foundations of the electroweak standard model. Prototypical examples are particular nuclides along the $N = Z$ line, with N being the neutron number and Z being the proton number, i.e. the superallowed β-emitters between analogue states with spin/parity 0^+. Their type of decay, being a pure Fermi transition, allows for a direct determination of the vector-coupling constant g_V, and when being conducted for different nuclides along $N = Z$, for a test of the conserved vector current (CVC) hypothesis. Including the weak coupling constant g_F from muon decay, the up-down matrix element $V_{ud} = g_V^2/g_F^2$ can be derived in order to test the unitarity of the first row of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix.

Moreover, it has been recently pointed out [9] that nuclear mirror transitions between $T = 1/2$ isospin doublets offer an additional source to test the unitarity of the CKM matrix. Such a source is then complementary to the pure Fermi transitions, neutron decay and pion decay.

At present, the unitarity test of the CKM matrix is confirmed by the average Ft-value from 13 individual values of different nuclides [10]. Hence, further improvements are first to be expected in the validation of theoretical corrections [11]. These can be assessed by including additional, heavier nuclides, where the structure-dependent corrections are large, such as ^{66}As and ^{70}Br. If the consistency in Ft is remaining in case of additional contributing nuclides, the test of an averaged Ft value gets more demanding and hence even more reliable. After a verification of CVC and the derivation of the weak-interaction vector-coupling constant g_V, the first-row matrix element V_{ud} of the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix can be derived for a unitarity test.

So far, no experimental information for these heavier isotopes exists on the branching ratios, while the mass excess values have