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ISOLDE AND NEUTRON TIME-OF-FLIGHT EXPERIMENTS COMMITTEE (INTC)

EMISSION CHANNELING LATTICE LOCATION EXPERIMENTS WITH SHORT-LIVED ISOTOPES

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SUMMARY

Emission channeling with position-sensitive detectors is a well-established technique at ISOLDE for studying the lattice location of radioactive impurities implanted into single crystals. In the case of electron emitting isotopes, however, due to count rate and noise-related limitations of the detection systems, the technique was restricted to isotopes with half lives above 6 h and electron energies above 40 keV. Recently, major technical developments have been realized and new equipment has been acquired which has allowed these limitations to be overcome and made feasible electron emission channeling experiments with short-lived isotopes and at low electron energies.

As first application, making use of two new on-line emission channeling setups at ISOLDE, we propose to investigate the lattice location of the transition metals Ni (2.5 h) and Co (1.6 h) in semiconductors, in particular in ZnO and GaN, by means of on-line β^- emission channeling experiments. In addition, we would like to study the lattice location of the acceptor dopants ^{27}Mg (9.5 min) in GaN by means of β^- and of ^{8}Li (838 ms) in ZnO by means of α emission channeling.

A number of test isotopes are requested as well in order to explore the possibilities for using low-energy electrons below 40 keV, in particular Auger electrons, for lattice location purposes.

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1) Introduction

The principle of emission channeling [1] is to dope single crystals with radioactive probe atoms that decay by the emission of charged particles such as α, β^- or β^+ particles or conversion electrons, which, on their way out of the crystal, experience channeling or blocking effects along low-index crystal directions. The resulting anisotropic particle emission yield from the crystal depends in a characteristic way on the lattice sites occupied by the emitter atoms and is recorded with the aid of position sensitive detectors. In comparison to conventional lattice location techniques by means of ion beam channeling, the main benefit of emission channeling is a roughly four orders of magnitude higher sensitivity. This allows one to perform detailed lattice location studies with very good statistical accuracy at low fluences of implanted probe atoms, usually as a function of post-implantation annealing temperature, which is not feasible by other methods.

At ISOLDE, the use of position-sensitive detectors (PSDs) for emission channeling was first established in 1990 in lattice location studies of the short-lived *alpha* emitter ^{8}Li ($t_{1/2}$=838 ms) [2, 3] using Si detectors which apply the principle of resistive charge division. In 1996, for the first time *electron* emission channeling experiments at ISOLDE applied position-sensitive detection. However, unlike the commercially available alpha detectors, the Si pad detectors used for electrons had initially been developed at CERN for X-ray imaging [4] and were adopted and extensively tested for their use in electron emission channeling by members of the present collaboration [5-7]. The physics case which was addressed in the emission channeling experiments was the lattice location of electrical, magnetic and optical dopants in semiconductors and oxides. In particular, studies on the lattice location of transition metals [8-24] and rare earths in semiconductors [5, 6, 9, 21] and on electrical dopants in novel wide band gap semiconductors [25, 26] have been quite fruitful. However, the *electron* PSD systems used since 1996 had one serious limitation, which prohibited their use for short-lived isotopes. Due to the simple but slow detector readout procedure (the so-called “backplane triggering technique”), the maximum achievable count rate was around 200 events/s. This practically limited the application of the detection systems to lattice location studies of isotopes with half lives greater than roughly 6 h, since efficient studies with short-lived isotopes require the ability to measure with count rates at least in the kHz region, corresponding to sample activities in the MBq range. In addition, relying on the comparatively noisy backplane signal to trigger the detector readout also limited the minimum energy range to around 40 keV.

Recently new technical developments have been undertaken and new equipment has been built or acquired in order to overcome these limitations. The main new development supported by the ITN Sacavém/CFNUL Lisbon group in collaboration with CERN, was the implementation of self-triggering readout chips for the Si pad detectors. This new readout system allows **count rates of several kHz**, sufficient to measure samples in the MBq range. In addition, a position-sensitive detector suited for **low energy electrons** (below 20 keV) has been acquired by the University of Göttingen [27]. This detector, which was developed at the Max Planck Institute for Extraterrestrial Physics in Garching for satellite-based X-ray imaging [28], uses a charge-coupled device (CCD), and, besides unrivaled low-energy capabilities, also achieves count rates in the kHz range. In order to allow coupling to the ISOLDE beam lines, as is required during measurements of short-lived isotopes, two on-line implantation and channeling chambers have been built by ITN/CFNUL and the University of Göttingen. Both setups will be permanently available at ISOLDE, in addition to the three off-line setups already maintained by ITN/CFNUL and IKS Leuven.

The aims of the presented proposal are as follows:
- establish the successful use of novel, short-lived isotopes for *electron* emission channeling experiments using position-sensitive electron detectors;
- explore the possibilities to use low-energy electron (conversion or Auger electrons < 40 keV) emitting isotopes for emission channeling experiments;
- extend the successful work in the fundamentally and technologically relevant field of the lattice location of transition metals and dopants in semiconductors using as new probes the isotopes ^{65}Ni (2.5 h), ^{61}Co (1.6 h), and ^{27}Mg (9.46 min);
- re-establish lattice location studies of the short-lived *alpha* emitter ^{8}Li (838 ms) with experiments on the lattice location of Li in ZnO.

Due to the fact that the proposed on-line experiments require considerable resources with respect to equipment and manpower, all groups working on emission channeling at ISOLDE have decided to collaborate as the "EC-SLI" experiment and present this common proposal.

2) New developments

As was already mentioned in the introduction, the position-sensitive Si pad detector systems which have so far been used for *electron* emission channeling [4-7] had the shortcoming that the readout of the detector relied on the so-called "backplane triggering technique". One side of the 3×3 cm^2 sized pad detectors is segmented in 22×22 pixels of 1.3×1.3 mm^2 size, with 4 VA1 preamplifier chips of 128 channels each [29] attached to the pixels, while the other side consists of a common backplane electrode coupled to a charge-sensitive preamplifier. In the backplane trigger technique, the readout of the detector is triggered when an electron signal is detected on the backplane of the detector. All 484 pixels are then read out sequentially, followed by analysis of the charge collected in each preamplifier channel in order to identify the pixel that received the electron. Since the whole readout and analysis procedure requires around 2 ms, the maximum achievable count rate is limited to around 200 events/s. While this readout technique has the advantage that it relies on relatively simple and inexpensive preamplifier chips, its obvious drawback is its slowness. In addition, the noise level of the common backplane is high since it is subject to the capacitance and leakage current of the detector as a whole. The minimum energy of electrons which could be detected using this technique was around 40 keV [7].

2a) Si pad detectors using self-triggering readout chips

In order to overcome the limitations of the backplane triggering technique, a research and development project was initiated by ITN/CFNUL in collaboration with P. Weilhammer, A. Rudge and C. Lacasta from the Compton Camera project at CERN [30]. As a result of these efforts, a completely new emission channeling detection system equipped with a 0.5 mm thick 22×22 pad detector and four self-triggering VATAGP3 readout chips [29] has been made operational (Fig. 1). In contrast to the VA1 chips, the VATAGP3 preamplifier chips allow to be operated in a readout mode where only the channels with a trigger (i.e that actually received a signal above an externally set threshold) are read out. This considerably speeds up the readout process and count rates of several kHz have already been realized. The readout is controlled by VME based electronics, which is coupled to a LINUX PC by means of an optolink. The software for data acquisition and on-line display was developed by C. Lacasta from the University of Valencia in Spain.

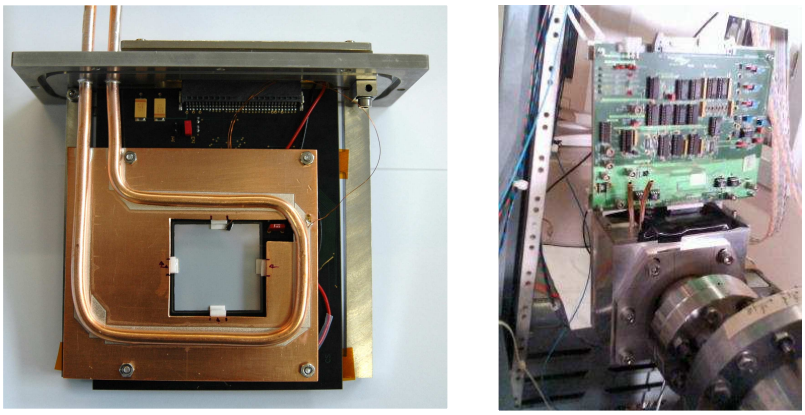

Figure 1: (left) The Si pad-detector with fast readout electronics mounted on the flange which is used to insert it into its vacuum chamber. The four self-triggered preamplifier chips, which are directly attached to the detector via microbonds and operated under vacuum, are cooled by means of four Peltier elements and the water-cooled copper plate and tubing visible in the picture.
(right) The fully mounted detector chamber and readout electronics attached to a vacuum sample chamber for testing purposes.

Since the power consumption of the VATAGP3 chips is considerable (several W per chip), detector cooling is imperative in order to limit the detector temperature under vacuum operation. For that purpose, an active cooling system based on 4 Peltier elements and water cooling was developed [7], which allows to remove the heat created by the preamplifier chips and stabilize the detector operating temperature at any value between 30°C and –30°C.

The newly developed readout software displays the energy spectrum and channeling patterns during data acquisition and is capable of data-taking at rates of several thousand events/s, as is required for on-line experiments with short-lived isotopes. Figure 2 shows as example the data obtained from a $SrTiO_3$ sample implanted with ^{111}In. The energy spectrum shows the four major conversion electron lines of ^{111}In at 145, 168, 219 and 242 keV and the corresponding channeling pattern around the $SrTiO_3$ <100> axis. Note that the trigger level was set around 35 keV in order to exclude the Cd X-rays from the data acquisition process.

An added advantage of the fact that the VATAGP3 chips generate the trigger signal internally is that the detector readout procedure does no longer rely on the relatively noisy backplane signal, thus considerably decreasing the accessible measurement range of the energy deposited in the detector. Tests have shown the capability to detect X-rays of energy as low as 13.4 keV with a FWHM of 1.2 keV. However, for the detection of extremely low-energy conversion electrons, the accessible energy range and energy resolution will be limited by the energy loss of the radiation in the dead layer of the detector (around 1500 Å) and the performance in that respect still remains to be determined (which is part of the current proposal). It is expected that the electron detection limit will be around 25 keV. The main purpose of this detector will therefore not be in the detection of extremely low energy electrons (for which the new CCD detector with its excellent noise behaviour and ultra-thin entrance window is much better suited) but in the detection of short-lived beta and higher energy conversion electron emitters.

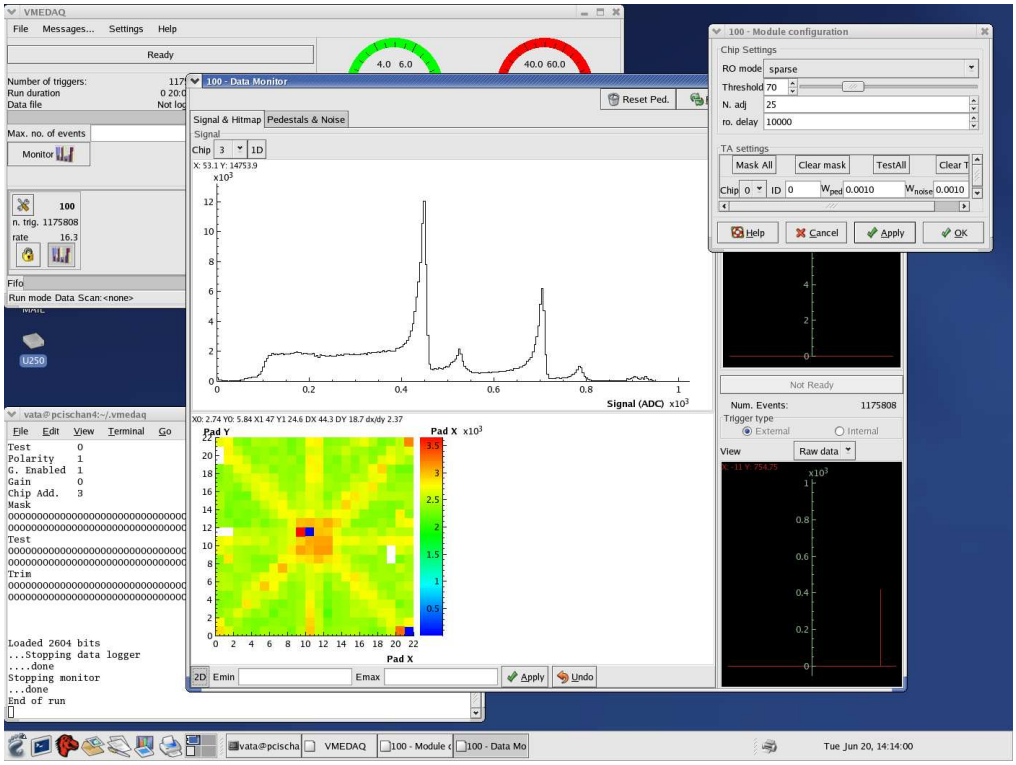

Figure 2: Screendump of the LINUX based readout software for on-line emission channeling experiments with the new, fast Si pad detection system. The data visible in the center of the screen was obtained from a $SrTiO_3$ single crystal implanted at ISOLDE with ^{111}In for test purposes. It shows the energy spectrum of the conversion electrons from ^{111}In and the corresponding emission channeling pattern of the $SrTiO_3$ <100> direction, as displayed during the measurement.

2b) The new ITN/CFNUL on-line emission channeling chamber for Si pad detectors

In 2006 a new vacuum chamber has been constructed at ITN/CFNUL, fulfilling the requirements posed by on-line experiments with the new, fast pad detector system, i.e. suitable in principle for implanting and measuring at the same time. The basic layout of the chamber can be seen from Figs. 3 and 4.

In order to assure proper beam positioning on the sample, which is crucial for on-line channeling experiments, the ISOLDE beam will pass through two collimators. A first set of exchangeable collimators of different sizes (realized on a rotatable disk) is located in a small vacuum chamber around 50 cm in front of the sample. Since this part of the setup will accumulate most of the radioactivity during the implantations, it is shielded by several cm of lead. Proper positioning of the beam on the sample is guaranteed by the final collimator of diameter 1 mm, which is positioned 5.4 cm in front of the sample. For on-line experiments where implantation and measurement occur at the same time, the high-precision remote-controlled 3-axis goniometer with *x,y,z* stage from the University of Göttingen will be used, while for off-line use of the chamber simpler 2-axis hand-operated goniometers are available. All goniometers are equipped with in-situ sample heating up to 900°C. At a later stage it is planned to upgrade the chamber with a closed cycle He refrigerator, which should allow to reach temperatures around 50 K. The beam current can be measured in a Faraday cup located behind the sample (for precise measurements after moving the sample upwards) or directly on the sample (for monitoring current during implantation).

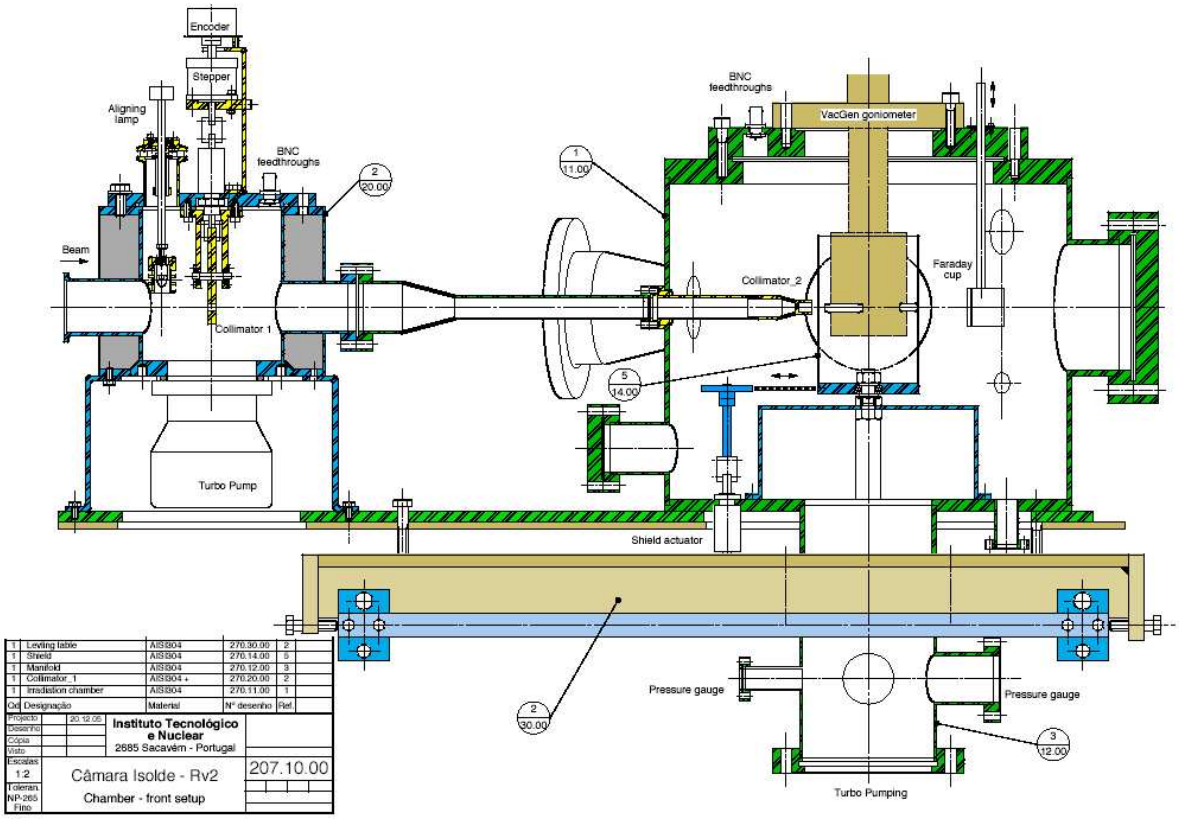

Figure 3: Schematic side view of new implantation and measuring chamber for on-line emission channeling experiments built by ITN/CFNUL. The ISOLDE beam enters the chamber from the left and is collimated by two apertures before impinging on the single crystalline sample, which is mounted in the goniometer inserted in the main chamber from the top.

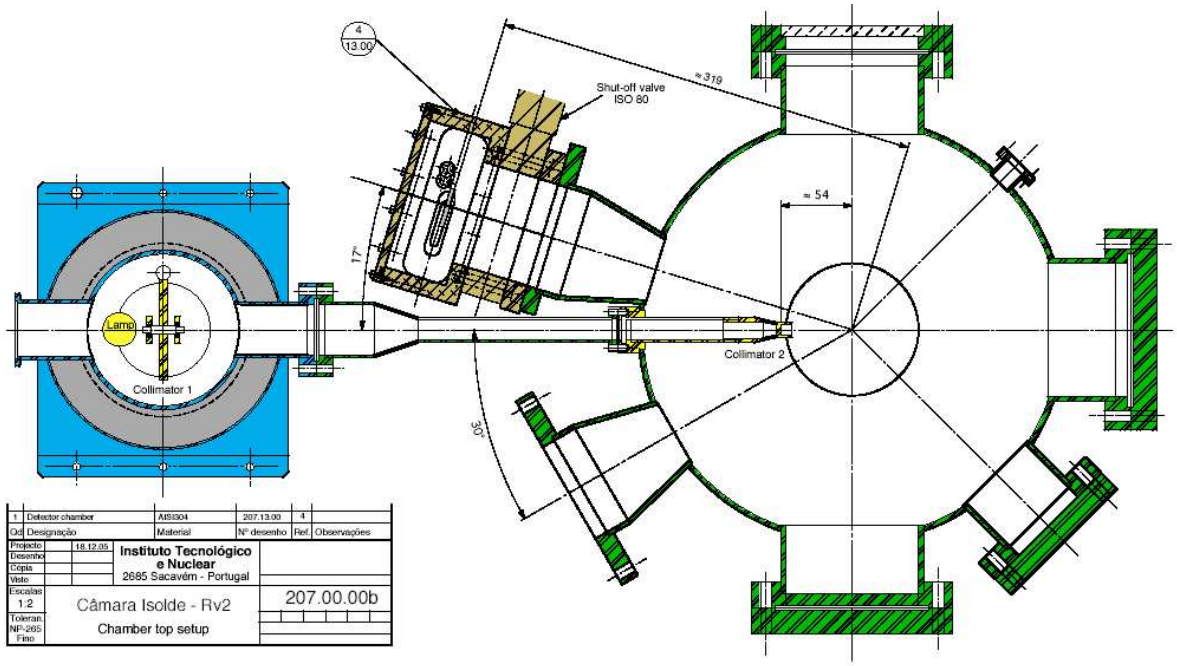

Figure 4: Schematic top view of new implantation and measuring chamber for on-line emission channeling experiments built by ITN/CFNUL. The position-sensitive Si pad detector with newly developed readout system is shown coupled to the sample chamber with a vacuum valve under a backward angle of 17°, thus allowing experiments where implantation and emission channeling measurements occur simultaneously.

The chamber has two flanges, at backward angles of 17° and 30° to the beam, where position-sensitive pad detectors can be mounted at a distance of 319 mm from the sample (Fig. 4). The 17° position, where the angle between beam and detector is minimized as much as possible, is suitable for on-line experiments where implantation and measurement take place at the same time. The position-sensitive detector can be shut off from the chamber by means of a vacuum valve, thus allowing the detector to remain cooled during sample exchange or annealing. The whole setup is mounted on an *x*,*y*,*z* adjustable table, and the stand of the setup is equipped with the ISOLDE fast load-lock floor positioning system, thus allowing for easily reproducible and precise alignment before the beam time.

The different mechanical and vacuum pieces of the chamber have been manufactured in Portugal and are about to be shipped to CERN, where the whole chamber will be assembled. Testing will take place during the next months so that the chamber will be fully operational for the 2007 beam times.

2c) CCD detector for ultra-low energy electrons

In 2005 a position-sensitive CCD detector system, developed at the Max Planck Institute for Extraterrestrial Physics in Garching [28], has been acquired by the University of Göttingen. The 3×1 cm^2 sized detector is based on a 300 µm thick *pn*-Si CCD consisting of 200×64 pixels of size 150×150 µm. Figure 5 shows the detection system mounted in its chamber, which will be attached to the new Göttingen sample chamber by means of the vacuum valve visible in the picture. During operation the CCD sensor needs to be kept at 180 K, which is accomplished by means of a Stirling cooler. The effective dead layer of this detector is extremely thin and corresponds to only 200 Å of Si. Due to the small pixel size in combination with the low operating temperature of 180 K, the noise per pixel is 4-5 e^- rms only. Note that the readout of the CCD is not triggered by incoming radiation but initiated externally with a fixed periodicity. Despite the fact that the required readout time is 4.5 ms, effective count rates in the kHz range can be realized since, due to the large number of pixels and their small size, it can be tolerated that prior to each readout many pixels have responded to incoming radiation.

The system was previously tested for its response to the X-rays and conversion and Auger electrons of ^{111}In [27]. The tests confirmed the excellent energy resolution of the device (~500 eV for photons and ~1 keV for electrons around 20 keV, and ~3 keV for electrons

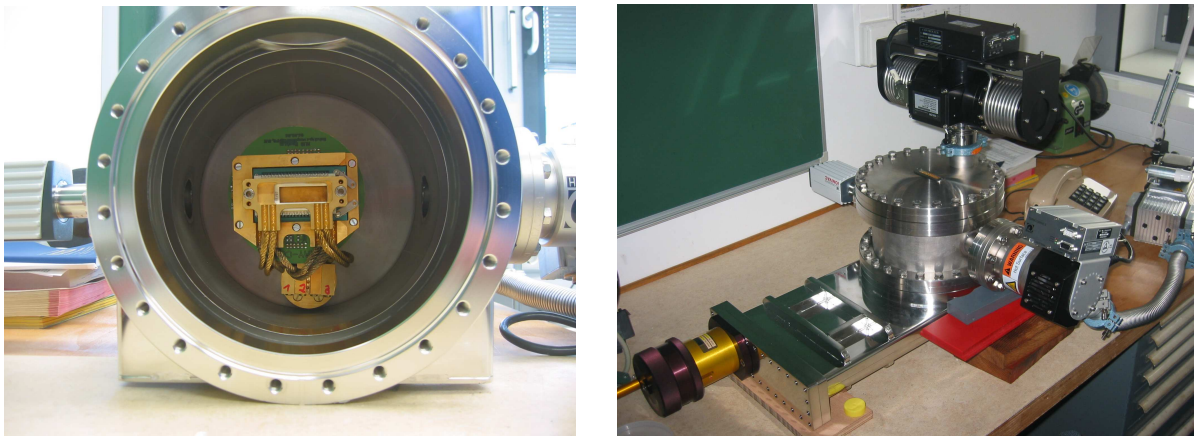

Figure 5: (left) Photograph showing the CCD detection system mounted in its chamber as it is seen by the sample. The rectangular-shaped 3×1 cm^2 sized sensor is visible in the center of the flange.
(right) Photograph showing the whole CCD detector chamber, which will be coupled to the Göttingen on-line channeling sample chamber via the valve visible at the bottom. The Stirling cooler used to maintain the detector operating temperature at 180 K is visible at the top of the picture.

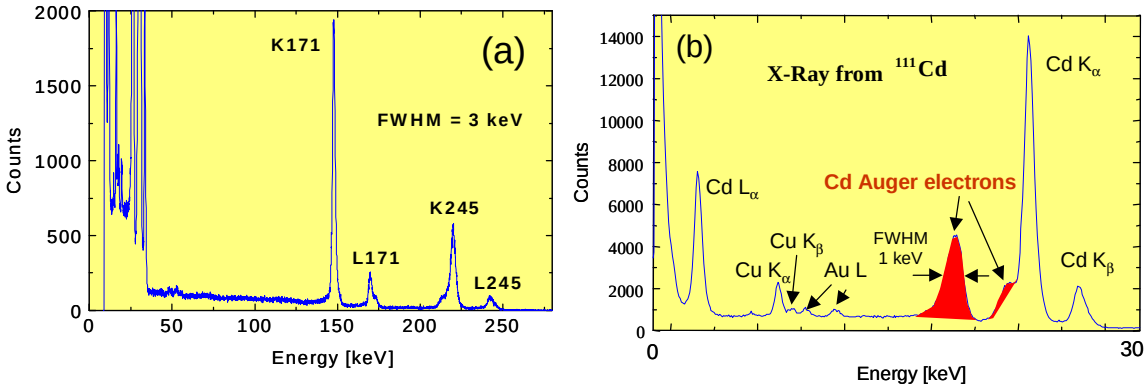

Figure 6: (a) Complete energy spectrum of ^{111}In as measured with the CCD detector, showing K and L conversion electrons between 150 and 250 keV.
(b) Low-energy part of the ^{111}In spectrum, showing the Cd X-rays and Auger electrons clearly separated. The Cu and Au X-rays, which are also visible, are caused by fluorescence processes in the detector housing and cryoshield.

around 200 keV) and its low energy capabilities. Such good energy resolution is essential, for instance, in order to separate Auger electrons and X-ray signals around 20 keV, as is shown in Fig. 6(b) for the case of Cd Auger electrons and X-rays from ^{111}In. The lower energy limit for electron detection with this detector has not yet been fully determined (which forms part of the current proposal) but lies certainly well below 18 keV.

2d) The Göttingen on-line emission channeling chamber

This chamber is a modified version of the emission channeling setup that was used by the University of Göttingen group until the year 2000 for on-line experiments at ISOLDE (experiment IS342). The major modification consists in adding the possibility to connect the CCD detector under an angle of 90° from the incoming beam, while keeping the major features of the chamber, i.e. a 1 mm collimator close to the sample and a port for a position-sensitive α detector under 18° backward angle geometry from the incoming beam. The special feature of this setup is that it is equipped with a high-precision, remote-controlled 3-axis goniometer with *x*,*y*,*z* stage, which allows samples to be reproducibly rotated along 2 tilt and 1 azimuthal axis of rotation from a distance. The setup will be transferred from Göttingen to CERN in 2007 and is to be used for experiments involving the CCD detector and the ^{8}Li lattice location experiments requiring position-sensitive detection of α particles.

3) Physics case

It is clear that the ability to use short-lived isotopes in emission channeling provides many opportunities for a wide range of new experiments. In the following we will present three examples, which we propose as initial fields of work on account of the fact that the related physics addresses currently relevant issues in materials science and will be well-embedded in ongoing research projects at our home institutes.

3a) Lattice location of transition metals in semiconductors

This represents an extension of the topics addressed by the previous experiment IS368, which studied the lattice location of ^{59}Fe (45 d), ^{67}Cu (61.9 h), and ^{111}Ag (7.45 d) in semiconductors. In the original proposal for IS368 it was stated:

"The behavior of transition metals (TMs) in semiconductors has been studied extensively throughout the last 40 years. From the viewpoint of fundamental semiconductor physics, transition metals represent model systems for deep impurities, i.e. impurities which have energy levels deep in the band gap of the semiconductor. Deep impurities are unsuited as electrical dopants but act as recombination centers, thus controlling the life time of excited charge carriers. From the viewpoint of applied physics, most transition metals are a major source of concern in semiconductor processing. Fe, Ni and Cu are of particular relevance because these elements passivate acceptors and are relatively abundant. Due to the fact that they are very fast interstitial diffusers in Si [E_M(Fe)=0.68 eV, E_M(Ni)=0.47 eV, E_M(Cu)=0.43 eV], which easily penetrate through whole wafers, even traces of Fe, Ni or Cu present severe difficulties in the fabrication of Si integrated circuits (ICs), and they are among the most-feared contaminants."

While this motivation to study transition metals remains still valid today [31-33], also new applications of TMs in the field of diluted magnetic semiconductors have emerged, which will be discussed in more detail below. Before addressing this point, we may add that IS368 was able to contribute considerable new information by assessing the lattice sites of Fe, Cu and Ag in a variety of semiconductor materials [8-24]. Most thoroughly studied were Si, GaN and ZnO, and in many cases significant differences were found between the lattice sites of these three TMs. For instance, in the case of Si, as a function of annealing temperature Fe was found consecutively on near-substitutional, near-tetrahedral interstitial and ideal substitutional sites (Fig. 7) [20, 24]. Cu in Si, on the other hand, was only seen on near-substitutional and ideal substitutional sites [8-11, 24] with lower thermal stability than Fe, while Ag was detected on near-substitutional and near-tetrahedral interstitial sites [13]. In zinc oxide Fe, Cu and Ag were always found on substitutional Zn sites, however, while Fe was showing near perfect

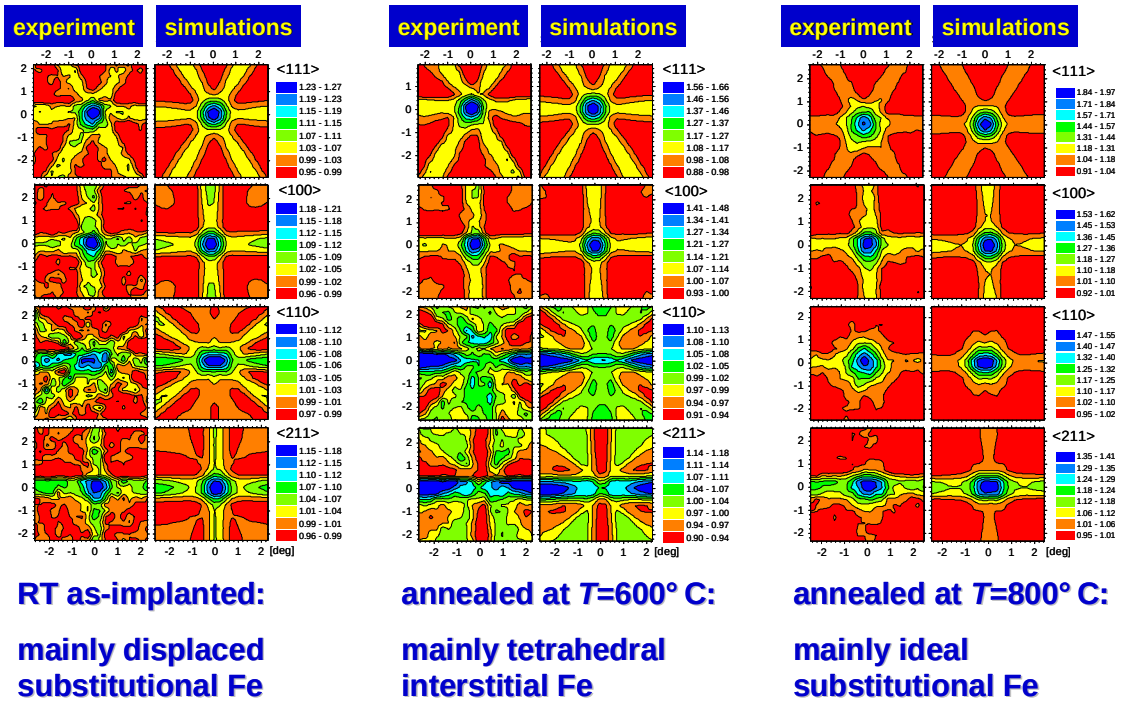

Figure 7: Experimental and simulated emission channeling patterns from ^{59}Fe in Si in the as-implanted state (left), and following annealing at 600°C (center) and 800°C (right). In each case the left column are experimental results along the four major axial directions <111>, <100>, <110> and <211>, while the columns to the right show the best fit of simulated emission patterns to the experimental data. As a function of annealing temperature, the majority of Fe atoms is consecutively found on three different lattice sites as indicated [20 ,24].

incorporation on Zn sites [19], Cu [18] and Ag [17] exhibited large rms displacements from the ideal Zn positions. These results show that, although there are common features in the behaviour of the transition metals in semiconductors, there exist also considerable differences, making it worth while to extend these studies by investigating also Ni and Co, which will now be possible by using the short-lived isotopes ^{65}Ni ($t_{1/2}$=2.5 h) and ^{61}Co ($t_{1/2}$=1.6 h).

While the study of the transition metals Ni and Co will also be addressed in Si, we will concentrate, however, to a large extent on the wide band gap semiconductors GaN and ZnO, due to the following reasons. Room temperature ferromagnetism in semiconducting materials is an important feature for the realization of future spintronic devices and has already been reported for a number of transistion-metal doped semiconductor systems based on GaN and ZnO [34-38], so-called dilute magnetic semiconductors. However, the nature of the ferromagnetism is poorly understood. As a matter of fact there are reasons to believe that "*conventional super-exchange or double-exchange interactions cannot produce long-range magnetic order at concentrations of magnetic cations of a few percent*" and that these systems hence "*challenge our understanding of the magnetism in solids*" [39]. It was suggested by the same authors that "*ferromagnetic exchange in dilute magnetic ZnO and nitrides is mediated by shallow donor electrons that form bound magnetic polarons. … However, there is growing evidence of another source of magnetism in dilute magnetic oxide films, besides the cations with d-electron character. The tell-tale symptom is that the moment per cation can exceed the spin-only value in the dilute limit. … This suggests that defects introduced at film/substrate interface are always involved.*" Such defect-mediated interaction would also constitute a new type of ferromagnetism. However, one of the key unanswered questions is whether the "*materials indeed contain uniformly distributed transition-metal elements or contain clusters, precipitates or second phases that are responsible for the observed magnetic properties*" [38]. One review on the subject states in its conclusions: "*In particular, methods … that establish lattice location or chemical state should be applied in order to give more insight into possible mechanisms for the observed ferromagnetism*" [36]. It has consistently been pointed out that a successful explanation cannot be reached without a detailed understanding of the structural properties of the doped materials [34-38].

For most studies reported in the literature, dilute magnetic semiconductors have been produced by introducing the dopant during growth, for instance during bulk crystal growth, or by means of molecular beam epitaxy (MBE) or metal-organic chemical vapour deposition (MOCVD) of single crystalline layers, or sputter deposition or pulsed laser deposition (PLD) of thin polycrystalline layers. However, ion implantation is becoming an increasingly important tool in that respect [34-38]. The advantage of ion implantation is that it is less likely to suffer from clustering or the formation of second phases and hence may be superior with respect to the realization of single-crystalline magnetic layers. This is due to the fact that during the implantation process itself the ions have a very low probability for reacting with each other while the formation of clusters during thermal annealing can be controlled by optimizing the thermal budget versus the diffusion coefficients of the implants.

Our proposed emission channeling studies will be the first detailed lattice location experiments of Ni and Co in semiconductors. In a later stage of the proposal, it is planned to also investigate samples that have been pre-implanted with stable Ni or Co up to the % range. Similar experiments were started using the probe atom ^{59}Fe (45 d) this year (still within the scope of IS368) and offer the opportunity to combine lattice location studies and magnetic characterization methods of the same sample. We would like to continue these studies, too, and hence ask also for some shifts of the isotope ^{59}Mn (4.6 s) $\rightarrow$ ^{59}Fe (45 d).

Proposed experiments: We propose to study the lattice location of Ni and Co in Si, ZnO and GaN by means of β^- emission channeling using the short-lived isotopes ^{65}Ni ($t_{1/2}$=2.5 h) and

^{61}Co ($t_{1/2}$=1.6 h). While ^{56}Ni can be directly obtained at ISOLDE from Ni-RILIS laser ion sources, ^{61}Co is to be implanted via the precursor isotope ^{61}Mn, exploiting the decay chain ^{61}Mn (0.71 s) $\rightarrow$ ^{61}Fe (6 min) $\rightarrow$ ^{61}Co. These experiments will make use of the newly developed on-line setup from ITN/CFNUL and the self-triggered position-sensitive Si pad detector system. Some shifts of the isotope ^{59}Mn (4.6 s) $\rightarrow$ ^{59}Fe (45 d) are also requested in order to continue lattice location studies in GaN and ZnO samples pre-implanted with stable isotopes of ^{56}Fe, in combination with magnetic characterization techniques.

3b) Lattice location of Mg in GaN

Mg is the most-commonly used *p*-type dopant in the technologically important wide band gap semiconductor GaN [40, 41]. Practically all applications of GaN involving *pn*-junctions such as blue laser diodes or LEDs and high-frequency power diodes rely on Mg doping. It is often assumed that Mg as a group II alkali element is electrically active as *p*-type dopant in the III-V material GaN once it occupies substitutional Ga sites. However, no lattice location studies on Mg are available. In particular, there is no knowledge to what extent it is possible to incorporate Mg on Ga sites by means of ion implantation, and what influence the post-implantation annealing temperature has on the lattice site occupancy of Mg. In electrical studies it was found that only around 1% of implanted Mg in GaN could be electrically activated as an acceptor [41]. However, it is unknown whether the large electrically inactive fraction is caused by Mg occupying other lattice positions than substitutional Ga (e.g. interstitial sites), by electrically active compensating defects resulting from ion implantation, or by other effects such as additional electrically active impurities [40]. Detailed lattice location studies of implanted Mg in GaN certainly could contribute to exploring the possibilities for ion-implantation doping of GaN. Emission channeling experiments using the short-lived isotope ^{27}Mg ($t_{1/2}$=9.46 min) are the only feasible lattice location technique for Mg, since it cannot be detected in GaN by means of Rutherford Backscattering, and only with difficulties by Particle Induced X-ray Emission (PIXE) or Nuclear Reaction Analysis.

Proposed experiments: We propose to study the lattice site of implanted short-lived ^{27}Mg ($t_{1/2}$=9.46 min) in GaN by means of β^- emission channeling. This experiment will make use of the newly developed on-line setup from ITN/CFNUL in combination with the Göttingen 3-axis goniometer, and the self-triggered position-sensitive Si pad detector system.

3c) Lattice location of Li in ZnO

ZnO is a technologically promising II-VI semiconductor which has the same hexagonal wurtzite structure and similar properties as GaN. As was the case in the beginning of GaN technology, reproducible *p*-type doping is now a major obstacle in the way of realizing ZnO based devices. The alkali metal Li is one of the impurities which are currently discussed as possible *p*-type dopants in ZnO [42-45]. As early as 1960 it had already been proposed that Li exists in ZnO not only as substitutional acceptor impurity on Zn sites but also in an interstitial donor form, and that Li would therefore be an amphoteric impurity [46]. Although this hypothesis was recently backed up by theoretical considerations [42, 43], to date no direct experimental proof of the existence of interstitial Li in ZnO is available, neither is it known which of the various interstitial sites in the wurtzite structure (T, H, O, AB etc. sites) is possibly preferred by Li.

In the past, the lattice location of Li has been successfully studied at ISOLDE by means of α emission channeling of ^{8}Li ($t_{1/2}$=838 ms) in a variety of semiconductors including Si, Ge, diamond, SiC, GaAs, AlGaAs, GaP, InP, InSb, ZnSe, ZnTe, CdTe, AlN and GaN (see e.g. [1-

3, 47]). One of the major conclusions drawn from these studies was that Li which is implanted at low temperatures occupies preferentially interstitial lattice sites, but in a certain transition temperature regime, related to the onset of interstitial Li diffusion, changes its lattice site. Remarkably, in all investigated III-V and II-VI compound semiconductors a site change from interstitial sites to substitutional cation sites was observed. In the case of GaN, which has very similar properties to ZnO, the site change occurred around 700 K [Dalmer 98], and we hence predict a similar behaviour for Li in ZnO. Our proposed emission channeling experiments of ^{8}Li in ZnO are therefore expected to unambiguously establish the existence of both interstitial Li_i and substitutional Li_{Zn} in ZnO, identify the preferred interstitial site of Li_i, and also yield valuable results on its diffusion behaviour.

Proposed experiments: We propose to study the lattice sites of implanted ^{8}Li (838 ms) in ZnO by means of α emission channeling as a function of implantation temperature between 50 K and 800 K. This experiment will make use of the on-line setup and the position-sensitive α detection system from the University of Göttingen, as previously used in IS342.

4) Test isotopes

A number of isotopes (Table 1) are requested in order to characterize the detector response to low-energy electrons below 40 keV and to investigate the possibilities to use such electrons for lattice location purposes. Such experiments will initially only be carried out with single-crystalline samples of reliably good crystalline and surface quality, for instance Si. In order to achieve a shallow implantation depth, which is crucial in order to minimize dechanneling of the low-energy electrons, we would occasionally ask for ISOLDE operation at 30 kV.

The isotopes foreseen for that purpose are chosen according to the criterium that they decay by electron capture (EC) or internal transition (IT) decays (in order to have no β background), and that they emit both low-energy and high-energy electrons. This will allow emission channeling data from low-energy electrons (conversion electrons and/or Auger electrons) to be compared directly to the well-established case of higher-energy conversion electrons.

A question of fundamental interest in that respect is the issue whether Auger electrons exhibit suitable channeling effects for lattice location purposes. High fractions of Auger electrons generally accompany radioactive decays that involve hole creation in inner atomic shells, e.g. electron capture (EC) decays or conversion electron (CE) emission. Note that, in contrast to conversion electrons which are emitted from the site of the nucleus as a result of direct electromagnetic interaction of the nucleus with the electron cloud, the emission of Auger electrons is an atomic process which follows the creation of a hole in one electron shell and is an alternative to X-ray emission. Auger electrons hence do not originate from the site of the nucleus and this should be reflected in their channeling patterns. Of practical interest in our case are only Auger processes where an initial hole in the K-shell is filled by an outer shell electron and simultaneously a second outer shell electron ejected, i.e. KLL, KLM, KMM etc Auger electrons. We note that it is well known that Auger electrons exhibit channeling effects. In Auger spectroscopy this is termed "enhanced forward scattering" [48, 49] rather than using the term "channeling". The fundamental question we want to answer is to what extent the effect can be used for foreign atom lattice location.

Proposed experiments: We propose to investigate the possibilities of using low-energy electrons (< 40 keV) for emission channeling lattice location studies using the test isotopes ^{67}Ga, ^{73}As, ^{111}In, ^{117m}Sn and ^{119m}Sn. Of particular interest is the issue whether Auger electrons

exhibit suitable emission channeling effects. These off-line experiments will utilize both the CCD detector and the self-triggered position-sensitive Si pad detector systems.

Isotope	$t_{1/2}$	decay	electron energy [keV]	fraction	electron type
^{67}Ga	3.26 d	EC	7-10 84	0.616 0.278	Auger CE
^{73}As $\rightarrow^{73m}$Ge	80.3 d $\rightarrow$0.499 ms	EC IT	8-10 12-13 42 52	0.876 0.737 0.760 0.133	Auger CE CE CE
^{111}In	2.8 d	EC	19-25 145 168 219 242	0.150 0.085 0.013 0.050 0.010	Auger CE CE CE CE
^{117m}Sn	13.6 d	IT	20-25 127 129 152 155	0.110 0.663 0.119 0.274 0.091	Auger CE CE CE CE
^{119m}Sn	293 d	IT	19 20-21 23 24-25 36 61-66	0.614 0.094 0.134 0.043 0.324 0.708	CE Auger CE Auger CE CE

Table 1: Suitable isotopes in order to test the possibility for low-energy electron emission channeling experiments. EC = electron capture, IT = internal transition, fraction = average number of electrons of this type emitted per decay, CE = conversion electrons, Auger = Auger electrons involving K shell holes (KLL, KLM, KMM etc.).

5) Beam request and experimental requirements

We request a total of 35 shifts over a period of 2-3 years for the isotopes specified below in Table 2. All requested targets are standard ISOLDE targets and the beam times can hence be shared with other users. While the yields of most isotopes are known from previous runs, the yields of ^{65}Ni, ^{61}Mn and ^{27}Mg have been taken from the ISOLDE yield data base, updated by information from Th. Stora and U. Köster. As is visible from the table, the yields are in most cases around or above 10^7 atoms/s/μA and should hence present little problems. The only exception is ^{61}Mn, however, in this case we intend to work on the Central beam line in parallel with the Mössbauer experiment IS443, which uses ^{57}Mn for extended time periods in GLM. Therefore both experiments could benefit from the Mn beams at the same time and thus make our experiments feasible without the request for an excessive number of shifts.

For the majority of our runs 60 kV would be the preferred acceleration voltage, while for implantations of the low-energy electron emitting isotopes occasionally ISOLDE operation at 30 kV would be requested.

For the short-lived isotopes, connection of an on-line setup to a position along one of the beam lines is needed, either on GLM or to a position on the Central beam line. As already mentioned, for the runs with ^{61}Mn an implantation position on the Central beam line is requested, since this would allow us to implant ^{61}Mn in parallel with the Mössbauer experiment IS443 using ^{57}Mn on GLM. The time needed for setup of the equipment before the run is one day, and half a day after the run for dismounting.

For implantation of the longer-lived test isotopes, we would use the standard solid-state physics implantation chamber and the corresponding measurements will be done off-line with the emission channeling setups located in our part of the ISOLDE laboratory for radioactive off-line experiments in building 275.

isotope	number of shifts	target	ion source	minimum yield [atoms/s/μA]
^{65}Ni (2.5 h)	7	UC_2-W	RILIS Ni	5×10^7
^{61}Mn (4.6 s) $\rightarrow$ ^{61}Fe (6 min) $\rightarrow$ ^{61}Co (1.6 h)	5	UC_2-W	RILIS Mn	2×10^6
^{59}Mn (0.71 s) $\rightarrow$ ^{59}Fe (45 d)	5	UC_2-W	RILIS Mn	10^8
^{27}Mg (9.5 min)	5	UC_2-W	RILIS Mg	10^7
^{8}Li (838 ms)	5	Ta	W surface ioniz.	10^7
^{67}Ga (3.26 d)	2	ZrO_2 or Nb foil	Hot Plasma or W RILIS Ga	10^7
^{73}As (80 d)	2	ZrO_2 or Nb foil	Hot Plasma	10^8
^{111}In (2.83 d)	2	UC_2-W	surface ioniz.	2×10^7
^{117m}Sn (13.6 d)	1	UC_2-W- or LaC	RILIS Sn	10^8
^{119m}Sn (293 d)	1	UC_2-W- or LaC	RILIS Sn	10^8
	Total: 35			

Table 2: Requested isotopes, number of shifts, targets, ion sources and minimum yield requirements.

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