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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Seeking the Purported Magic Number $N = 32$ with High-Precision Mass Spectrometry

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Abstract: Accounting for the appearance of new magic numbers represents an exacting test for nuclear models. Binding energies offer a clear signature for the presence (or disappearance) of shell closures. To determine the strength of the purported $N = 32$ shell closure, we propose using the Penning-trap spectrometer ISOLTRAP for mass measurements of $N = 34$ isotones ^{58}Cr ($Z = 24$), ^{55}Sc ($Z = 21$) and ^{54}Ca ($Z = 20$), as well as the $N = 32$ isotones ^{53}Sc and ^{52}Ca. We also propose measuring the mass of ^{60}Cr to test the shell model prediction of a new magic number at $N = 34$. In addition to the Penning-trap system at ISOLTRAP, we intend to use the newly commissioned multi-reflection time-of-flight mass separator, which enables direct mass measurements on nuclei with half-lives below 50 ms.

Requested shifts: We request 20 shifts using a UC (or YO) target with laser ionization. We request 7 additional shifts to develop the new technique of measuring short-lived species using the electrostatic isobar-separator stage of ISOLTRAP. To be scheduled in 3 separate runs.

1 Introduction

The nuclear shell model, a cornerstone of nuclear structure, was formulated from observations of particularly strong binding energies for shells that were filled to so-called "magic" numbers: 2, 8, 20, 28, 50, 82, and 126. With the advent of radioactive beam facilities, more exotic nuclear systems have now come under study with the surprising result that the magic numbers no longer seem to be magic.

The original case study for the disappearance of a magic number was that of $N = 20$ and the now-famous island of inversion, discovered from pioneering on-line mass spectrometry studies of sodium isotopes at CERN [1]. Instead of the increased binding energy (BE) normally associated with a closed shell, the derived two-neutron separation energies $S_{2n} = BE(Z,N) - BE(Z,N-2)$ exhibited an anomaly. Whereas a "normal" shell closure shows a kink at the magic number, the Na and Mg isotopes show no such kink at $N = 20$. Nuclear spectroscopy later revealed that the extra binding was due to deformation brought on by the inversion of so-called "intruding" pf orbitals that offered themselves for occupation. Shell model calculations using only the sd orbitals (following the "normal" quantum sequence) did not correctly account for the experimental results.

Aptly enough, not only have these magic numbers been found to exhibit disappearing acts far from stability, new magic numbers have also made apparitions (shell or sub-shell closures). This isospin-dependent re-ordering of the nuclear quantum states now points us to the improvements needed for a better theory of the nuclear interaction. A recent review article summarizes the copious collection of experimental and theoretical work and attests to the continued importance of monitoring the (dis)appearances of closed-shell effects for exotic nuclides [2].

In 2001, spectroscopy studies by Prisciandaro *et al.* [4] indicated that $N = 32$ was a new sub-shell closure for ^{56}Cr, given the relative maximum of its first 2^+ state energy. Evidence for the $N = 32$ sub-shell closure is also given by Coulex measurements on ^{56}Cr [3]. The small $B(E2)$ value for $N = 32$ shows that the collectivity of the 2_1^+ state in ^{56}Cr is significantly lower than that of neighboring isotopes and also indicates a sub-shell closure. This situation is illustrated in Fig. 1 (taken from [3]). Fig. 1 also shows theoretical predicitons (discussed in the next section), which have some difficulty explaining all of the experimental restuls.

More recent results from β spectroscopy by Crawford *et al.* [5] also support the $N = 32$ sub-shell closure for Ca.

The binding energy is decisive for the ordering of shell occupation and as such needs to be determined in order to corroborate interpretations regarding shell closures, as an example see [6]. As with the $N = 20$ case, it is instructive to study the two-neutron separation energies. More critically, the relative decrease of the two-neutron separation energy after the shell closure gives an indication of the strength of the shell closure. Since the relative energy scale is quite small (a few hundred keV) compared with the canonical shell strengths (4-5 MeV), the masses must be measured with a low uncertainty.

Measurements by ISOLTRAP of the ^{56,57}Cr masses pointed to a small enhanced binding effect possibly connected to a (sub-)shell closure [7]. In this proposal, we aim at a precision determination of the shell gap for ^{56}C, which requires a precision measurement of ^{58}Cr. In order to further explore the case of $N = 32$, we also propose measuring the masses of the

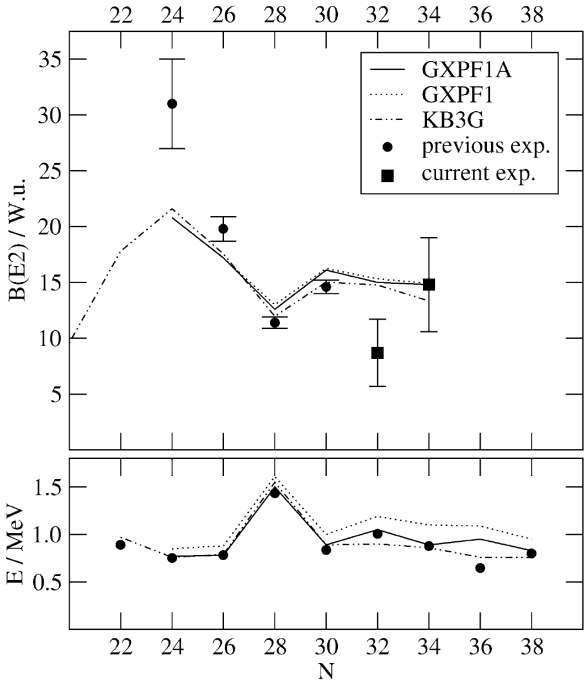
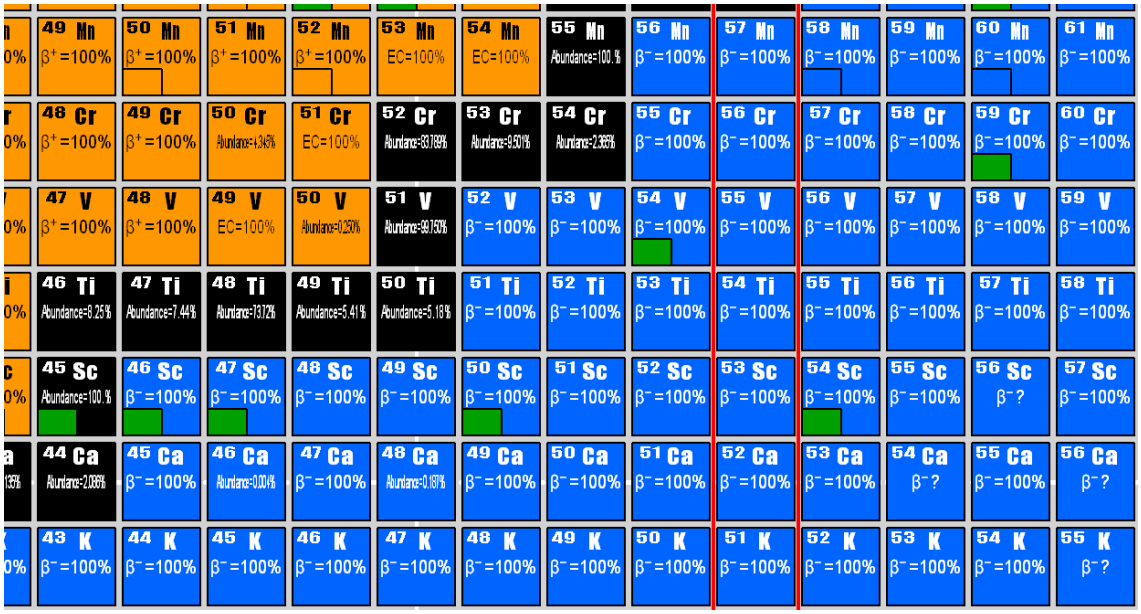


Figure 1: The experimental excitation energies $E(2_1^+)$ and the $B(E2, 2_1^+ \rightarrow 0^+)$ values for the Cr isotopes as a function of neutron number N are displayed. For details see text. Figure taken from [3].

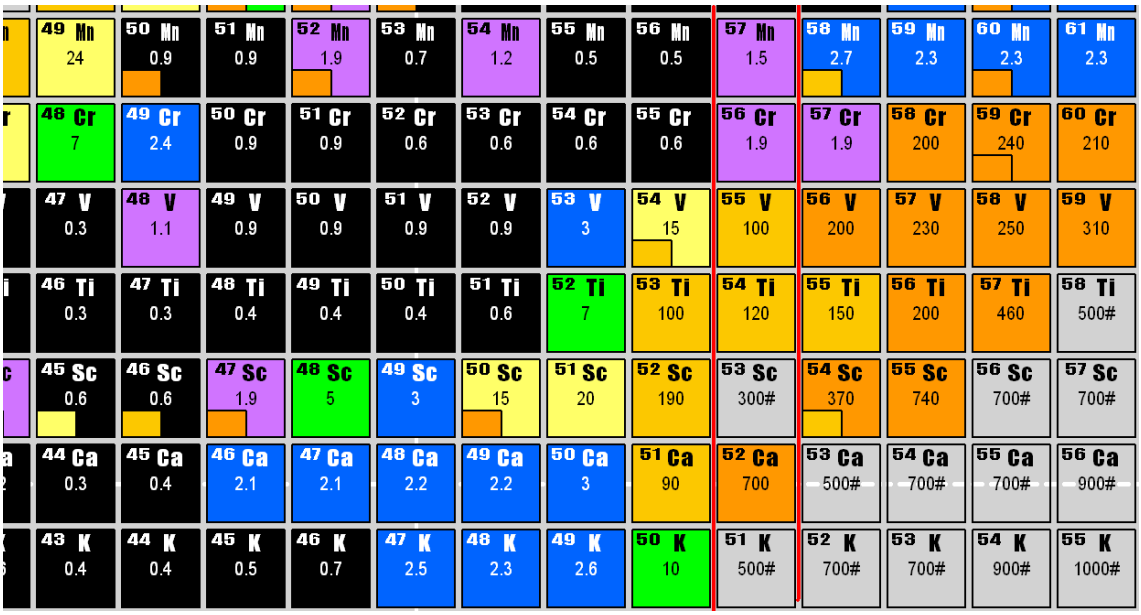
$N = 32$ and $N = 34$ isotones for Ca and Sc. These Ca isotopes are planned to be studied by laser spectroscopy as well at the COLLAPS setup at ISOLDE with a new proposal [8].

2 Physics Interest and Experimental Program

Figure 2 shows the region of the nuclear chart concerned by this proposal with decay mode (top) and the precsion of mass-excess values (bottom). The result of Prisciandaro *et al.* for the new magic number $N = 32$ in ^{56}Cr (in fact, they reported it as a new sub shell) was explained as being due to the removal of protons from the $f_{7/2}$ shell (from $Z = 28$ to $Z = 20$), weakening the proton-$f_{7/2}$ - neutron-$f_{5/2}$ monopole interaction strength, pushing the neutron-$f_{5/2}$ orbital up in energy, thus increasing the energy gap between this orbital and orbitals below giving rise to the new sub-shell closure. Shell-model calculations by Honma *et al.* using the GXPF1 effective interaction have predicted such a shell gaps, not only at $N = 32$, but also at $N = 34$ for $Z \leq 24$ (Cr) [10, 11]. In the pf shell, protons and neutrons occupy the same major shell leading to a relatively strong proton-neutron interaction. The relative energies of the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ orbits determine as a function of valence proton number where collectivity or sub-shell closure occurs. Therefore, it is interesting to test this model further and confirm whether the $N = 32$ sub shell really exists - not only for $Z = 24$, but also for lower Z (i.e. Ca and Sc). Moreover, it would also be important to have clear evidence for (or against) such a (sub-)shell closure for $N = 34$.



(a) Nuclear chart around doubly-magic ^{48}Ca: decay modes.



(b) Nuclear chart around doubly-magic ^{48}Ca: mass-excess precision.

Figure 2: (a) The area of the nuclear chart showing (mostly neutron-rich) isotopes of K ($Z = 19$) to Mn ($Z = 25$). Stable nuclei are shown in black. The (red) vertical lines show the $N = 32$ isotones. (b) Same area of the chart showing the absolute mass-excess precision (in keV). ISOLTRAP can easily reach a precision of a few keV in this region. Numbers marked with # are extrapolated (i.e. not measured) values [9].

So far, spectroscopic studies dedicated to this question by Liddick *et al.* [12] and Fornal *et al.* [13] have not revealed evidence for the magicity of $N = 34$. Also, a recent theoretical paper by Rodriguez and Egido, using a microscopic (beyond-mean-field) model, concludes that while the $N = 32$ shell closure exists for Ca, Ti, and Cr, an $N = 34$ shell closure

does not [14].

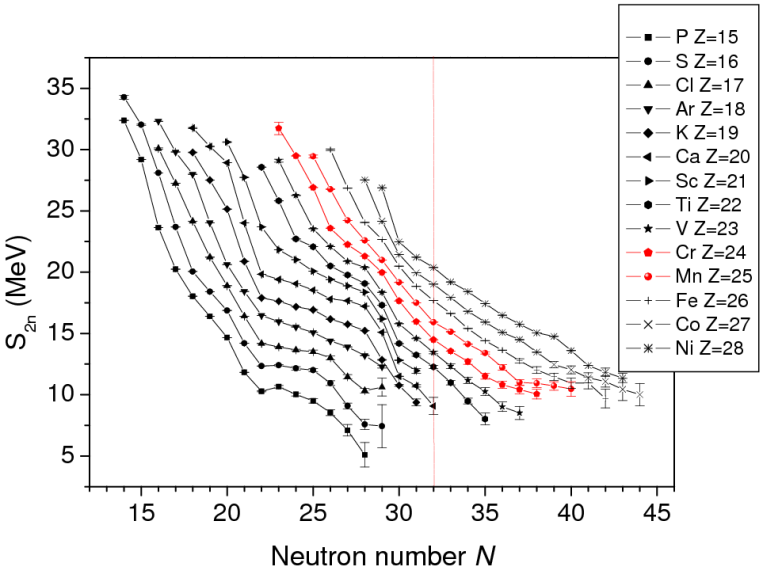


Figure 3: Two-neutron-separation energy versus N for P to Ni [7]. The shell closure at $N = 28$ is visible from the downward kink. At $N = 32$ for Cr, there is at present no evidence visible for a sub-shell closure. However the uncertainties need to be improved before making such a fine mapping. Notice that there is no data for the cases of Sc and Ca.

The behavior of the two-neutron-separation energies versus N can be examined in Figure 3. At $N = 28$, a downward kink is plainly visible for the isotopic chains below Cr. At present, there is no clear downwoard kink visible at $N = 32$ for Cr, which is in contradiction to the above mentioned evidence for a sub-shell closure at $N = 32$. Therefore, it is mandatory to probe the Cr isotopes more finely and to decrease the mass uncertainty on the isotopic chain to be able to confirm the available spectroscopy data. In addition, no mass data exist beyond $N = 32$ for the cases of Sc and Ca. The new data proposed here would offer an extremely interesting look into this exotic area.
The nuclides chosen for this study are complementary. While $^{58-60}$Cr are not so far from the valley of stability, the proton number ($Z = 24$) lies between the magic cases of $Z = 20$ and 28. Ca, on the other hand, has a closed proton shell ($Z = 20$) but ^{54}Ca ($N = 34$) is quite far from stability. Sc ($Z = 21$) is also complementary, with odd-Z and lying just above the magic Ca.

3 Mass Measurements at ISOLTRAP

The Penning-trap mass spectrometer ISOLTRAP has been performing mass measurements with high-precision for many years giving input to many physical topics reaching from nuclear structure studies to astrophysical applications, which has been documented in many publications [15].

3.1 Experimental Setup

Precision mass measurements have been performed with the Penning-trap mass spectrometer ISOLTRAP with a relative uncertainty routinely reaching 10^{-8} [16]. A recent summary of all measured masses since 2006 is given in [17]. Fig. 4 shows the current experimental setup which can be used without modifications for all of the proposed mass measurements. Up to recently, ISOLTRAP consisted of three parts: a radio-frequency quadrupole (RFQ) ion trap for beam preparation and two Penning traps [16]. The linear, gas-filled RFQ ion trap cools the $30 - 60$ keV quasi-continuous ISOLDE beam via buffer gas cooling. Furthermore, the ions are accumulated and leave the so-called buncher as ion bunches towards the preparation Penning trap where contaminants are removed with a resolving power of up to 10^5. The ions are then transferred to the second, precision Penning trap for the mass measurement. The time-of-flight detection technique is employed to determine the frequency of an ion stored in a Penning trap, from which the mass can be extracted in conjunction with a reference mass measurement [18]. During the year 2010, a multi-reflection time-of-flight (MR-ToF) mass separator was installed and successfully commissioned [19]. The MR-ToF mass separator acts as an auxiliary device for isobaric purification of rare-isotope ensembles, which not only conserves a high ion-of-interest throughput – in the case of strong contamination, but also works on shorter time scales than the preparation trap, thus enhancing the capabilities of ISOLTRAP significantly.

3.2 Current Performance of ISOLTRAP

High-precision mass measurements over the whole nuclear chart are possible with ISOLTRAP. The relative, mass-dependent systematic error over a wide mass range of 250 u was determined as an upper limit to $8 \cdot 10^{-9}$ [20]. At room temperature and a pressure of roughly $1 \cdot 10^{-8}$ mbar, the overall transport and detection efficiency for short-lived nuclei lies around $0.3\,\% - 1\%$ depending on the half-life or charge-exchange losses of the nuclide of interest. The system has adressed nuclei with half-lives down to 65 ms [21] with a yield of some few hundred ions per second. Isomeric states can be resolved well below 100 keV excitation energy [22]. With the newly installed MR-ToF mass separator with a pressure of $5 \cdot 10^{-9}$ mbar and usual trapping times of $5 - 30$ ms one can reach a resolving power of 200,000. A Bradbury-Nielsen beam gate installed directly behind the MR-ToF mass separator reaches a suppression factor for contaminating ions of four orders of magnitude, thus considerably enhancing the performance of ISOLTRAP when dealing with large contamination ratios [19]. Furthermore, the MR-ToF mass separator can in principle be used to perform direct mass measurements, first studies at ISOLTRAP during the running period 2011 lead to a relative mass uncertainty of $5 \cdot 10^{-7}$. With this,

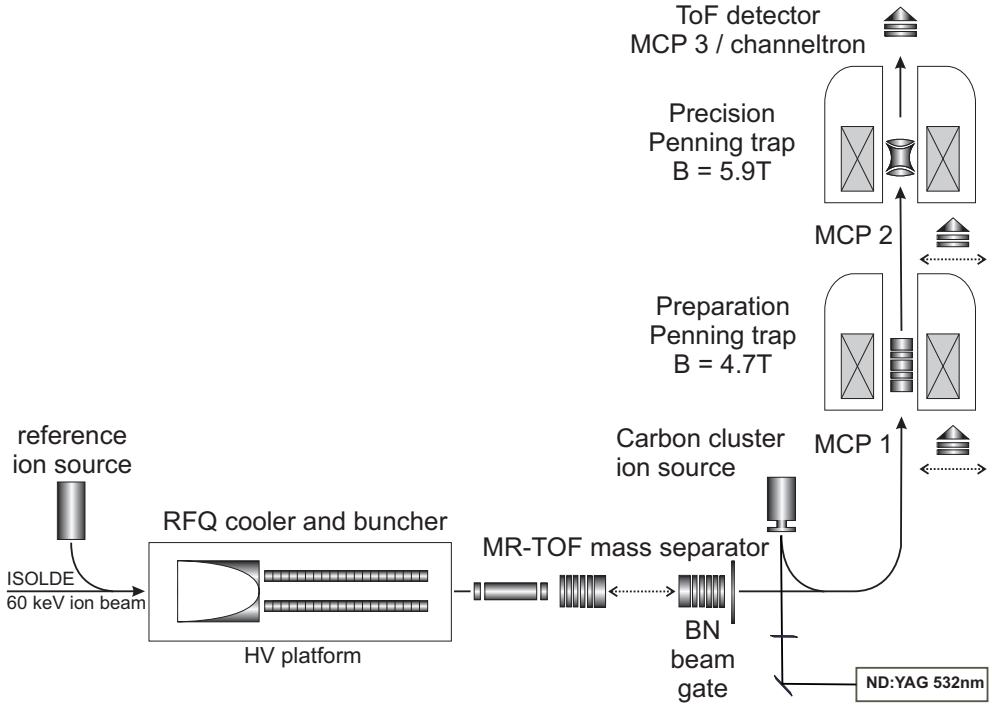


Figure 4: Schematic view of ISOLTRAP. For details see text.

ISOLTRAP is able to expand its range of addressable half-lives for nuclei to 5 ms. Additionally, the stacking scheme with the MR-ToF mass separator was also successfully implemented, in which the ions of interest are collected in the preparation trap after multiple repetitions of the purification with a repetition rate of roughly 100 Hz. In this way, ions with lower production yields than $10^2/\mu$C come within reach for direct mass measurements at ISOLTRAP. This measurement scheme has to be tested under online conditions.

4 Beam Time Requests

The beam time request of 20 shifts for precision mass spectrometry is detailed in tables 1 and 2. Table 1 shows all isotopes which we plan to measure through Penning-trap mass spectrometry with the required shifts, table 2 lists the isotopes to be measured with the MR-ToF mass separator. Half-lives and current mass uncertainty are taken from taken from [9]. Values extrapolated within the AME evaluation are marked with #. The expected yields were taken from the ISOLDE yield database or communicated by Thierry Stora. Here, the numbers marked with $ are extrapolated from available production yields or based on the preceding discussion. Moreover, the target-ion-source combination is listed for the different isotopes. For the removal of isobaric contamination, the MR-ToF mass separator needs to be calibrated for each mass number A individually for Penning-trap mass spectrometry, which requires 0.3 shifts per A and beam time. Since mass measurements are intended on 10 different masses during 3 different beam times, in total 3 additional shifts are needed for this calibration. The isotopes of interest

are further discussed regarding the feasibility of producing the desired radioactive ion beams. In general, the competition for mass measurements in this region of the nuclear chart is strong. With the ideas below, ISOLDE can hold its head start compared to the experimental program elsewhere, which underlines the importance of performing these measurements within the running period of 2012.

Table 1: Penning-trap mass measurements

nuclei	half-life	δm/keV	yield (ion/μC)	shifts	target	ion source
^{58}Cr	7.0 s	200	$1{\cdot}10^{4}$	1	YO	RILIS
^{59}Cr	460.0 ms	240	$1{\cdot}10^{3}$\$	2	YO or UCx	RILIS
^{60}Cr	560.0 ms	210	$1{\cdot}10^{2}$\$	3	YO or UCx	RILIS
^{52}Ca	4.6 s	700	$1{\cdot}10^{3}$	2	UCx	RILIS
^{53}Ca	90.0 ms	500#	$1{\cdot}10^{2}$\$	3	UCx	RILIS
^{52}Sc	8.2 s	190	$1{\cdot}10^{3}$\$	2	UCx	RILIS
^{53}Sc	$>$ 3.0 s	300#	$1{\cdot}10^{2}$\$	3	UCx	RILIS

Production yield for Cr isotopes without expected RILIS ionization enhancement.
The expected production yields for Ca and Sc isotopes are listed for the atomic ions.

Table 2: Mass determination with the MR-ToF mass separator

nuclei	half-life	δm/keV	yield (ion/μC)	shifts	target	ion source
^{54}Ca	50.0 ms#	700#	$1{\cdot}10^{1}$\$	1	UCx	RILIS
^{54}Sc	260.0 ms	370	$1{\cdot}10^{1}$\$	1	UCx	RILIS
^{55}Sc	105.0 ms	740	$1{\cdot}10^{0}$\$	2	UCx	RILIS

- **Neutron-rich Cr isotopes:** Several Cr isotopes have already been successfully produced at ISOLDE even from two different targets. The yields of ^{56}Cr of $3.6 \cdot 10^{4}/\mu$C from the YO446 unit (YO target coupled to a plasma ion source) in 2011 as well as $950/\mu$C on ^{56}Cr and $310/\mu$C on ^{57}Cr for a UCx unit demonstrate the expertise which is currently only available at ISOLDE [23]. In addition, the development of a laser-ionization scheme is part of the plans of the RILIS team during the shutdown 2011-2012 as part of the PhD thesis of Daniel Fink (member of ISOLDE RILIS Team) [24] and could be tested on radioactive Cr beam at the beginning of the running period 2012. The neutron-deficient Cu, Co, and Ni isobaric contamination, as well as neutron-rich ^{58}Mn are not expected to hamper the proposed measurements, since they are not easily surface ionized. The laser-ionization scheme would have to be tested under online conditions, for which shifts have to be reserved either directly preceding the ISOLTRAP run or at some point earlier in the running period of 2012.

- **Ca isotopes:** Ca isotopes have already been studied at ISOLDE, yields from the ISOLDE database give $1 \cdot 10^4$ ions/μC for ^{51}Ca [25] still for ISOLDE at SC. Due to a new target production mechanism, the yields are now expected to lie an order of magnitude higher [23]. The yield of Ca isotopes could further be enhanced in the meantime by a factor of 5-10 using a laser-ionization scheme from RILIS [26]. The main contamination is expected from surface-ionized Sc and K isotopes, which would then be directly measured as well. To separate stable Cr isotopes, a resolving power on the order of 10^3 is required which can already be achieved by the separator magnets of ISOLDE. An alternative production mechanism would be to work with more volatile CaF molecules, where the risk of contamination is much lower, however, the laser-ionization scheme could then not be utilized. In this case, a UCx target would be used with a fluorine gas leak and a neutron converter to suppress the production of contaminating Ga isotopes.

- **Sc isotopes:** The ISOLDE yield database gives $1 \cdot 10^1$ ions/μC for the isotope ^{52}Sc via surface ionization [25]. A laser-ionization scheme with 15% overall ionization efficiency has been tested at ISOLDE RILIS yielding already a ratio of surface to laser-ionized ions of more than 200 [26, 27]. In the meantime, auto-ionizing states in Sc have been found in an experiment at the University of Mainz [28]. It is foreseen to work on an ionization scheme consisting of Dye and Ti:Sa lasers which would not only address the auto-ionizing state but also excite ions from both, the ground and a very low-lying excited state of scandium. The foreseen yield enhancement should be more than two orders of magnitude [24]. The laser-ionization scheme tested at ISOLDE should be updated by the newly available developments and tested under online conditions, which could be schedule prior to the ISOLTRAP run. The expected contaminations are with production yield and required resolving power well within the limits of the ISOLTRAP mass spectrometer. Another possibility would be to measure the Sc isotopes from in-trap decay of calcium, either the atomic ion or a calcium-floride molecule. At present, Nobuaki Imai (member of the ISOLDE Target Group) is working at ISOLDE on breaking up ZrF molecules with UV light. Theses studies could be combined with ScF molecules as a test case towards the end of the running period 2012 to demonstrate the feasibility of this newly developed method under online conditions.

- **Calibration of the MR-ToF mass separator:** For nuclei with half-lives below 50 ms, the ISOLTRAP mass spectrometer cannot be used in the conventional way. However, the MR-ToF mass separator offers an intriguing new possibility where the mass of the ion of interest can be determined via its time of flight in the mass separator with a relative uncertainty of $5 \cdot 10^{-7}$ in much less time than in a Penning trap. The quicker measurement cycle of a few 10 ms as opposed to a few 100 ms to 1 s with the Penning-trap system could also be used to address nuclei with a production yield below $10^2/\mu$C since more statistics can be collected during the same time. For this purpose, the mass separator needs to be calibrated with an isobar triplets to test the new measurement scheme under online conditions. Therefore, we ask for development beam time to confirm our offline tests, which were performed with different masses, and to try to achieve an even lower relative mass uncertainty.

ISOLDE can provide an radioactive ion beam of isobars either on mass 40 with a triplet of Ca, K, and Ar from a Ti foil target or on mass 26 with a triplet of Mg, Al, and Na from a SiC target using a plasma ion source in each case. As an alternative, it is also possible to look in the mass region $A \geq 100$ for measuring on an isobaric triplet utilizing a UCx target, which could be in combination with other users. Since the stacking scheme should be confirmed under online conditions, we ask in total for 4 shifts, 3 shifts of development beam time for the calibration of the MR-ToF mass separator and 1 shift for testing the stacking scheme, details can be found in table 3. The development beam time should be scheduled early in the running period 2012, in any case well before any of the proposed ISOLTRAP runs.

Table 3: Development beamtime with calibrant ions for the MR-ToF mass separator

nuclei	half-life	δm/keV	yield (ion/μC)	shifts	target	ion source
^{40}Ca	stable	0.021	$1{\cdot}10^5$	0.5	Ti foil	plasma
^{40}K	1.521 Gy	0.1	$1{\cdot}10^5$	0.5	Ti foil	plasma
^{40}Ar	stable	0.0023	$1{\cdot}10^6$	0.5	Ti foil	plasma
^{26}Mg	stable	0.03	$1{\cdot}10^6$	0.5	SiC	plasma
^{26}Al	717.0 ky	0.06	$1{\cdot}10^4$	0.5	SiC	plasma
^{26}Na	1.07 s	4	$1{\cdot}10^5$	0.5	SiC	plasma

Summary of requested shifts: In summary, 27 are requested, 20 shifts for the actual mass measurements either with the conventional method or the MR-ToF mass separator, as can be seen from tables 1 and 2. 3 shifts are requested for calibration of the MR-ToF mass separator before and during each run and 4 shifts for development beam time for the MR-ToF mass separator.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: ISOLDE central beam line and ISOLTRAP setup. The preliminary safety file is the document "safety-requirements-ISOLDE-ISOLTRAP" with the corresponding attached documents dealing with the different hazards: acetone, cadmium, ethanol, helium, isopropanol, nitrogen, and noise. Furthermore, the existing ISIEC file "ISIEC_ISOLTRAP_2010-11-18" is also part of the safety documents made available for the ISOLTRAP experiment.

Part of the	Availability	Design and manufacturing
ISOLTRAP setup	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISOLTRAP installation.