EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

21st April 2008

Proposal to the ISOLDE and neutron Time-of-Flight Experiment Committee

Fast-timing studies of nuclei below ^{68}Ni populated in the β-decay of Mn isotopes

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Abstract

We intend to investigate structure of nuclei populated in the β-decay of Mn isotopes via the ATD $\beta\gamma\gamma$(t) technique. With this method we will measure dynamic moments in Fe isotopes and their daughters in order to characterize the role of particle-hole excitation across the N=40 sub-shell closure and the development of collectivity.

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1 Introduction

One of the major challenges in nuclear physics is understanding the modification of shell structure when moving out from stability. During the last years exotic nuclei with large N/Z ratios have been extensively studied with both theoretical and experimental approaches. The expectation is that the change of shell structure may lead to the disappearance of the stable magic numbers and the appearance of new ones. One of the most conspicuous examples is the weakening and eventual vanishing of the N=20 shell gap in the island of inversion around ^{32}Mg. The structure away from stability, and in particular the presence of deformed ground-state configurations, comes as a consequence of the lowering of states from higher lying shells that, in these exotic conditions, intrude in the normal lower lying shells. This is not only due to shifts in the single particle energies but also to the interaction between the valence nucleons in the proton or neutron shells and to the interaction between valence protons and neutrons. A proper understanding of these effects requires detailed information on the nuclear structure of chains of nuclei across the regions of interest.

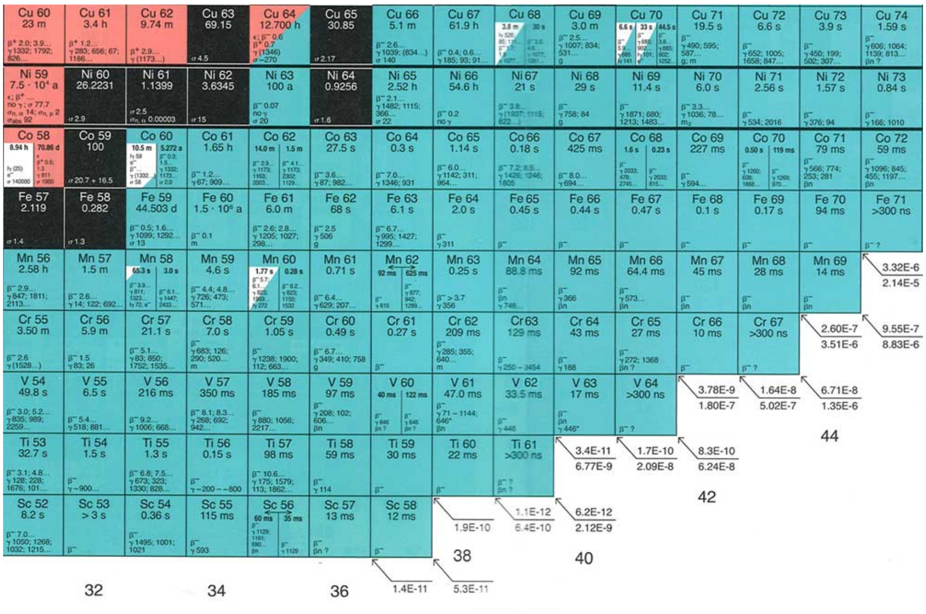

Figure 1: The region of nuclei around N=40 and below Z=28 where the ATD $\beta\gamma\gamma$(t) technique will provide structural information by the determination of dynamic moments

With this aim we propose to undertake the study of neutron rich nuclei near $^{68}_{40}$Ni populated in the β-decay of Mn isotopes. The experiment is ideally suited for the ISOLDE facility, where good quality n-rich Mn beams with intensities appropriate for fast-timing studies up to ^{67}Mn, are delivered. We propose the Advanced Time-Delayed (ATD) $\beta\gamma\gamma(t)$ technique [1, 2] to measure dynamic moments in Fe (and daughter nuclei) for transition de-exciting states populated in the β-decay of n-rich Mn isotopes. The technique is well established at ISOLDE and has shown its complementarity to other experimental approaches employed at the facility, for instance Coulomb excitation or hyperne interaction methods. ATD measurements have already provided key information on a number of exotic nuclei, helping elucidate their observed low-energy structure. Recent applications include nuclei in the Mg island of inversion and nuclear systems a few nucleons away from the doubly magic ^{132}Sn.

2 Nuclei below $^{68}_{40}$Ni

The region of interest is shown in Figure 1. For ^{68}Ni, with 28 protons and 40 neutrons, the N=40 neutron sub-shell gap has been established based on the high energy of the first 2^+ state above 2 MeV and the small B(E2) rate for the transition to the first 0^+ state [3]. Yet collective effects around N=40 have been described both for nuclei above and below Z=28. Neutron-rich nuclei below ^{68}Ni are particularly interesting due to the competition of several effects affecting the N=40 gap between the $p_{3/2}f_{5/2}p_{1/2}$ and $g_{9/2}$ neutron orbitals.

For even-even nuclei the systematics of the first 2^+ state energy and the B(E2; $2^+ \rightarrow 0^+$) values is illustrated in Figure 2 for Cr, Fe, Ni and Zn isotopes. In nuclei above $_{28}$Ni, like $_{30}$Zn [4, 5, 6], there is a decrease of the 2^+ energies and an enhancement of the B(E2; $2^+ \rightarrow 0^+$) values when moving from N=38 to N=44. The situation is less clear for nuclei below $_{28}$Ni, and for $_{26}$Fe isotopes in particular, where there is a decrease in the 2^+ energies but there is a lack of experimental information on the B(E2; $2^+ \rightarrow 0^+$) values. As pointed out in [7] the energy ratio of the 4^+ and 2^+ energies does not increase as expected when quadrupole collectivity is increasing.

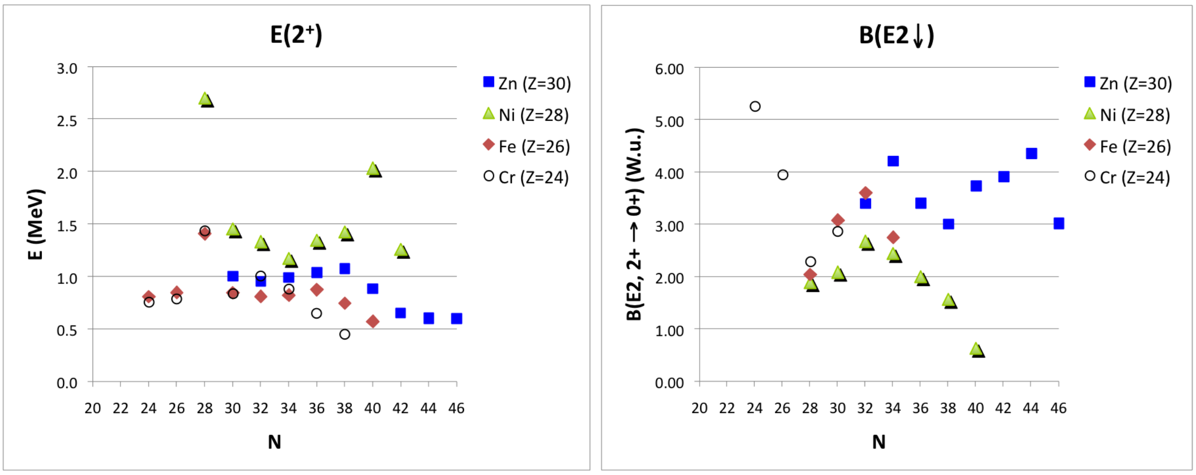

Figure 2: Systematics of the 2^+ energies (in MeV) and B(E2↓; $2^+ \rightarrow 0^+$) values (in W.u.) for Cr, Fe and Ni nuclei (Z=24, 26 and 28, respectively) as a function of the neutron number (N). The data are taken from [4, 5, 6, 7, 8, 9, 10, 11].

For odd-A Fe isotopes there is scarce information on the level schemes and virtually no information on the possible short half lives of excited states. The $g_{9/2}$ neutron orbital plays a crucial role in the evolution of these isotopes since it governs the relative position of the negative parity $p_{3/2}f_{5/2}p_{1/2}$ and positive-parity $g_{9/2}$ states. A summary of the decay schemes for odd-A ^{59,61,63,65}Mn is shown in Figure 3.

Two counteracting effects contribute to the observed features in the region. On the one hand recent calculations performed with an effective interaction labelled GXPF1A [12] use a reduced $\pi f_{7/2}$ - $\nu f_{5/2}$ monopole interaction when protons are being removed from the $f_{7/2}$ shell, in combination with a strong spin-orbit splitting for the $\nu p_{3/2}$-$p_{1/2}$ orbitals to reproduce the observed experimental 2^+ energies for even-even Ti and Cr isotopes just above N=28. The spin-orbit effect is predicted to debilitate when more neutrons are added, due to the increased diffuseness of the neutron surface. In the case of exotic nuclei around N=40 this would lead to a reduced splitting of the $\nu p_{3/2}$-$p_{1/2}$ and of the $\nu g_{9/2}$-$g_{7/2}$ orbitals and thus an enhancement of the N=40 sub-shell.

On the other hand, the proton-neutron tensor interactions act in the opposite direction. The repulsion between the $\nu g_{9/2}$ and the $\pi f_{7/2}$ orbitals and the attraction between the $\nu g_{9/2}$ and the higher lying $\pi f_{5/2}$ (above Z=28) has the overall effect of a weakening of the N=40 (and Z=28) shell gaps. The latter is reflected in the quadrupole deformation, since the energy of the two first Nilsson sub-states of the $g_{9/2}$ orbital decrease as the deformation increases.

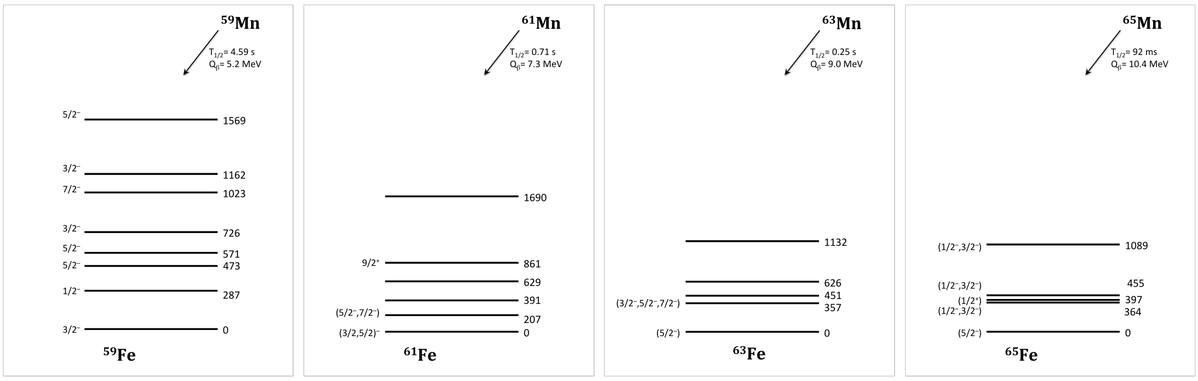

Figure 3: Decay schemes of ^{59,61,63,65}Mn isotopes. The data are taken from references [10, 13, 14]

The interplay between these opposite effects can be only elucidated with a systematic study of n-rich nuclei around N=40, and specifically those below Z=28. Furthermore, the filling of neutrons in the positive-parity $0g_{9/2}$ orbital and in underlying pf-shell negative orbitals ($p_{3/2}$, $f_{5/2}$, $p_{1/2}$) gives rise to states with opposite parity and high difference in J quantum number. This leads to forbidden electromagnetic transitions and the presence of long-lived nuclear states[1)]. The ATD $\beta\gamma\gamma$(t) technique [1] gives access to lifetimes of such states in the nanosecond and subnanosecond regime and key information on the nuclear structure. The knowledge of the region and the input to effective interactions will undoubtedly improve with new experimental information on dynamic moments.

3 Experimental details

A recent accepted proposal at ISOLDE [14] aimed at the study of n-rich Fe isotopes and decay products via beta-gamma spectroscopy using a novel event correlation method based on retarded coincidences with digital electronics. As mentioned above we propose to complement such experiment with the investigation of lifetimes in Fe nuclei and daughter products populated in the decay of Mn isotopes. Sizable P_n branches have been observed for the heavier Mn nuclei. The direct β-decay of ^{A}Mn and the β-delayed neutron emission $^{A+1}$Mn can populate complementary levels in Fe due to the selection rules.

Our ATD setup is optimized for excellent timing resolution and good efficiency with a specially designed beta detector and timing scintillator crystals in close geometry. We propose to use an array of five detectors similar to what is shown in Fig. 4: a fast plastic scintillator for beta detection, two fast $LaBr_3$(Ce) timing crystals and two large HPGe detectors. Apart from the $\gamma - \gamma$ coincidences providing information on the level schemes, the $\beta\gamma\gamma$(t) coincidences yield the lifetimes of the excited states in the nanosecond and subnanosecond range, selected by a given decay branch. A precision down to a 1-2 ps is reachable in the most favourable situations.

1) Isomers have been observed in the region with lifetimes of up to hundreds of ms.

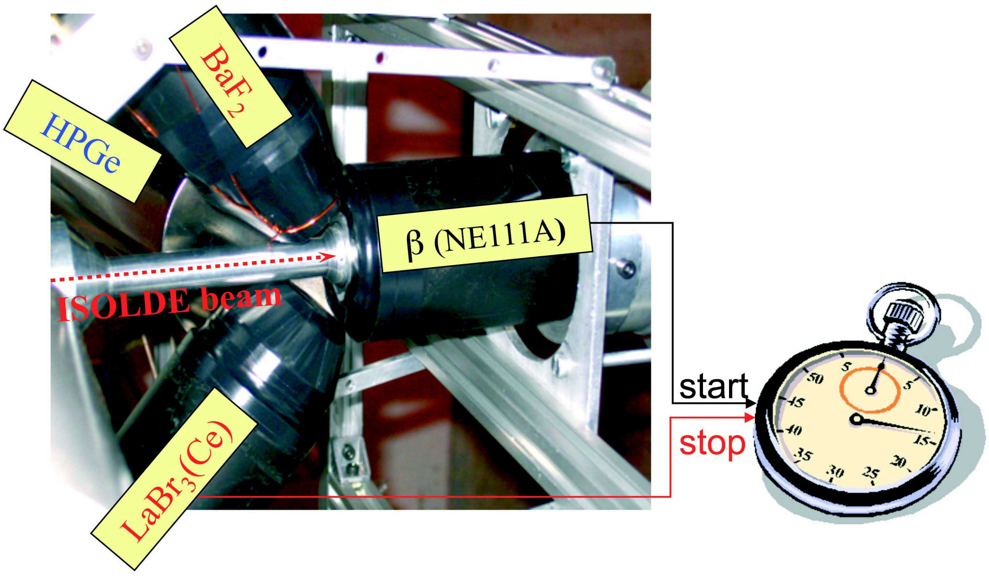

Figure 4: A photograph of a compact ATD setup used in β-decay studies at ISOLDE.

In a short beam test performed at ISOLDE in June 2006 the decay of neutron-rich $^{59-66}$Mn isotopes could be tested with fast timing detectors. A standard UC_x target unit and the RILIS was used. The test lasted for about 3 hours but it showed the possibilities of the application of the ATD method in the region. Many of the lifetimes of interest in these nuclei, corresponding to the first few excited states, are in the range of 5-25 ps and therefore good statistics and good timing data quality is needed to reach meaningful results. We provide below a couple of examples to illustrate the capability of the method.

During the test data were collected on A=63; β-γ coincident events were accumulated for around 270 s whereas data-taking on β-γ-γ coincidences lasted roughly 1000 s. With this low intensity a frist coincidence analysis could be performed [15]. An example is shown in Figure 5, where the beta-gated Ge-Ge coincidence spectrum gated on the ^{63}Mn 424 keV line is plotted. Coincident gamma lines at 93, 357, 451 and 658 keV lines clearly show up. The preliminary level scheme obtained from γ-γ coincidences is shown in Figure 6. The beta decay mostly feeds the low-lying 357, 451 and 1132 keV states.

A preliminary analysis of the timing spectrum has been also performed. The beta-$LaBr_3$ timing spectrum selected on the 357 keV line is shown in Figure 5. It presents two timing components: one of them corresponds to $T_{1/2}$=110 ps for the 357 keV level and the longer one to $T_{1/2}$=780 ps for the 451 keV level. From these preliminary values reduced transition probabilities for the de-exciting transitions of these two levels can be obtained. From the values obtained and the B(Xλ) systematics of the region we find that the 357 keV and 93 keV transitions are probably of M1 character, whereas the 451 keV line is most likely E2. This would point to a spin sequence $1/2^-$ - $3/2^-$ - $5/2^-$ for the ground, 357 keV and 451 keV states, in concordance to what is observed in ^{57}Fe. For a full investigation of this nucleus data with higher statistics are needed, in particular to perform β-γ-γ triple coincidence analysis. We estimate in 2 shifts the required amount of beam time to study this nucleus. A similar situation is expected for the other odd-A Fe nuclei, for which timing information will be also of great value.

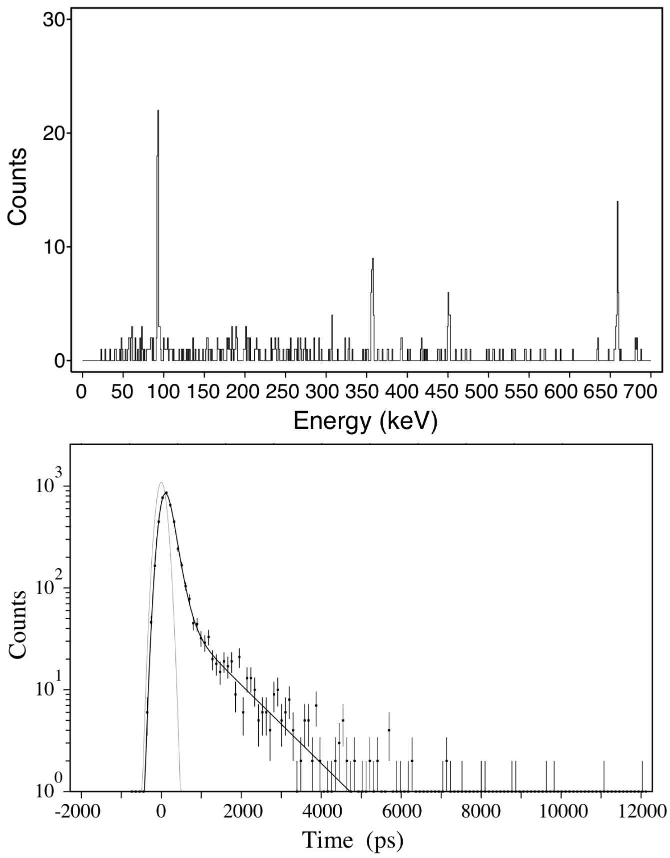

Figure 5: Analysis of ^{63}Mn data from [15]. (Above) Beta-gated Ge-Ge coincidence spectrum gated on the 424 keV line in ^{63}Mn. (Below) Beta-LaBr$_3$ timing spectrum selected on the 357 keV line. Two timing components clearly show up, see text for details.

The second example is is ^{66}Fe, a case of specific interest where the ATD method can yield important results. In [10] neutron-rich Mn nuclei up to ^{69}Mn were measured; in particular candidates for the 2^+ states in ^{64,66}Mn were identified, and later confirmed by in-beam studies [16]. The 2^+ state was found lower in excitation as compared to ^{64}Fe (and ^{62}Fe), following the trend of other isotopic chains below Z=28 like Cr nuclei (see Figure 2). This points towards an earlier appearance of collectivity than in nuclei above Z=28 like Zn and Ge. As mentioned above this has not yet been confirmed by the reduced probability of the E2 transition to the 0^+ ground state and thus a direct measurement of the lifetime will provide very important information. The lower excitation energy makes it possible to measure the lifetime via the ATD method. If we take as a reference the value compiled for ^{60}Fe, which gives B(E2$\uparrow$; $0^+ \rightarrow 2^+$)=13.8(26) W.u., τ=11.6(22) ps, and we consider an increased B(E2$\uparrow$) value of $\sim$20 W.u. due to the enhanced collectivity, we obtain a mean lifetime for the 573 keV level in ^{66}Fe of the order of $\tau\sim$42 ps (T$_{1/2}\sim$30 ps). This should be well within reach by the centroid shift method. The beam time estimated to accomplish this measurement is 5 8-hour shifts.

4 Beam time request

Mn beams are produced at ISOLDE with standard UC$_x$ target units and ionisation with the selective RILIS. The Mn yields as given in [17] and quoted in the ISOLDE online yield user database [18] for a 1.0 GeV proton beam incident on a UC$_x$ 51 g/cm^2 target.

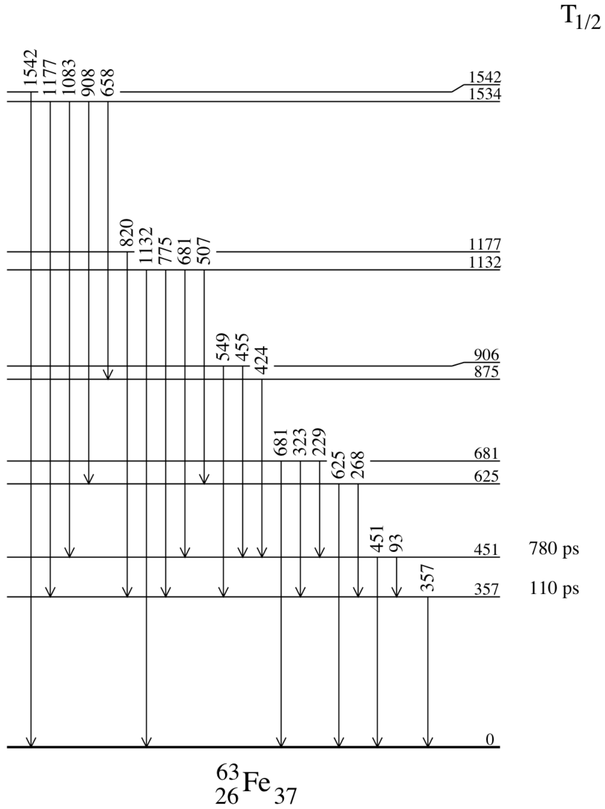

Figure 6: Preliminary level scheme of ^{63}Fe populated in the β-decay of ^{63}Mn [15]. Lifetimes in the subnanosecond regime have been found.

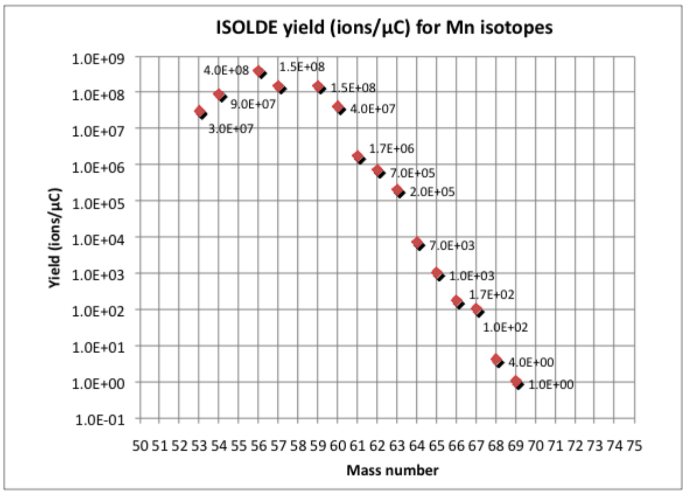

Figure 7: Yields of Mn isotopes from [17] as shown in [18]. The values are given in ions/μC for a 1.0 GeV proton beam incident on a UC_x 51 g/cm^2 target.

They are plotted in Fig. 7. For Mn isotopes closer to stability (for instance ^{57}Mn) higher yields than those quoted in the online database have been reached in the last few years. We expect the presence of surface-ionised Ga isobars in the Mn beams, but due to the different lifetimes of the Ga isotopes as compared to Mn (shorter below A=62 and longer above) it can be dealt with by a proper gating of the release. In the test performed in 2006 with low proton intensity the estimated yields up to ^{66}Mn are consistent with the database values. Based on the above we can estimate the beam time required for each isotope, with the proviso that the counting rate should not exceed 30 kcounts/s in the timing beta detector and 10 kcounts/s in the HPGe detectors. The requests are summarized in Table 1. The beam time would eventually start on the more exotic ^{66}Mn and then focus on lighter masses.

Table 1: Summary of requested beam time

Nuclide	Target	Ion source	Yield (ions/μC)	Shifts (8 hours)
Setup	UC$_x$	(WSI)		1
^{59}Mn	UC$_x$	RILIS	1.5E+08	1
^{60}Mn	UC$_x$	RILIS	4.0E+07	2
^{61}Mn	UC$_x$	RILIS	1.7E+06	2
^{62}Mn	UC$_x$	RILIS	7.0E+05	2
^{63}Mn	UC$_x$	RILIS	2.0E+05	2
^{64}Mn	UC$_x$	RILIS	7.0E+03	3
^{65}Mn	UC$_x$	RILIS	1.0E+03	4
^{66}Mn	UC$_x$	RILIS	1.7E+02	5
Calibrations	UC$_x$	(WSI)		2

In addition to the 21 shifts for Mn isotopes we request 2 shifts for precise timing calibrations and one shift for the optimization of the setup with radioactive beam. The total request is **24 8-hour radioactive beam shifts**. We would like to make use of the ISOLDE VME DAQ and CERN data storage system.

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