Proposal

Nuclear spectroscopy with copper isotopes of extreme N/Z ratios

Technische Universität München¹ - Ludwig Maximilians Universität München² - Technische Universität Braunschweig³ - Max-Planck-Institut für Kernphysik, Heidelberg⁴ - Universität zu Köln⁵ - Gesellschaft für Schwerionenforschung, Darmstadt⁶ - Institut Laue Langevin, Grenoble⁷ - Instituut voor Kern- en Stralingsfysica, K.U. Leuven⁸ - Institute of Spectroscopy of the Russian Academy of Sciences, Troitzk⁹ - ISOLDE Collaboration, Genf¹⁰

Jürgen Eberth⁵, Till von Egidy¹, Herbert Faust⁷, Valentin Fedoseyev⁹, Serge Franchoo³, Thomas Friedrichs³, Martin Groß², Dieter Habs², Marc Huyse⁸, Ulli Köster¹, Jacques Lettry¹⁰, Viatcheslav Mishin⁹, Wilhelm Mueller⁸, Jürgen Ott², Helge Ravn¹⁰, Ernst Roeckl⁹, Dirk Rudolph², Dirk Schwalm⁴, Peter Thirolf² and Piet Van Duppen⁸

Spokesperson: Dieter Habs
Local Contact: Ulli Köster

Summary

Our collaboration intends to study the beta-decay of very neutron-rich and neutron-deficient copper isotopes by using part of the MINIBALL and its data acquisition system. The copper isotopes should be ionized with the ISOLDE laser ion source to provide beams with low cross contamination.

Status report on test measurements of Cu release (Letter of Intent I-24)

On-line release tests of copper were performed with a standard Nb foil target, a RIST [1] tantalum foil target, and a uraniumcarbide/graphite target. The release of copper from the metal foil targets showed to be very slow, the time to release 50% of the produced copper nuclei was longer than 100 s for Nb and about 90 s for Ta. Thus the yields of short-lived nuclei were considerably suppressed. In a short test with a uraniumcarbide/graphite target the delay time of copper could be determined to about 13 s, which is not very fast, but should be sufficient for the proposed experiments with neutron-rich copper isotopes.

For the neutron-deficient side we believe that a zirconium oxide target could give much faster release than a niobium foil target, which is indicated by yield data available from the SC. For a 20 cm long target of zirconium oxide powder a production rate in the target of about $10^4$ to $10^5$ $^{60}$Cu per second and $\mu$A proton current can be estimated with the empiric cross section formula of Silberberg and Tsao [2].
New experimental data

At the Leuven on-line separator neutron-rich nickel isotopes up to $^{74}\text{Ni}$ have been separated with the laser ion source [3] and used for $\gamma$-ray spectroscopy. However, some lines could not be assigned unambiguously to either Ni or the Cu daughter nuclei [4]. More extensive Cu decay schemes (compared to [5, 6, 7]) including also smallest branches would help to clarify this situation and make full use of the available data on the Ni isotopes.

T. Pawlat et al. populated high-spin states in $^{70}\text{Zn}$, $^{72}\text{Zn}$ and $^{74}\text{Zn}$ via bombardment of heavy metal targets with $^{76}\text{Ge}$ and $^{64}\text{Ni}$ at the INFN in Legnaro. Their decay schemes confirm the previous assignments of the low spin levels found in $\beta^-$ decay and added a number of intermediate spin states [8].

Recently, a number of in-beam experiments in the A=60 region have been performed to investigate the high-spin structure in the vicinity of $^{58}\text{Ni}$. While neighbouring nuclei revealed a number of new exciting results (including the identification of the $T_z = -1/2$ nucleus $^{58}\text{Ni}$ [15] and the observation of a highly deformed structure in $^{58}\text{Cu}$ the bandhead of which was found to decay by prompt discrete proton emission into a (spherical) state of $^{57}\text{Ni}$ [16]. The spectroscopy of $^{56}\text{Ni}$ itself turned out to be difficult, and the very small population cross second hints on isomeric states at intermediate to high spins.

In a recent experiment at the GSI on-line separator new spectroscopic information on the decay of $^{56}\text{Cu}$ was collected. The half-life was estimated to 110 ms, somewhat longer than predicted by shell-model calculations [21] (compare also Table). Gamma-ray transitions could be identified at 1223, 2506, 2701, and 2780 keV with the $I^\pi = 4^+$ levels populated [17] as illustrated in Fig. 1.

<table>
<thead>
<tr>
<th>$^{58}\text{Cu}$</th>
<th>$^{60}\text{Cu}$</th>
<th>Reference</th>
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<td>$T_{1/2}$ (ms)</td>
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<tr>
<td>10</td>
<td>100-400</td>
<td>[9]</td>
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<td>101</td>
<td>[10]</td>
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<td>42</td>
<td>134-450</td>
<td>[12]</td>
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<td>58</td>
<td>133</td>
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Experimental program

Neutron-deficient copper isotopes

The general motivation for the study of Fermi (F) and Gamow-Teller (GT) $\beta$ decays near the $N = Z$ line includes the question of "GT quenching". In particular, the mass $A \approx 50$–60 allows to compare the experimentally measured GT transitions to those predicted by microscopic large-scale full $f_p$ shell-model calculations. In a recent study, Martinez-Pinedo et al. deduced an average GT quenching factor to achieve good agreement between the known cases and theory [18]. However, newly evaluated residual interaction two-body matrix-elements reveal problems at the $sd$ and lower $f$ shell near $^{40}\text{Ca}$ [19]. Second, the GT strength may be compared to that extracted from charge-exchange reactions in isospin-mirror systems, e.g., the decay of $^{58}\text{Zn}$ vs. the $^{58}\text{Ni}(p, n)^{58}\text{Cu}$ reaction. Moreover, precise knowledge of excitation energies of (potential) $(p, \gamma)$ threshold states in proton rich nuclei provide valuable information with respect to the astrophysical $rp$ process path.

Detailed knowledge on the decay strength of $^{56}\text{Cu}$ into distinct levels may also shed some light on how well defined the double magicity of $^{56}\text{Ni}$ in fact is: Recent calculations suggest that $^{56}\text{Ni}$ is only 50–60% doubly magic, i.e., there are large core polarizations, mainly due to the $f_{7/2}p_{3/2}$
correlations [20]. This manifests, e.g., in the comparatively small experimental \( B(2^+ \rightarrow 0^+) \) energy of \(^{56}\text{Ni} \) and even more in the large \( B(E2; 2^+ \rightarrow 0^+) \) value of \(^{56}\text{Ni} \). It is yet to be determined whether this "collectivity" shall be incorporated in shell-model matrix-elements. Finally, decay studies near \(^{56}\text{Ni} \) have a direct impact on those (much more difficult to access) near \(^{100}\text{Sn} \): The shell structure is very similar for both "doubly magic" \( N = Z \) nuclei, i.e., the correlations between the \( 1f \) and \( 2p \) shell \((^{56}\text{Ni})\) compared to the \( 1g \) and \( 2d \) shell \((^{100}\text{Sn})\).

The ground state of the \( T_z = -1 \) isotope \(^{56}\text{Cu} \) is predicted to have the same spin \( I^\pi = 4^+ \) as its \( T_z = +1 \) mirror partner \(^{56}\text{Co} \). The situation is illustrated in Fig. 1 which, starting from the left, shows (i) the predicted feeding pattern of the \(^{56}\text{Cu} \ 4^+ \) decay [21], (ii) some calculated levels in \(^{56}\text{Ni} \), (iii) the experimental level scheme of \(^{56}\text{Co} \) at low excitation energies [22], and (iv) the (preliminary) decay scheme of \(^{56}\text{Cu} \) deduced recently at GSI [17]. The experimental \( \beta \)-branching ratios have error margins of some 30 %. Energy systematics, i.e. the Coulomb energy shift with respect to the ground state of \(^{56}\text{Co} \), together with the large beta-decay feeding, identify the \( 4^+_3 \) level at 0.43 MeV as a member of the \( T=1, A=56 \) triplet. While the \( 4^+_2 \) is also well described, the large population of the yrast \( 4^+ \) state is in strong mismatch with the predictions (factor of four!). The possible explanation are unobserved fragmented \( \gamma \)-ray transitions from higher lying levels which were not observed in the previous experiment due to the limited statistics. In particular, considerable branches are expected for the IAS \( 3^+ \) (10 %) and \( 5^+ \) (2 %) states shown in Fig. 1. The detection of this missing strength via \( \gamma \gamma \) coincidence techniques is the major aim of this part of the proposed experiment. In addition, the \( \beta^+ \)-decay may populate medium-spin states in the \( T_z = 0 \) nucleus \(^{56}\text{Ni} \) at high excitation energies. The \( Q_\beta \) window is as large as 15 MeV for the \(^{56}\text{Cu} \) decay [23, 17] while it amounts to only some 2.1 MeV for \(^{56}\text{Ni} \) itself. Therefore, we hope to identify the presumed isomers (see above) or by-passes (which then could allow to make full use of the high-spin data).

The higher yield of \(^{57}\text{Cu} \) will enable us to allow a more comprehensive study of its \( \beta \)-decay, especially by efficiently detecting high-energy \( \gamma \) rays which directly relates to the question of GT quenching. In particular, the previous (tentative) spin assignment of the 3701 keV level of \(^{57}\text{Ni} \) (\( 5/2^- \)) is to be checked. A recent high-spin study identified this level as the exclusively populated daughter state of the prompt monoenergetic proton decay of the bandhead of the deformed second well in \(^{58}\text{Cu} \) (8.9 MeV excitation energy relative to the ground state, cf. Ref. [16]). A \( 5/2^- \) 3701 keV level has to be populated with at least a fraction of the GT strength of the \( 3/2^- \) ground state of \(^{57}\text{Cu} \) while it should not if it were the \( g_{9/2} \) single particle state as it is proposed from the high-spin experiment.

The large \( Q_\beta \) windows on the proton rich side may lead to high \( \gamma \)-ray transition energies (up to 6 MeV). Hence, we foresee the use of large composite detector systems by the time the experiment being scheduled. Conservative estimates provide a photopeak efficiency of two times 2 % at 1.3 MeV and two times 1 % at 3 MeV \( \gamma \)-ray energies for two large (composite and segmented) Ge-detectors in close geometry.

**Neutron-rich copper isotopes**

Nuclear spectroscopy of heavy copper isotopes will allow to probe the predicted shell quenching along the \( N = 50 \) shell [25] in the direct vicinity of the magic proton number \( Z = 28 \). The necessary spectroscopic information shall be extracted by combining quantities deduced from several experimental methods:
Gamma-ray spectroscopy

We intend to do systematic investigations of the decay of heavy copper isotopes via multiple-fold $\gamma\gamma$-coincidences. With the expected beam intensities we will be able to identify the lowest levels in nuclei at least as neutron-rich as $^{78}$Zn. The energy of the first levels (2+, 4+ and 0+) of the even Zn nuclei are already for $^{72}$Zn, $^{74}$Zn and $^{76}$Zn considerably below the shell-model predictions [6, 7] and it is therefore very interesting to follow this systematics towards the N=50 shell. Fig. 2 shows an extrapolation towards $^{78}$Zn.

The detailed decay schemes of the neutron rich copper isotopes will moreover help for a better evaluation of decay data from heavy Ni isotopes produced at the on-line separator in Leuven in recent ($A \leq 74$ [4]) and future experiments ($A > 74$ [24]).

For the first multiple-fold $\gamma\gamma$-experiments we want to use two sixfold segmented encapsulated Germanium detectors of the MINIBALL array in close geometry to the location of implantation. This can be used as a prototype experiment for later experiments at REX-ISOLDE. Therefore, the reliability of the detectors and the data acquisition system may be tested under real experimental conditions (RF noise from the copper vapor lasers, etc.).

Beta-delayed neutrons

To get the half-life of the (recently discovered, [26]) isotope $^{80}$Cu we will make use of the intrinsic selectivity when detecting $\beta$-delayed neutrons. The only neutron emitting contaminant on this mass, which is extracted from the source, is $^{80}$Ga. The way to suppress its contribution is discussed above. The branching ratio for $\beta$-delayed neutron emission from $^{80}$Cu gives direct information on the shell strength for $^{80}$Zn.

For the masses below $A = 79$ $\beta$-delayed neutron emission has not been observed for the Ga isotopes, so there is no neutron background from the beam expected. However, to determine the $P_n$ values reliably it is still necessary to keep the $\beta$-background from Ga nuclei as low as possible.

$Q_{\beta}$ measurements

The measurement of the total $\beta$-decay energy by means of $\beta$-$\gamma$-coincidence spectroscopy is an indirect but very general method to determine mass differences and thus indirectly the masses of exotic nuclei. A particular advantage of this method is the fact that it does not imply any inherent limitations for the lifetimes of the examined nuclides.

Our usual experimental set-up, described in detail in [27, 28], consists of a HP-Ge-detector (efficiency 150 %) for the $\gamma$ counting and a plastic scintillator telescope (diameter 120 mm, thickness 1 mm and 70 mm for the $\Delta E$ and the E part respectively), which provides a full energy peak efficiency of $\geq 80$ % for electrons with up to 15 MeV kinetic energy.

If there are no doubts on the decay scheme this method has typical uncertainties of less than 50 keV.

We propose to use this set-up initially for the determination of the $Q_{\beta}$ values of $^{72}$Cu, $^{74}$Cu and $^{76}$Cu. For these isotopes, partial decay schemes are already known [29, 6, 7], so that no prior investigations by means of time resolved $\gamma$- and $\gamma\gamma$-measurements will be necessary. So far for the neutron-rich copper isotopes $^{72+x}$Cu only mass values from systematic trends are known. The estimated errors vary between 200 and 900 keV [23].

Apart from the extension of the experimental database, a special interest in the properties of these copper isotopes comes from the vicinity of nickel with a closed proton shell, and especially from the doubly magic nucleus $^{78}$Ni. In order to judge correctly the validity of magic numbers...
far from stability (probe for “shell quenching”, see e.g. [25]), it is necessary to have a precise and experimentally based knowledge of the properties of the neighboured nuclei. The spectroscopic method we intend to use is well suited not only to determine the decay energy of $^{72}\text{Cu}$, $^{74}\text{Cu}$ and $^{76}\text{Cu}$, but also to check simultaneously for the existence of isomers which are known to exist for $^{68}\text{Cu}$, $^{70}\text{Cu}$ and $^{72}\text{Cu}$ [7]. However, until now no indications of isomers have been found for $^{72}\text{Cu}$ and $^{74}\text{Cu}$.

In order to determine the $Q_\beta$-values with an error of less than 100 keV, about $10^8$ to $10^9$ particles have to decay in our setup. Staying in a reasonable measurement time we can investigate nuclei with yields down to about $10^3$ s$^{-1}$. The $Q_\beta$ measurements will be done parasitically at GLM, while the heavier masses are investigated with $\gamma$- and neutron-detection in the central beam line.

**Laser Ion Source**

There are no easily surface ionizable contaminations for the masses planned for experiments on the neutron deficient side. Therefore, the experiment will not suffer from beam contaminations, but will solely depend on the accommodated copper yields themselves.

In an earlier experiment at ISOLDE-II dedicated to the neutron-rich side the half-lives and part of the $\beta$-neutron branching ratios for $^{74}\text{Cu}$ to $^{79}\text{Cu}$ were measured with an UC target but a rather unselective plasma ion source [30].

With a plasma source the ionization efficiency is about equal for neighboured elements, so the main background arises from zinc. With resonant laser ionization zinc will be practically completely eliminated due to its high ionization potential (> 9 eV). Attention has still to be paid to contaminations from gallium (and for the heaviest masses also rubidium), which get surface ionized in the hot cavity. This situation is comparable to the problem of indium and cesium contaminations of laser ionized silver beams. However the ionization potential of gallium (6.0 eV) is higher than the one of indium (5.79 eV) which makes it easier to be suppressed by choosing an ionizer cavity from a low work function material (TaC, Nb, ...) and running it at a reduced temperature. Moreover it is simpler to subtract a background from a single gallium decay time than one from indium with a possible mixture of different isomers. Using the time structure of the laser ionized beam (bunches with a repetition rate of 10 kHz) a fast beam gating can be applied to suppress the DC current of surface ionized isobars and increase the copper to background ratio by a factor of about 5. This method was recently successfully applied for the discovery of $^{129}\text{Ag}$ [31].

Another beam contamination due to doubly ionized nuclei of double mass which is typically found with plasma ion sources, is completely excluded with a laser ion source. This background of betas and beta delayed neutrons showed to be important at masses up to 74 (heavy Cs, Ba and La isotopes) [32].

Compared to experiments at the SC, the pulse structure of the PSB is a natural advantage to do the necessary beam bunching for decay time measurements. For very short-lived isotopes (< 100 ms) this may increase the usable beam intensity by up to one order of magnitude. The expected increase in production cross section due to the increase of the proton energy from 600 MeV to 1 GeV [33] still has to be verified experimentally.

The experimental conditions should thus allow to measure the halflife of $^{80}\text{Cu}$, to deduce the branching ratios for $\beta$-delayed neutron emission of $^{74}\text{Cu}$ to $^{78}\text{Cu}$ which are not precisely known today and to significantly expand the knowledge of level schemes of the heavy Zn isotopes.

Another powerful feature of the laser ion source is the ability to select between low- and high-spin isomers. The hyperfine splitting for copper is comparable to that of silver, where this new technique was recently applied successfully to separate different isomers [34]. A further
improvement of this selectivity could be made with a new narrow bandwidth dye laser in 1998.

Beam request

To prepare the experiments on the neutron deficient side we ask for a comprehensive target test (2 shifts) with a ZrO$_2$ target. Note that this target test is of general interest for potential users of neutron-deficient copper isotopes (see, e.g., plans to measure the nuclear moments of $^{57}$Cu to $^{59}$Cu [36]).

With an extrapolated yield of 5 atoms per second $^{56}$Cu we estimate 3 shifts to collect sufficient statistics in the $\beta$-$\gamma$ coincidence set-up to collect some 100 counts in transitions of $\sim$ 3 MeV with a relative yield of 2%. In parallel, these three shifts will provide enough statistics to deduce a detailed decay scheme of $^{57}$Cu (estimated 50 atoms per second) at the $\gamma\gamma$ coincidence set-up. Another 6 shifts are envisaged to place the identified single $\gamma$-rays into a level scheme via $\gamma\gamma$ coincidences with two large (composite and segmented) Ge-detectors.

To determine the lifetime of $^{80}$Cu we need at least some 10$^5$ counts after background deduction in a time window of 200 ms after stopping the collection. We will use a 4$\pi$ neutron long counter of about 20% efficiency, the predictions for $P_{1n}$ and $P_{2n}$ are 40% and 20% respectively [14] and a conservative estimation of the beam intensity is some 0.1 to 1 $^{80}$Cu atoms per $\mu$As. Without microgating and a relatively hot Nb ionizer we measured in the same time window a background of some 10 neutrons per $\mu$As from $^{80}$Ga. Using a TaC ionizer tube and the microgating with a duty cycle of 20% the background of gallium ($P_n$ = 0.8%) may be reduced by at least one order of magnitude. We will thus need about 2 shifts for this measurement.

The determination of the $P_n$ values for $^{74}$Cu to $^{78}$Cu will depend mainly on the achievable purity of the beta spectra. Enough statistics for the neutron counts can be taken within 2 shifts altogether, including the measurement of the even isotopes at two different laser settings to separate possible isomers.

For $^{78}$Cu we expect some 10 atoms per s. Within 2 shifts of measurement time (including the "laser-off" spectra) we will be sensitive to gamma transitions with up to 2 MeV and relative intensities of some 1%.

For the lighter Cu isotopes the yields are significantly higher. At the SC yields of 2 \cdot 10$^7$ per $\mu$C and 7 \cdot 10$^4$ per $\mu$C for $^{70}$Cu and $^{72}$Cu respectively had been measured with a 9 g/cm$^2$ UC graphite cloth target and a hot plasma source. These beam intensities are two orders of magnitude higher than the ones used for the earlier spectroscopy work at the GSI on-line separator [5]. Taking into account the higher detection efficiency of our set-up we will thus reach for the $^{72}$Cu decay within some hours a detection limit for gamma transitions with a relative intensity of some 10$^{-4}$ at 3 MeV energy. For the heavier masses the sensitivity will be reduced according to the beam intensities. The even masses will be measured separately at 2 laser settings, to separate high- and low-spin isotopes. For the single $\gamma$-ray measurements additionally "laser-off" spectra have to be taken to deduce the background from the spectra. Thus we would need about 9 shifts for the gamma spectroscopy up to $^{76}$Cu.

An additional shift has to be foreseen to determine the surface ionized background, to optimize the copper to background ratio by variation of the ionizer temperature, to tune of the beam chopper and to do the frequency calibration for isomer separation.

We will use the set-up for $Q_\beta$ determination in parallel to the $\gamma\gamma$ coincidence and $\beta n$ measurements.

The total request are 11 shifts with a zirconium oxide target for the experiments on the neutron deficient and 16 shifts with an uranium carbide/graphite target for the neutron rich side.
Bibliography


[31] K.L. Kratz et al., to be published


Fig. 1: Predicted decay scheme of $^{56}$Cu (T=1, Tz=-1) and calculated excited levels [21] in $^{56}$Ni (Tz=0) (left). The preliminary experimental decay scheme [17] is shown on the right hand side. All levels shown have positive parity. The observed and predicted beta-branching ratios are given in percent. The middle shows levels in $^{56}$Co (T=Tz=1). The IAS states in $^{56}$Ni are expected between 6 and 8 MeV excitation energy. The $0^+\text{IAS}$ at 7.90 MeV (1.45 MeV in $^{56}$Co) has been identified earlier, and the $4_3^+$ state at 6.43 MeV is a strong candidate for the IAS of the $^{56}$Co ground state. Decay branches into $3^+$ and $5^+$ IAS states are expected but not yet observed.
Fig. 2: Experimental level energy systematics of heavy Zn isotopes [7] extrapolated to $^{78}$Zn. The expected ground state spin of $^{78}$Cu (p3/2 x g9/2, I=3-6) will be large enough to populate spins up to at least I=4. The energy of the second (deformed intruder) 0$^+$ state is predicted to further decrease while the states of the first minimum shall remain constant or, approaching N=50, increase again.