1. Introduction

In May 2005, a first g factor measurement (according to our proposal) was carried out under most realistic conditions with a $^{138}\text{Xe}$ beam applying the technique of projectile Coulomb excitation in inverse kinematics combined with transient magnetic fields (TF) in ferromagnetic gadolinium. The $^{138}\text{Xe}$ beam has been chosen as its production and preparation for REX-ISOLDE was considered to be relatively easy and free of isobaric contaminants and at the same time the purity and intensities of Te beams were not known. As the measurement should be mainly (but not only) a feasibility test of the proposed experiments in view of the large experimental challenges, technicalities related with the beam conditions and the accelerator’s performance ought to play a minor role. In order to prepare the experiment at REX-ISOLDE in the best possible way two similar experiments have been performed with stable beams at the Cologne tandem accelerator, where the MINIBALL detector array was temporarily stationed, to test the experimental setup. In these experiments it has been demonstrated for the first time that particle-$\gamma$ angular correlations and spin precessions can be measured with fixed positions of the MINIBALL detectors.

In the following we summarize the results and experiences of the two precursor experiments and of the measurements at REX-ISOLDE.

2. Preparatory experiments at the Cologne tandem accelerator

a) Measurements with 100 MeV $^{48}\text{Ti}$ beams

For the g factor measurement a stable $^{48}\text{Ti}$ beam of 100 MeV was provided by the Cologne
tandem accelerator. The $^{48}\text{Ti}$ nuclei were Coulomb excited primarily to the $2_1^+$ state at 0.984 MeV with lifetime $\tau = 5.7(2)$ ps and a $g$ factor, $g(2_1^+) = + 0.39(2)$ [1]. Four out of six modules of the MINIBALL detector array were used, each module consisting of three 6-fold segmented Ge crystals. The four modules were placed in pairs symmetric to the beam direction (in the backward and forward hemispheres) at face distances as close as possible to the target position. They were operated in coincidence with forward scattered carbon ions registered in an annular Si detector at $0^\circ$ to the beam axis. The ORTEC Si detector with an effective area of 450 $mm^2$ and a depletion layer of 100 $\mu m$ possessed a centre hole of 8 $mm$ diameter which permitted the main intensity of the beam ions to pass to a down-stream Faraday cup. This condition is particularly crucial when dealing with a radioactive beam which has to be transported to a place far away from the target area so that the $\gamma$ detectors can be well shielded from the $\gamma$ radiation of the radioactivity thus reducing disturbing background radiation in the coincidence spectra. In addition, the Si detector was fully covered with a Ta foil to stop beam particles from straggling by the target layers (see also [2]). The foil, however, was thin enough, so that the target ions were detected over the total detector acceptance. The multilayered target consisted of 0.38

![Figure 1: Scheme of target and detector arrangements for precession measurements.](image)

$mg/cm^2$ of natural carbon, deposited on a 3.3 $mg/cm^2$ Fe layer which was evaporated
on a 2.4 mg/cm² Cu foil. The carbon nuclei served for Coulomb excitation of the ⁴⁸Ti projectiles and the magnetized Fe layer provided the TF for the spin precession, and the copper backing for stopping the excited nuclei in a hyperfine-interaction-free environment. Fe was used instead of Gd because due to its high Curie temperature it does not require cooling. A dewar which can be mounted inside the spherical MINIBALL frame was under construction but not yet ready when this measurement took place. The schematics of the detector arrangement and the target composition, indicating also the trajectories of the beam and target ions for the coincidence measurement, is shown in Fig. 1. A γ spectrum from the coincidence with all particles is displayed in Fig. 2 exhibiting all prominent γ lines from Coulomb excitation and fusion reactions as well. Spectra were taken for alternating field directions to determine the spin precession of the excited nuclear state. Particle-γ angular correlations were derived from the photopeak intensities of the (2⁺⁺ → 0⁺⁺) γ transition at fixed and well-determined angle positions of the individual Ge crystals. For this purpose the relative efficiencies of the segmented crystals were determined using the nearly isotropic ⁵⁵Fe γ lines (see Fig. 2) produced in a fusion reaction between ⁴⁸Ti and the carbon target. The angular correlation derived is shown in Fig. 3 together with the logarithmic derivative which determines the spin precession angle Φ_{exp}. The average precession angle obtained,

Φ_{exp} = 11(3)mrad, \hspace{1cm} (1)

is in good agreement with expectations based on the linear parametrization of the TF strength using a strength parameter a(Fe) = 12(1) Tesla [1], the known g factor and the thickness of the Fe layer.
The main goal of this test experiment was to demonstrate that angular correlations can be reliably determined for fixed positions of the MINIBALL detectors which had not been shown before and is therefore new with respect to conventional measurements in which the detectors are moved in their angle positions. This goal has clearly been achieved. Furthermore, precession angles in TF conditions, even of small magnitude, can be measured with MINIBALL detectors in a well-acquainted manner.

b) Measurements with 100 MeV $^{50}$Ti beams

The main purpose of the second experiment at Cologne was to test under realistic conditions the performance of the new self-fabricated dewar (with a volume of 2.5 l) for cooling the target to LN temperature. In this experiment, essentially the same set-up was used as in the $^{48}$Ti measurements. The only differences were the use of a $^{50}$Ti instead of a $^{48}$Ti beam and a cooled Gd layer for spin precession instead of a Fe layer. The advantage of the $^{50}$Ti beam (in comparison to $^{48}$Ti) consisted in a lower Coulomb excitation cross-section, thereby better simulating the conditions of a low-intensity radioactive beam. On the other hand, the $2^+_1$ state at 1.554 MeV with a lifetime $\tau = 1.62(7) \text{ ps}$ has a $g$ factor, $g(2^+_1) = +1.44(8)$ [1], which is more than 3 times larger than the corresponding value of $^{48}$Ti thus favouring the measurement of the precession angle.

The settings of the MINIBALL detectors and the Si particle detector with its specific ingredients were identical to those in the former measurements. $^{50}$Ti beams were provided with sufficient intensity by the Cologne tandem accelerator. The de-excitation $\gamma$ rays were measured in coincidence with forward scattered carbon ions. A typical $\gamma$-coincidence spectrum is shown in Fig. 4 with prominent $\gamma$ lines labelled accordingly.
Particle-γ angular correlations and spin precessions have been measured with the same settings of the MINIBALL detectors relative to the beam axis as for $^{48}$Ti. During the run the dewar for target cooling was connected to the automatic filling system as used for the MINIBALL detectors which worked very well. The target temperature was monitored using a thermocouple attached to the target frame, demonstrating that target cooling worked well. Since the MINIBALL data acquisition was still under development during this experiment, it was unfortunately not possible to perform a careful off-line analysis to evaluate the spin precessions in the Gd layer from the “up”-“down” spectra. The on-line data, however, allowed to conclude that TF measurements with Gd targets are feasible.

3. Measurements with a 2.8 MeV/u radioactive $^{138}$Xe beam

a) Details of the experimental set-up

Our specific target chamber, including the magnet, was installed at REX-ISOLDE in the centre of the MINIBALL detector array (see Fig. 5). A collimator with 4 mm aperture was mounted in the beam line a few cm before the entrance tube of the chamber. On the exit side of the target chamber a Parallel-Plate-Avalanche-Counter (PPAC) was installed which served as a highly sensitive monitor for the low-intensity beam while steering it through the collimator onto the target.

The multilayered target was clamped between the pole tips of the electromagnet which was built into the cryostat for target cooling purposes (see above). The precession target consisted of

1.1 mg/cm$^2$ elemental $^{50}$Ti, deposited on 6.16 mg/cm$^2$ Gd, backed by 3.9 mg/cm$^2$ Cu.
We would like to mention already here that the target layer thicknesses were optimized for an expected beam energy of 3.1 MeV/u as requested in the proposal. For this energy the energy-dependent straggling of the beam in the target, that is the spreading of the beam ion’s trajectories, was carefully simulated using the computer code TRIM [3] and the layer thicknesses chosen accordingly. Unfortunately, the energy of the beam during our experiment was limited to 2.8 MeV/u due to problems with one of the resonators. The $^{138}$Xe projectiles were Coulomb excited in collisions with the $^{50}$Ti nuclei and the magnetized Gd layer provided the TF for spin precessions of the Xe nuclei in their excited states. Due to the inverse kinematics both the $^{50}$Ti target nuclei and the excited $^{138}$Xe beam nuclei were moving in the beam direction through the target layers, thereby losing energy which led to the stopping of the Xe ions in the Cu layer, while the emerging Ti ions were detected in an annular Si detector positioned at 0° to the beam axis. A Cu layer was used as a hyperfine-interaction-free environment. The recoiling $^{50}$Ti target nuclei detected by the annular Si detector were the crucial trigger for the detection of the
γ rays emitted from the excited Xe nuclei. The same annular Si detector, already tested in the earlier measurements with stable beams, has been used in the present measurements. The only difference consisted in a 5 μm thick Ta foil in front of the detector, intended for stopping beam particles which are elastically scattered (in particular by the Gd layer) at angles between ±20° and ±26°. The total aperture of the detector was ranging from ±20° to ±35° where no shield existed between ±26° and ±35°. This "differential" stopping was arranged as the Ti ions have at large scattering angles such low energies that they would be stopped in the Ta foil. Due to the fact that the large scattering angles correspond to large Coulomb excitation cross-sections, such a loss could not be afforded.

b) First measurements with the $^{138}$Xe beam

In the first step of the experiment, with no target mounted, the radioactive beam was carefully steered through the collimator and the centre hole of the annular detector, downstream to the PPAC. In this situation a prominent beam profile, with sharp edges in the radial extension, was observed reflecting the size of the collimator slits. A much weaker signal was obtained in the PPAC when the precession target was mounted. In this case, the profile exhibited rather shallow edges from the straggling of the Xe ions by the target layers, enhanced by the low beam energy. The target was in fact too thick for the lower beam energy, associated with more straggling and scattering of the ions, which finally results in a reduced transmission of the beam through the Si detector and consequently the accumulation of radioactivity in places too close to the target area (see below).

Before discussing the problem of beam scattering in more detail we would like to mention that we encountered a second problem which was related to the time structure of the pulsed beam with a pulse width of 50 μs and a repetition frequency of 3 Hz. The short beam pulses drove the preamplifier of the particle detector into saturation. The number of particles during the pulse was too high ($\approx 7 \cdot 10^9$) so that the particles were piling up during the 50 μs decay time of the preamplifier pulses. Only by reducing this time to $\approx 2 \mu$s appropriate energy signals were obtained in the spectroscopy amplifiers, but still the beam intensity was restricted to $10^4$ ions/s.

Coming now back to the problem of the scattering of beam ions into the Si detector, this problem turned out to be so severe that no prompt peak was observed in the time spectrum and the particle coincidence spectrum only showed a broad bump, which we originally falsely attributed to the Ti target ions. In the γ coincidence spectra under these conditions there was no indication of the expected 588 keV ($2^+ \rightarrow 0^+$) γ line from Coulomb excited $^{138}$Xe. To proof that the origin of all these problems is indeed beam scattering in the target, the thick multilayer precession target was replaced by a thin 1.0 mg/cm$^2$ nat Ti foil. Now the γ ray from the Coulomb excitation of $^{138}$Xe was clearly seen in the γ-coincidence spectrum and the time spectrum showed then a prominent peak. Particle-, time- and γ-coincidence spectra obtained under these conditions are displayed in Fig. 6. This test demonstrated that the beam was correct and the electronics as well as the data acquisition worked properly. In view of these encouraging results beam scattering was considered as the origin of the problem when using the precession target. Evidently, the scattering was very much reduced in the case of the "thinner" Ti foil where the Xe ions emerged at much higher energies from the target. This behaviour was obviously very...
different when using the "thick" precession target. In that case no peak was visible in the time spectrum because it was flooded with random coincidences arising from scattered beam ions. For the precession target it was found in TRIM calculations that this effect might be improved by factors 2-3 by raising the beam energy to 3.1 MeV/u. Hence, for the available energy of 2.8 MeV/u this target was just too thick.

With these facts in mind, the Ta foil in front of the Si detector was replaced by an Al foil of 3.2 mg/cm$^2$ thickness covering the total active surface of the annular detector (see also Fig.1). By this procedure a breakthrough in the measurement was achieved. We obtained a peak in the time spectrum and clearly saw for the first time using the precession target the 588 keV $\gamma$ line of Coulomb excited and stopped $^{138}$Xe. However, according to calculations with the program TRANSI [2], the price to pay was that only the very few fast $^{50}$Ti ions were detected in the Si detector while the majority of the ions was stopped in the Al foil. As the detected Ti ions correspond to the most forward angles, where the Coulomb excitation cross-section is relatively small, only a very low $\gamma$-coincidence rate has been obtained. Unfortunately, a thinner Al foil was not available. In spite of this deficiency the target was then cooled to LN temperature and for the remaining time of about six hours precession data were taken. Yet, only a fraction of this time ($\sim 2h$) could be utilized since the MINIBALL detectors were exposed to substantial $\gamma$ radiation from the radioactivity of the beam as well as X-rays from the last resonator of the accelerator. Through heavy shielding of the MINIBALL detectors by a lead wall against those X-rays and additional shielding against the beam radioactivity deposited on the collimator and
Figure 7: Random $\gamma$-coincidence spectrum obtained with the $^{138}\text{Xe}$ beam on the precession target (see text). All $\gamma$ lines have been identified and refer to transitions in $^{138}\text{Cs}$ and $^{138}\text{Ba}$, both produced via $\beta$-decay of $^{138}\text{Xe}$.

the exit tube of the target chamber, it was possible to reduce considerably this background radiation. A random coincidence spectrum displayed in Fig. 7 shows all prominent $\gamma$ lines which can be attributed to transitions in $^{138}\text{Cs}$ ($T_{1/2} = 33.4$ m) and $^{138}\text{Ba}$ (stable), the daughter nuclei of the $^{138}\text{Xe}$ ($T_{1/2} = 14.08$ m) beam. By gating with the prompt peak of the time spectrum these $\gamma$ lines were almost completely suppressed. Relevant spectra under these conditions are shown in Fig. 8. The accumulated photopeak intensity of the $(2^+_1 \rightarrow 0^+_1)$ $\gamma$ line of $^{138}\text{Xe}$ was not sufficient to derive a statistically significant precession angle.

4. Conclusions and consequences for future experiments

On the basis of the first experimental campaign for measuring $g$ factors with radioactive beams at REX-ISOLDE, the following conclusions are drawn and consequences for future experiments are derived:

- Straggling of the beam ions by the thick multilayer target is the most severe problem in this type of experiment. The target layer thicknesses must be carefully optimized with respect to the actual beam energy and the corresponding energies of the target ions.
  → For future experiments several targets will be prepared optimized for different beam energies (e.g. 3.1 and 2.8 MeV).

- Even when using an optimized target beam straggling can never be completely
avoided. It is therefore important to shield the annular particle detector using Ta foils of proper thicknesses and angular acceptance ranges for a given beam energy. Large acceptance angles should in general be free of shielding in order to avoid the stopping of the low energetic target ions at angles which correspond to large excitation cross-sections. In view of the beam straggling problem a significantly thinner second foil as shield should be taken into consideration.

→ The angle dependence of the energy of both the scattered beam ions as well as Coulomb excited target ions has to be carefully calculated for each possible beam energy and target combination in order to determine the optimal thicknesses of one or more absorber foils in front of the Si detector.

• The collimator section and the exit area of the target chamber must be well shielded against γ radiation emitted from deposited beam radioactivity and deposition of such activity needs to be reduced.

→ In future experiments the exit area of the target chamber will be modified in such a way that much less scattered beam will be deposited on the walls of the beamtube. In addition the shielding from the collimator section will be improved.

• Sufficient shielding of the MINIBALL detectors against X-rays from the resonators, in particular from the last HF resonator which is closest to the experimental set-up, is crucial in order to limit the count rate in MINIBALL.

→ Since this is a general problem concerning all MINIBALL experiments, we request
that sufficient shielding will be implemented.

- In the test experiment, the beam intensity which could be handled was limited by the pile-up of signals in the preamplifiers of the particle detectors during the 50 \( \mu s \) beam pulses. Generally, the duty cycle of the pulsed beam is a severe limitation on the intensity one can cope with.
  → This experiment will greatly benefit from the extended pulse width of 200 \( \mu s \) which will be available after implementation of the slow extraction from the EBIS source. In addition, for future experiments we plan to replace the annular Si detector used in the experiments described in this report by a segmented annular Si detector of similar size in order to reduce pile-up and dead time.

With the aforementioned improvements we want to measure in 2006 the g-factor of the first 2\(^+\) state in \(^{138}\)Xe, as requested in the proposal. For this experiment we will need 5 days instead of the originally requested 2 days. The main reason is the fact that the measured beam intensity of \(5 \cdot 10^5\) pps (as used in experiment IS 411) is a factor of 4 lower than the beam intensity assumed in the proposal. At the same time we have gained from the test experiment good experiences with the real working conditions. Therefore, we do not need a factor of 4 more beam time; 5 days will allow us to determine the g-factor with a precision of about 10 percent.

For the g-factor measurement on the Te isotopes we will request appropriate amounts of beam time for 2007, once the currently ongoing beam development has been completed and the achievable beam purity and intensity has been measured at REX-ISOLDE.

References