Report on novel experimental techniques for static moments and lifetime measurements

The aim of subtask 4 of the EWIRA JRA was to develop methods for nuclear moment studies, of isomeric and short-lived nuclear stated, to be used with radioactive beams at the presently running or at future, next generation, facilities. The results from the work of this subtask were related to three main methods, namely:(i) Studies of the nuclear orientation obtained using the Tilted Foils (TF) technique;(ii) Application of the Time Dependent Recoil in Vacuum (TDRIV) technique for nuclear moment studies of short-lived excited states;(iii) Investigation of the nuclear orientation in incomplete fusion and/or multinucleon transfer reactions. In order to fulfil the foreseen studies we have applied for beam-time and performed experiments at 2 international facilities - ISOLDE, CERN and ALTO, Orsay, France. The results from these three experiments are presented here after.

Within the subtask 1 of the EWIRA JRA two tasks were completed. The first task dealt with the design of a plunger device for lifetime measurements of excited nuclear states with the recoil distance Doppler-shift method with tracking capabilities for beams with energies of few MeV/u. We designed a multifunctional enlarged plunger end cap which allows to install detector arrays for particle detection for two different experimental techniques. The first option is the use for Coulomb excitation experiments in inverse kinematics. An array of photodiodes or, alternatively, a double-sided silicon strip detector (DSSD) is mounted in forward direction behind the plunger degrader/stopper foil for the observation of target recoil nuclei. As a second option this endcap can be used in fusion-evaporation and light ion transfer experiments. In this case a solar cell calotte can be placed under backward angle with respect to the beam to allow for an identification of light charged reaction products to trigger on different reaction channels.

The second task was the design of a plunger device for medium (10 MeV/u) and high energy radioactive beams with energies up to 200 MeV/u for HISPEC at FAIR. Within this task we completed a Technical Design Report on such plunger that was already approved by FAIR. We present a design study for a plunger for these special experimental conditions taking into account, e.g., large beam diameters of several centimeters, the option to operate this plunger very precisely at small distances between target and degrader foils of few micrometers for beam energies around 10 MeV/u, but also at large distances up to 3 cm for relativistic beam energies up to 200 MeV/u and thus large recoil velocities up to 60% of the speed of light.

Contents

I. NUCLEAR SPIN ORIENTATION USING THE TILTED FOILS TECHNIQUE AT ISOLDE, CERN

The nuclear spin polarization is an essential ingredient of most of the nuclear-moments studies techniques. Obtaining a nuclear spin-polarized ensemble, especially for short-lived states, is a not-trivial task and requires a rigorous control over the atomic and the nuclear spins and their interaction from the moment of the population of the state of interest up to its decay. The Tilted Foils technique is based on the possibility of obtaining an atomic spin-polarization and on the transfer of this orientation to the nuclear spins. When an ion beam passes through a foil, tilted at an oblique angle with respect to the beam direction, the spins of the atomic electrons are oriented in a direction perpendicular to the beam velocity ($\vec{v}$) and the axis normal to the foil ($\vec{n}$). The direction of the polarization ($\vec{v}\times\vec{n}$) can be easily reversed by reversing the normal axis of the tilted foil. When the ions are flying in vacuum behind the foil the interaction between the atomic and the nuclear spins leads to a certain level of polarization transfer from the atomic- to the nuclear-spin ensemble. The use of a stack of foils can increase the level of nuclear polarization due to the sequence of polarization transfers.is method has been proposed and tested for a limited number of cases still in the 1980's. However, due to the difficulties for detecting the level of nuclear polarization for stable ions, the technique has been applied to a limited number of cases. With the advent of the radioactive beams, and especially with the possibility of using post-accelerated radioactive ion beams, this method could be applied to a larger variety of cases. In order to develop it further, and to study it in depth, we have installed a combined Tilted Foils and beta-NMR setup at REX-ISOLDE. During the commissioning tests in July 2012 we have used ^{8}Li beam accelerated to 300 keV/u from the REX LINAC. The beam was further sent to the TF apparatus, positioned right in front of the beta-NMR setup that was used for determining the level of the nuclear polarization. The results obtained (see Fig. 1) have shown a nuclear polarization on the level of 3.6±0.3 % that needs to be considered rather as a lower limit for the present measurement. They demonstrate that the combination of post-accelerated radioactive beams with the Tilted Foils technique is well suitable for nuclear moment studies of radioactive nuclei and, in more general aspect, for obtaining spin-oriented radioactive beams. The results of this work were published as

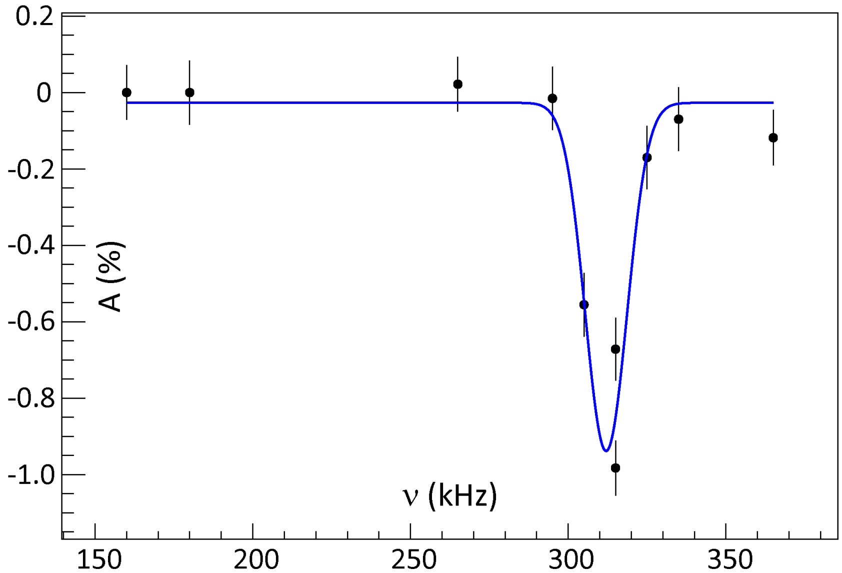

FIG. 1: Observed nuclear asymmetry as a function of the applied RF field.

conference proceedings from the EMIS 2012 Conference in Matsue, Japan [1].

II. TIME DEPENDENT RECOIL IN VACUUM. G-FACTOR MEASUREMENTS OF SHORT-LIVED EXCITED STATES

In order to perform a nuclear moment study it is necessary to provide a sufficiently strong perturbation to the state of interest so that a sizeable modification of the nuclear spin ensemble can occur within the lifetime of the state. If the lifetime of the studied state is of the order of picoseconds than the strength of the magnetic field needs to be of the order of thousands of Tesla's - fields that are not achievable at present with macroscopic devices. Therefore hyperfine fields are usually used in this type of measurements. A precise determination of the hyperfine field for a complex atomic configurations is quite challenging task and the use of simple configurations is desirable whenever possible. For example the application of H-like charge states, a single electron around the nucleus, is the simplest possible configuration and its hyperfine field can be determined with very high accuracy from first principles. In the here reported study we used H-like configuration to revisit the g factor of the 2+ state in ^{24}Mg (lifetime of 2 ps) applying the Time Dependent

Recoil In Vacuum technique. The time-dependent measurement provides a well-defined frequency of the observed oscillations of the nuclear spin ensemble allowing for a high-precision g-factor value.

In the standard TDRIV technique the state of interest is populated in a target foil and is allowed to recoil in vacuum. In the vacuum the interaction between the electron spin J and the nuclear spin I leads to a rotation of the later around a random axis resulting in a decrease of the observed angular distribution of the detected gamma-rays. After exactly one period of rotation the direction of the nuclear spins is restored to its initial value and thus the observed angular distribution. Therefore an oscillation pattern can be observed as a function of time, provided that the interaction time can be well determined. For this purpose a plunger device can be used. It adds a stopper foil at a well-defined distance, respectively time, behind the target. In the stopper foil the atomic and the nuclear spins are decoupled and the electron - nuclear spin interaction is canceled immediately. The novelty of our approach was that the Coulomb excited ^{24}Mg nuclei were not stopped in the second plunger foil but were let go through it. This leads to a "reset" of the electron configurations. In such a way the time-dependent part of the electron-nuclear spin interaction (between the target and the reset foil) is well defined. The contribution of the time-integral part of the interaction (after the reset foil) is summed up to the time-dependent part, leading to a damping of amplitude of the observed oscillation pattern. More details on the experiment, as well as on the technique, can be found in [2]. The replacement of the stopper foil with a reset one is of special interest for radioactive-beam measurements in which the beam cannot be stopped in the center of the setup (would lead to a build-up of very high level of activity that would soon blind the gamma-detectors). The TDRIV experiment on ^{24}Mg was performed in December 2012 at the ALTO facility in Orsay. The g factor that could be obtained from the R(t) function (see Fig. 2) is in agreement with the previous measurement but is twice more accurate. This allowed to constrain the nuclear theories and, for the first time, to experimentally confirm the expected deviation of the g factors of N=Z nuclei from the 0.5 limit. The work is accepted for publication in Physical Review Letters [2].

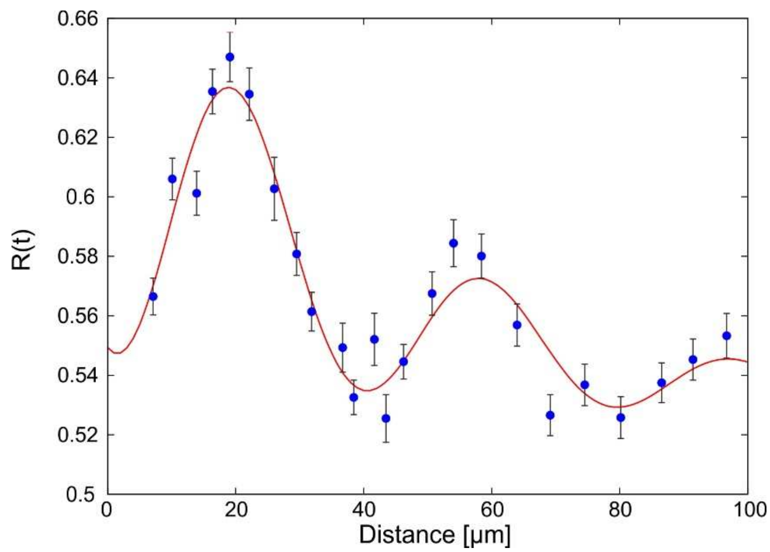

FIG. 2: Experimental R(t) function for the 2^+ state in ^{24}Mg

III. NUCLEAR SPIN-ORIENTATION IN INCOMPLETE FUSION/ MULTI-NUCLEON TRANSFER REACTIONS

The nuclear spin alignment is an essential ingredient for any nuclear moment studies of isomeric states. Spin alignment is readily obtained in fusion-evaporation reactions. However this type of production mechanism is not considered viable for investigating isomeric states far from the stability line. Therefore it is necessary to explore other reactions that are expected to be applicable with radioactive ion beams and, at the same moment, provide sufficient degree of spin orientation. Single-nucleon transfer reactions have demonstrated to be a widely applicable for the population of excited states using radioactive beams. They can provide as well certain degree of spin orientation, already used for nuclear moment studies with stable beams. However, the difficulty with the application of single-nucleon transfer reactions for nuclear moment studies of isomeric states with radioactive beams stems from two contradictory parameters:

- the isomeric state is relatively long lived (nanoseconds or higher) and therefore the nuclei need to be stopped in the reaction target;
- the energy/momentum transfer between the projectile and target nuclei, for single-

nucleon reactions, is relatively small. This does not allow for an efficient separation between the radioactive beam that needs not to be stopped in the target, and the reaction products - isomeric states that need not to get out of the target.

Therefore we have considered that single-nucleon transfer reactions would be difficult to be used as a production mechanism for isomeric-states studies with radioactive beams. In order to favor the energy/momentum transfer between the projectile and target nuclei we decided to look for the possibility of using incomplete fusion/multinucleon transfer reactions. This type of production mechanism has been used for a number of studies on the neutron-rich side of the nuclear chart. However no clear cut investigation of spin-orientation has been reported up to now.

As a test case we decided to look for the reaction products of ^{7}Li beam impinging on ^{64}Ni target. Some of the most abundant channels lead to the population of the ^{65}Ni and ^{66}Cu isotopes. They both have isomeric states, suitable for nuclear moment studies. In order to evaluate the level of spin alignment we applied the Time Dependent Perturbed Angular Distribution (TDPAD) technique. In a TDPAD measurement the amplitude of the R(t) function can directly provide the degree of spin orientation. The experiment was performed at the ALTO facility in Orsay in December 2013. The data analysis is still not finalized, however, the preliminary results (see Fig. 3) show that considerable level of spin alignment can be obtained in incomplete fusion/multinucleon transfer reactions.

It is interesting to note that the ^{66m}Cu case demonstrates a level of spin alignment considerably higher than the ^{65m}Ni case. In the presentation of ^{66}Cu as a "pn" transfer from the ^{7}Li beam to the ^{64}Ni target the ^{65}Ni could be considered as a single neutron transfer. In these representation it could be speculated that the higher number of nucleon transfer might lead to a higher level of spin-alignment. A careful completion of the data analysis should allow for more quantitative conclusions. In this third experiment we have already demonstrated that incomplete fusion/multinucleon transfer reactions can provide a working tool for nuclear moment studies of isomeric states using radioactive ion beams.

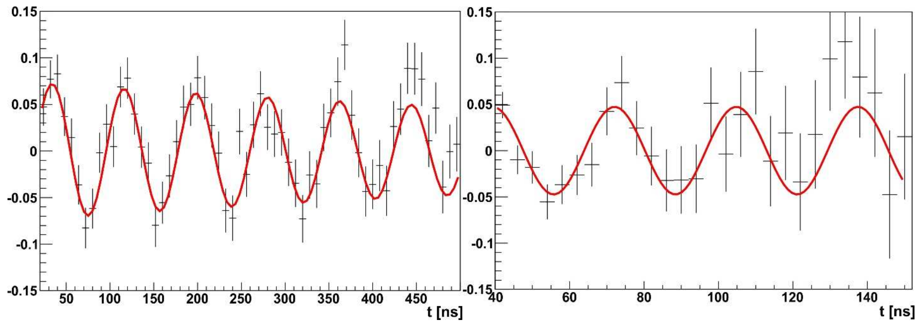

FIG. 3: R(t) functions for ^{66m}Cu (left) and ^{65m}Ni(right) obtained with ^{7}Li beam impinging on ^{64}Ni target.

IV. DESIGN OF A PLUNGER WITH TRACKING CAPABILITIES FOR LOW-ENERGETIC BEAMS

Here we present the design of a plunger device for lifetime measurements of excited nuclear states with the recoil distance Doppler-shift method (RDDS) with particle tracking capabilities. Two different options are provided. For Coulomb excitation experiments in inverse kinematics a solar cell array or a double-sided silicon strip detector (DSSD) is placed under forward angle with respect to the beam axis directly behind the plunger. With these detector systems it is possible to determine the energy and the angular distribution of the target recoils in experiments with Coulomb excitation in inverse kinematics where both projectile and target nuclei are preferentially scattered in forward direction. A protection foil to shield the detector system from projectiles, i.e., (scattered) beam particles, is also included. The observation of the target recoils in coincidence to the γ-rays emitted after Coulomb excitation of the beam particles has two advantages:

- Due to a possible large angle spread of the excited nuclei after the target a reconstruction of the kinematics is highly needed to achieve a reasonable γ-ray resolution and thus a sufficient separation of the Doppler-shifted components of the γ rays of interest,

- gating on target recoils results in the observation of projectile Coulomb excitation on the target only in the γ-ray spectra. Without this gating condition a significant contribution from Coulomb excitation of beam particles on the degrader must be considered that results in a increase of the observed intensity of the degraded or stopped component of the γ ray of interest. This would cause the need for a correction of the γ-ray intensities and thus would cause larger experimental errors.

As a second option a plunger device with tracking capabilities to be used for fusion-evaporation or light ion transfer reactions for low-energy beams is designed. The reaction products often have a low angle spread. Therefore, a reconstruction of the reaction kinematics is typically not required. However, in many cases a large number of reaction channels exists preventing the analysis of weak reaction channels. These can be separated by gating on light charged ejectiles of the reaction of interest with an array of photodiodes placed under a backward angle with respect to the beam axis. The latter serves mainly to protect the particle detectors from scattered beam particles that would cause significant radiation damage.

For the construction of an endcap providing the option to mount such detector arrays the following requirements were thus taken into account.

- The endcap must provide sufficient space for these particle detector systems including a mounting structure where limitations due to the geometry of the corresponding γ-ray spectrometers have to be taken into account. This includes that the endcap wall thickness has to be built as thin as possible in front of γ-ray detectors.

- A sufficient number of vacuum feedthroughs is needed especially when using highly segmented DSSD detectors.

- The construction must allow easy access to target and degrader/stopper foils for precise alignment and must be flexibel enough to house the aforementioned different position sensitive particle detectors.

Fig. 4 shows a sectional view of a plunger endcap designed to meet these specifications for a γ-ray spectrometer where germanium detectors are mounted under backward angles. Target and degrader foils are stretched over cones to achieve a high surface quality in order to measure especially at small target–degrader distances of few micrometers. This also requires the use of a feedback system to keep the distance between the foils constant

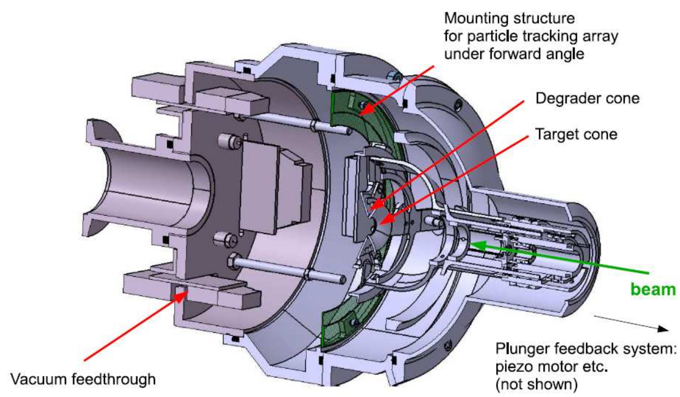

FIG. 4: Sectional view of a plunger endcap with tracking capabilities for low-energy beams (see text). Not shown is the mechanics of the plunger feedback system.

during an experiment which is already existing. The mounting structure for a particle tracking array under forward angle and several multipin vacuum feedthroughs are clearly visible. For clarity, the particle detector array (solar cell calotte) mounted under backward angle directly in front of the target cone is not shown.

Measurements performed by the Cologne group both with Coulomb excitation in inverse kinematics and light ion transfer experiments already proved the high potential of these methods for particle tracking in RDDS experiments for lifetime determination of excited nuclear states.

V. DESIGN OF A PLUNGER FOR HIGH- AND MEDIUM-ENERGY RADIOACTIVE BEAMS

The HISPEC plunger for high- and medium-energy radioactive beams is a core device for the HISPEC-DESPEC program, part of the NuSTAR collaboration within FAIR. This plunger is meant to be used in experiments measuring level lifetimes in nuclei far from stability, produced in secondary reactions induced by radioactive ion beams separated by the Super-FRagment Separator (Super-FRS). The excited exotic nuclei produced at the secondary (plunger) target will recoil into vacuum with velocities up to $\beta = 60\%$ before being slowed down in a degrader and identified further downstream with the LYCCA array. The analysis of the intensities of Doppler-shifted γ rays emitted between the secondary target and the plunger degrader or after the degrader will provide lifetimes of low-lying excited states. The design of the plunger needs to be compact as to minimise the absorbtion of γ-rays and the beam induced background. It has to fulfill the constraints given by large beam diameters which are typically in the range of several centimeters. The technical solution is to use three synchronized linear actuators to move the target with respect to the degrader, while three TESA probes will be used to check for thermal drifts and deviations from parallelism.

For low-energetic beams, and, therefore, low recoil velocities of the reaction products, thin and well stretched target and degrader foils have to be used that can be mounted in parallel to each other with a precision of the order of few μm. In addition, a position accuracy of the plunger device of around 1μm is needed for such experiments despite the large diameters of the foils of several centimeters.

On the other hand, relativistic beams with energies up to 200 MeV/u and low beam intensities often down to a few thousand particles per second make necessary the use of massive and heavy target and degrader foils with thicknesses in the order of hundreds of mg/cm^2. Here, the limitations of the precision arise from such large diameter foils that will have surface roughness in the order of 10 μm. However, for large recoil velocities of several ten percent of the speed of light in these experiments a high precision is not required, but the plunger must be able to be operated at large target–degrader distances up to 3 cm due to the reaction kinematics.

The plunger device should be installed in a dedicated vacuum chamber because of special needs regarding vacuum feedthroughs, alignment of the plunger, adjustment of foils and mounting of additional particle detectors. Such a chamber is designed within this task, too.

The experimental conditions at HISPEC thus cause several constraints for the construction of this plunger device which are listed in the following.

- Target/degrader diameter: 8 cm.

- Beam entrance clearance: 9 cm.
- The maximum plunger vacuum chamber diameter is 42 cm (inner diameter of the AGATA detector array that will be used for γ-ray detection).
- At the HISPEC setup the AGATA array will be placed under forward angle with respect to the beam axis to detect γ rays under most sensitive solid angles due to the Lorentz boost for relativistic beams. Therefore, material which absorbs γ radiation should be reduced in this direction.
- A connection to LYCCA for particle identification must be foreseen.
- A mounting structure for a DSSD detector must be included inside the plunger chamber downstream of the target/degrader foils. This detector both serves a time-of-flight start detector for LYCCA and to reconstruct the interacting point on the target.
- The mechanical supports for the chamber and the beam line have to be located upstream of the plunger chamber.
- The option to move the plunger upstream by up to 100 mm to optimize the angle relative to the AGATA detectors depending on the experimental conditions is foreseen.
- Depending on the beam energy thick, massive or thin targets/degraders have to be used. Thin foils with thicknesses of few $10\,\text{mg/cm}^2$ for low beam energies have to have a very good surface quality and thus are stretched by gluing the foils to a support ring which is then screwed to a cone until the foil becomes homogeneously stretched and perfectly plane. Thick foils for relativistic beams with thicknesses up to $5000\,\text{mg/cm}^2$ have to be glued directly to the cones.
- The range of target/degrader separations is 0–30 mm.
- Precision of the separations (for small distances and perfect target and degrader foils only): $1\,\mu$m.

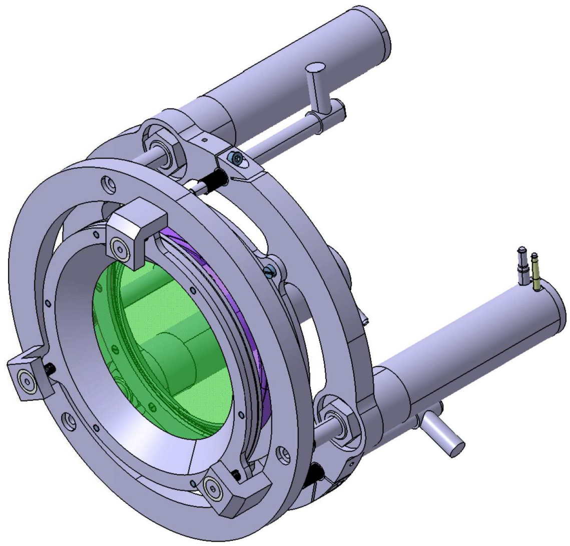

FIG. 5: Schematic drawing of the HISPEC plunger device. Near to each of the three linear actuators an inductive sensor is mounted which is clearly visible close to the upper actuator to measure independently the movements induced by the actuator.

Based on these constraints a design study for the HISPEC plunger device including a sophisticated plunger chamber was performed. Exemplarily, Fig. 5 shows a schematic drawing of the HISPEC plunger device. The distance between target and degrader is set with three linear actuators, which are also used for the feedback system to keep the distance between target and degrader foils constant with a precision of few micrometers and provide an additional option to align the foils automatically to paralleltity. Three inductive sensors close to each motor are used to measure the motor movement independently. In addition, the software needed to operate the feedback system was developed and tested within this task.

[1] H. Törnqvist, C. Sotty, et al., Nuclear Instruments and Methods in Physics Research B 317 (2013) 685

[2] A. Kusoglu, et al., Phys. Rev. Lett. (2015) in print

[3] A. Dewald, O. Möller and P. Petkov, Prog. Part. Nucl. Phys. **67**, (2012), 786-839.