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Proposal to the ISOLDE and N-ToF Experiments Committee (INTC)

Nuclear moments, spins and charge radii of copper isotopes from N=28 to N=50 by collinear fast-beam laser spectroscopy

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Abstract

We aim at establishing an unambiguous spin determination of the ground and isomeric states in the neutron rich Cu-isotopes from A=72 up to A=78 and to measure the magnetic and quadrupole moments between the N=28 and N=50 shell closures. This study will provide information on the double-magicity of ^{56}Ni and ^{78}Ni, both at the extremes of nuclear stability. It will provide evidence on the suggested inversion of ground state spin around A≈74, due to the monopole migration of the $\pi f_{5/2}$ level. The collinear laser spectroscopy technique will be used, which furthermore provides information on the changes in mean square charge radii between both neutron shell closures, probing a possible onset of deformation in this region.

This programme requests in total 37 shifts of radioactive beam, which will be spread over several runs for a period of two years, commencing spring 2006.

1 Introduction

High-resolution optical spectroscopy of radioactive beams provides measures of model-independent nuclear properties; spin, moments and changes in the nuclear charge radii. Of the many spectroscopic techniques developed in the last quarter of a century collinear fast-beam laser spectroscopy offers both high resolution and high sensitivity. The work at ISOLDE by the COLLAPS collaboration has refined this technique further, improving its sensitivity and application. Recent highlights have been the high precision measurement of the ground-state g-factor and quadrupole moment of ^{11}Li [1, 2] and studies of the neon [3] and magnesium chains with the direct confirmation of a deformed ground state in ^{31}Mg [4, 5, 6].

We propose to study the copper chain between the N=28 and N=50 shell closures using collinear fast-beam spectroscopy on the COLLAPS experimental line. This work aims to assign the nuclear spins and to measure nuclear moments and changes in the mean square charge radius of ground and long-lived excited states across the copper chain. We will use the new RFQ cooler-buncher in order to reach the limits of stability [7].

The project can be divided into several stages. An initial on-line period will study the copper isotopes closer to stability, which have high production yields and for which the use of the RFQ cooler-buncher is unnecessary. During this first stage we will study the copper isotopes $^{62-72}$Cu, which will provide new or more detailed spectroscopic information allowing evaluation of the atomic parameters associated with the isotope shift. To probe the neutron-deficient copper isotopes down to the N=28 shell closure we will require the use of the RFQ cooler-buncher to facilitate bunched-atomic spectroscopy for background suppression. Laser spectroscopy beyond ^{72}Cu critically hinges on the successful suppression of isobaric contaminants (primarily gallium [8]). The absence of large isobaric contaminants is crucial for the successful application of the RFQ cooler-buncher and laser spectroscopy of the neutron rich isotopes.

This project builds on previous in-source laser spectroscopy work undertaken during the IS365 experiment [9, 10, 11]. This technique proved to be highly selective and sensitive for very small yields. The work resolved the magnetic moments of the ground and isomeric states and measured huge isomeric shifts in both ^{68}Cu and ^{70}Cu. The resolution of the data was not sufficient to accurately extract the changes in mean-square charge radii [12] or the quadrupole moments. This was primarily due to the Doppler broadening within the hot cavity and the power-broadening associated with the lasers [11]. The experiments proposed here aim to greatly improve the measurements made under the IS365 program, while also extracting the changes in mean square charge radii and quadrupole moments across the copper chain.

2 Physical motivation

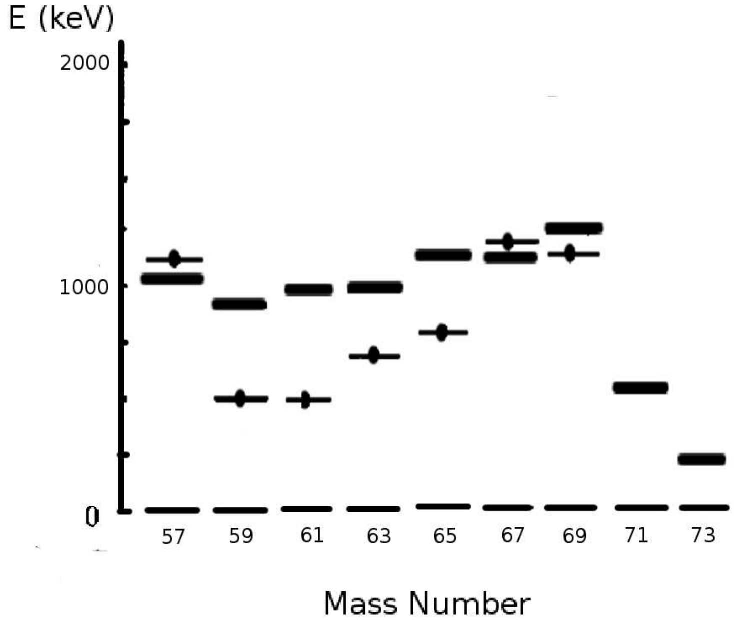

Figure 1: Energy levels of the odd-mass copper isotopes. Thick line highlights levels with spin and parity $5/2^-$, those with a solid circle show levels with spin and parity $1/2^-$

The accessible copper isotopes at ISOLDE straddle both the N=28 and N=50 shell closures. In both neutron-rich and deficient regions there are very interesting and outstanding nuclear structure questions. For the lightest copper isotopes there is significant evidence from large-scale shell-model calculations [13, 14, 15] pointing towards shell-breaking in $^{56}_{28}$Ni. For the heaviest copper isotopes recent $\gamma - \gamma$ and $\beta - \gamma$ spectroscopy of ^{71,73}Cu isotopes at the LLN LISOL has charted the migration of the $5/2^-$ level associated with the $\pi(f_{5/2})$ orbital. This level remains static between $^{57-69}$Cu at approximately 1 MeV, but as the $\nu g_{9/2}$ orbital is filled, the $5/2^-$ level systematically reduces in energy. The deduced energy level structure across the copper isotope chain is shown in Fig. 1, which also highlights the energy shift of the $1/2^-$.

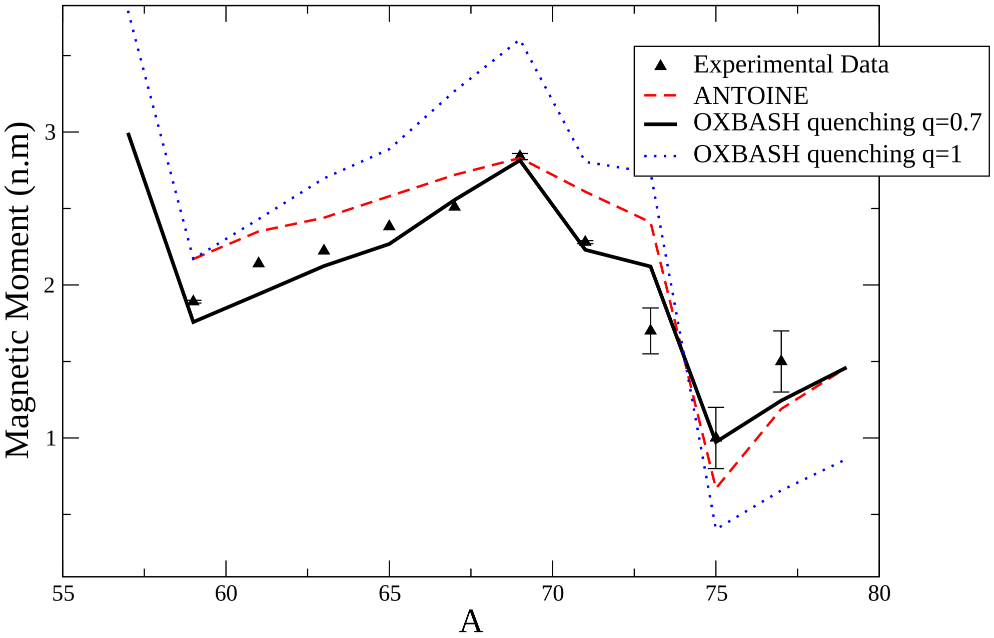

Figure 2: Measured magnetic moments of the copper isotope chain compared to theoretical calculations performed with a realistic interaction. Different monopole corrections were applied, showing that magnetic moments are very sensitive probes to test the effective residual monopole interaction. The measured magnetic moments for ^{73,75,77}Cu are from unpublished in-source laser data taken at ISOLDE, while the ^{57,69,71}Cu data come from recent β-NMR measurements in the NICOLE low-temperature device [16, 17, 18].

The effect of the migration of the $5/2^-$ state is seen also in the ground state magnetic moments, which are shown in Fig. 2. The measured magnetic moments have been compared to shell-model calculations performed by N.A. Smirnova [19] and A. Lisetskiy [20] using the ANTOINE and OXBASH codes respectively (with a quenched $0.7g_s$ factor, unless stated differently). Both calculations were performed with respect to a ^{56}Ni core, using a realistic interaction from a G-matrix approach, but adapted differently for the monopole part. The calculations by Smirnova et al. predict an inversion between the "normal" $3/2^-$ ground state (dominated by $\pi p_{3/2}$) and the $\pi f_{5/2}$ level at ^{79}Cu [19]. With the effective monopole by Lisetskiy et al [21], the inversion occurs at ^{73}Cu, whereas experimentally there is indication for an inversion at ^{75}Cu, but more spectroscopic information is needed to firmly establish this. The calculated magnetic moments are for the $3/2^-$ ground state in the lighter Cu, while from ^{75}Cu on the value for the $5/2^-$ state is represented. Reasonable agreement with experimental magnetic moments determined from IS365 is found and for

I	$\mu(\mu_{nm})$ Experimental	$\mu(\mu_{nm})$ Calculated
1	±0.92	± 2.03
2	±1.10	+2.76
3	±1.18	-2.74
4	±1.22	-0.99
5	±1.25	+0.43
6	±1.27	+1.66

Table 1: Possible ground-state magnetic moments deduced from in-source laser spectroscopy data assuming different ground state spins for ^{72}Cu, compared to calculated values for those spin-states.

^{73}Cu a more precise experimental value is needed to distinguish between both configurations. Notice that minor modifications in the monopole residual interaction has a rather strong influence on the calculated magnetic moments, thus illustrating the sensitivity of moments to this monopole term. That is why more precise magnetic moment values will help clarifying this issue. This proposal ultimately aims to go further than previous work and measure the magnetic moment of ^{78}Cu more precisely. The high resolution of collinear laser spectroscopy data also allows direct spin measurements, which will help in understanding the changing shell structure beyond A=73, due to the inversion of the proton single particle levels.

In odd-odd copper isotopes beyond N=40, the coupling of the valence proton in either the $\pi 2p_{3/2}$ or $\pi 1f_{5/2}$ with the unpaired neutron in the $\nu(1g_{9/2})$ orbital results in two multiplets of odd parity states. In the case of ^{72}Cu the suggested ground-state spin of $I = (2^+)$ by Mach [22] and recent β-decay studies [10] is not supported by either shell-model calculations [10] or in-source atomic spectroscopy. Table 1 compares the ground-state magnetic moment of ^{72}Cu determined from the in-source optical data for different ground state spins, with magnetic moments calculated using the addition theorem for known g-factors of the constituent nuclear states in neighbouring nuclei. The closest agreement in Table 1 occurs for spins 4 and 6. This proposal aims to resolve the present conflicting experimental evidence for ^{72}Cu.

Recent high-resolution mass measurements by ISOLTRAP show evidence for the onset of deformation, which can be seen in the two neutron separation energy as an upward kink beyond N=44 (Fig. 3), which coincides with the possible change in the ground state from $\pi(2p_{3/2})$ to the $\pi(1f_{5/2})$ state. The evaluation of the spectroscopic quadrupole moment and the change in mean-square charge radius will further address the possible onset of shape deformation with neutron excess. In addition to the change in ground-state mean-square charge radius, the isomeric shift will permit changes in the charge radius for different nuclear configurations to be studied.

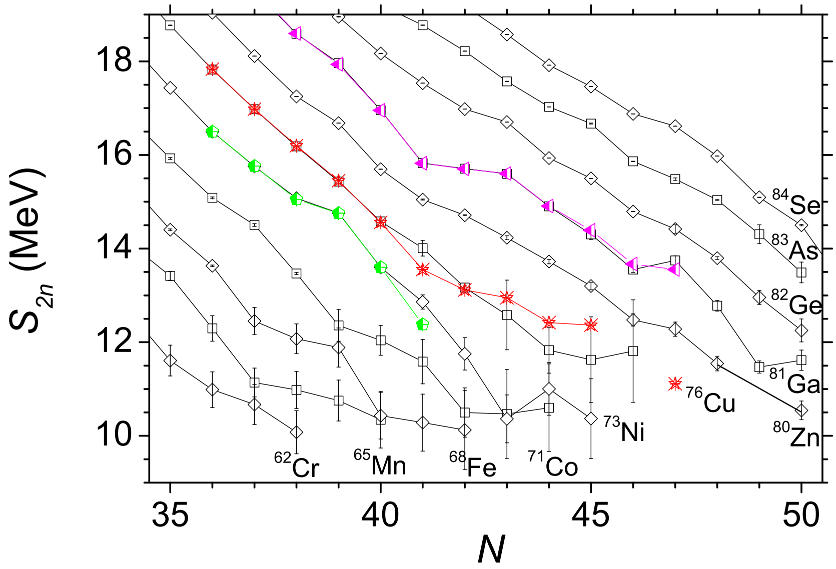

Figure 3: A plot of two neutron separation energy highlighting the possible onset of collective deformation in copper beyond N=44 (see text). Recent ISOLTRAP measurements are plotted in colour

3 Experimental procedure

At yields greater than 10^7 ions per micro-Coulomb , collinear laser spectroscopy using fluorescence detection is sufficiently sensitive to resolve the atomic structure above background. This technique is highlighted in Fig. 4, which shows a schematic of the COLLAPS beam line. The mass-separated ion beam is deflected through 10° and overlapped collinearly with a CW laser beam. The ion beam is then Doppler tuned onto resonance with the optical transition within the post-acceleration region.

For optical detection of atomic fluorescence, it is necessary to minimize the distance between the detection region and the neutralization point. This will act to reduce the degree of optical pumping, which in turn will diminish the overall optical detection efficiency. The copper atom has an alkali-like structure, with strong transitions between $^2S_{1/2} -^2 P_{3/2}$ and $^2S_{1/2} -^2 P_{1/2}$ at

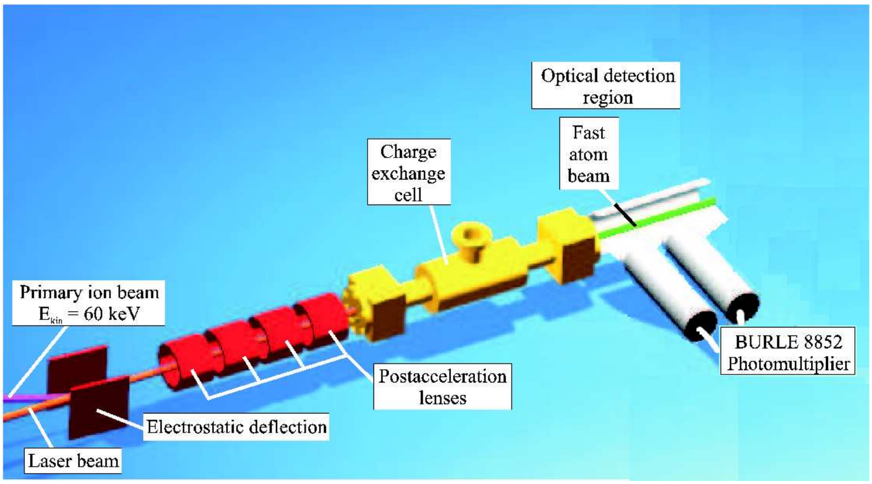

Figure 4: The COLLAPS beam line

wavelengths of 324.754 nm and 327.395 nm respectively. It is possible that metastable states within the atomic structure will be preferentially populated by the charge exchange process. The $^2D_{3/2}$ and $^2D_{5/2}$ states are energetically favourable candidates and have strong transitions at wavelengths of 282.437 nm, 261.836 nm and 219.975 nm. Production of these laser wavelengths requires doubling of the fundamental frequency of the light from a tunable dye laser using a nonlinear crystal such as BBO or $LiIO_3$. These wavelengths have been produced previously using intra-cavity doubling within the Coherent 699 dye laser. The recent β-NMR work undertaken on the Mg chain [4] employed an external cavity frequency doubler (Spectra-Physics WaveTrain), which has significantly improved the method of production.

4 Proposed experiment

4.1 Laser spectroscopy of copper isotopes from A=62-72

The initial stage of this project will study the Cu isotopes from A=62-72 using a UC_2 target and the RILIS in conjunction with the GPS. The measured yields using the PS-Booster are shown in Fig. 5. Fluorescence detection spectroscopy on the COLLAPS line currently requires beam yields greater than 10^7 ions per micro-Coulomb (shown by the dotted line in Fig. 5). The status of known nuclear moments and ground-state spins are presented in Table 2. These measurements will concentrate on the extraction of quadrupole moments

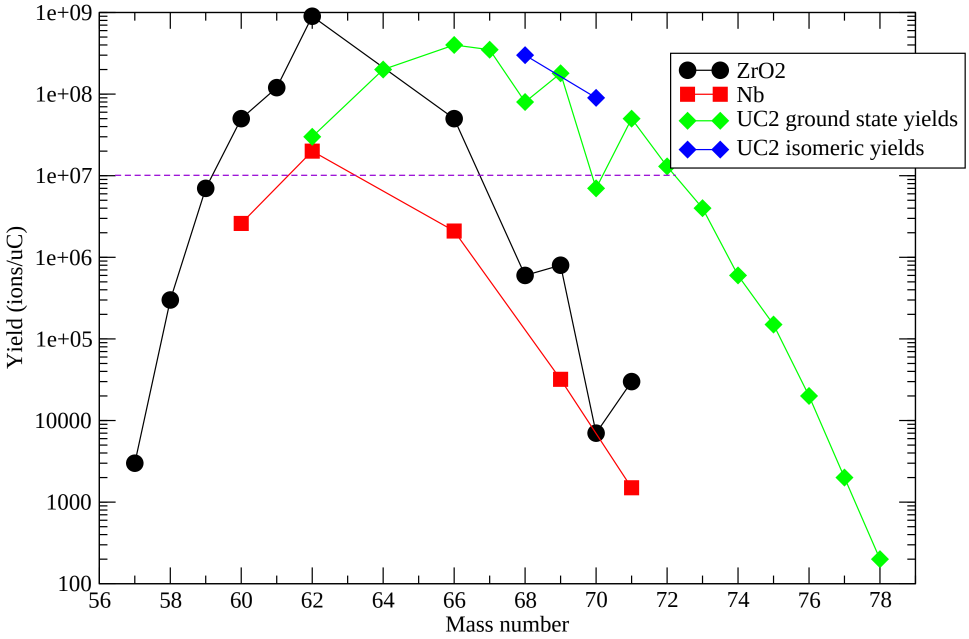

Figure 5: The measured Cu isotope yields from the ISOLDE RILIS [23]

and determination of the atomic factors for extraction of the changes in mean square charge radii.

In order to extract the mean square charge radius from isotope shift measurements an accurate account of the nuclear recoil (the mass shift) effect upon the atomic transition is required. The mass shift is a linear combination of two terms, the normal mass shift and the specific mass shift. The normal mass shift arises from the motion of the nucleus due to its finite mass and is trivial to account for. The specific mass shift arises due to the coupling of electron momenta and is in general a non-trivial problem. In view of the limited spectroscopic data on the D1 and D2 lines, this work will aim to accurately establish the atomic factors. The results are expected to determine whether these two lines are suitable for isotope shift analysis or if a further atomic transition is required.

These experiments will require a regular proton beam pulse sequence. The optical spectra are taken as a function of time and since the ISOLDE target yield has a "memory" over a few proton pulses it is essential that there is a regular pulse structure for the duration of the experiment. We therefore request (as in previous experiments) a number of equally spaced pulses per super-cycle.

Mass	I	μ_I (nm)	Q (b)	ref.
59	3/2–	+1.891(9)	–	[16]
60	2+	1.219(3)	–	[24]
61	3/2–	2.14(4)	–	[24]
62	1+	–0.380(4)	–	[24]
63	3/2–	2.227206(3)	–0.211(4)	[24]
64	1+	–0.217(2)	–	[24]
65	3/2–	+2.3817(3)	–0.195(4)	[24]
66	1+	–0.282(2)		[24]
67	3/2–	–		[25]
68g	1+	+2.48(2)(7)	–	[11]
68m	6–	+1.24(4)(6)	–	[11]
69	3/2–	+2.84(1)	–	[17]
70g	(6–)	(+)1.6(7) or 1.3(5)	–	[11, 26]
70m1	(3–)	(-)3.5(4) or 3.8(7)	–	[11, 26]
70m2	1+	+1.86(4)(6)	–	[11, 26]
71	3/2–	+2.28(3)	–	[24]
72	(2+)	–	–	[10]
73	3/2–	–	–	[27]

Table 2: Current status of moment measurements and spin assignment in the copper isotope chain.

4.2 Spectroscopy of exotic copper isotopes

Before work can be considered in the very neutron rich region of the copper chain close to the N=50 shell closure, the successful suppression of isobaric contaminants must be achieved. At present, one of the most physically interesting regions of the copper chain is masked by the high production yields of gallium isobars. The success of future measurements will be closely coupled to the ability to suppress the isobaric contaminants within the ion beam. If this problem is overcome then it is possible to consider the most exotic copper isotopes available at ISOLDE.

Several steps are currently being taken to reduce the background counting rates and improve the detection efficiency. This has the aim of allowing the COLLAPS line to perform collinear laser spectroscopy on weakly populated reaction channels. With regard to this project it is hoped that this will make it possible to perform measurements across the entire chain of copper isotopes produced at ISOLDE ($^{57-78}$Cu, see Fig. 5). A new light collection region is currently being commissioned, with the purpose of maximizing photon detection efficiency and minimizing scattered light, which forms the bulk of the background counting rate.

The additional ability of ISCOOL to produce bunched ion beams will permit the COLLAPS experiment to use the technique of bunched-laser spectroscopy pioneered in Jyväskylä [28]. The reduction in the background counting rate associated with a bunched ion beam scales as the ratio of the accumulation time within the trap to the temporal width of the released ions. A 15μs bunch width with an accumulation time between 100 and 300 ms is routinely used at the RFQ cooler in Jyväskylä. Optical detection is then gated so that photons are only recorded when the ions pass anterior to the light collection region. A suppression of the background by a factor 10^4 is achieved under these conditions. Recent collinear laser spectroscopy experiments at the IGISOL have benefited from the reduced phase space of the ion beam, with the associated improvement in efficiency and background suppression, which allows routine operation with yields of a few hundred ions per second.

We therefore propose to use the ISCOOL RFQ cooler once it has been installed and has been fully optimized to provide the COLLAPS line with bunched copper beams. This future work will be split into two separate runs. One will concentrate on the measurement of ^{57}Cu and ^{58}Cu using a ZrO_2 target and the RILIS. The second will require a UC_2 target to study the neutron rich nuclei up to and including ^{78}Cu. Both runs will use the HRS and the ISCOOL RFQ cooler. Before these runs are requested, extensive off-line testing using the ISCOOL in its bunched and continuous beam modes with stable copper will need to be undertaken. This work is essential for both the successful installation of the cooler and the development of the fast beam bunched atomic spectroscopy technique which will be used to study these most exotic cases.

5 Beam time request

The outlined beam time request for on-line radioactive data collection and the required time during the winter shutdown period for off-line tests is summarized below.

• Copper isotopes A=62-72 (UC_2/graphite target and RILIS using the GPS)	28 shifts
• Copper isotopes A=59-61 ($Zr0_2$/felt target and RILIS using the GPS)	9 shifts
Total request (radioactive beams)	37 shifts

The requested 37 shifts of radioactive beam time will be used in several short runs of typically 8 to 10 shifts each, over a period of two years. An additional 2 shifts of stable beam is required before each run, in order to tune the COLLAPS line and fully optimize the detection equipment.

As explained in this proposal, measurements beyond A=72 and below A=59 will require a fully operational ISCOOL. The neutron-rich isotopes beyond A=72 will also require the suppression of Ga, the dominant isobaric contaminant in this mass range. Large ion fluxes prevent the effective use of the ISCOOL in its bunching mode, due to the rapid attainment of the space-charge limit within the trap. We therefore make no beam time request for this part of the programme and will return to the INTC with an addendum to this work at a time when it is feasible to attempt the copper isotopes beyond A = 72 and below A = 59.

During the shut-down period (2005-2006) it is essential that access to stable copper beams can be provided using the RILIS. The neutralization of copper within the charge-exchange cell requires testing during this period, in order to account for the population of metastable states within the atomic structure.

• Stable copper isotopes using RILIS (during the winter shutdown period 2005-2006)	10 shifts

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