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Laser spectroscopy study on the neutron-rich and neutron-deficient Te isotopes.

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Abstract

We propose to perform laser spectroscopy measurements on the Te isotopes. This will give access to fundamental properties of the ground and rather long-lived isomeric states such as the change in the mean square charge radius ($\delta <r_c^2>$) and the nuclear moments. For these medium-mass isotopes, at this moment the optical resolution obtained with RILIS is not high enough to perform isotope shift measurements. Thus we will use the COMPLIS experimental setup which allows Resonant Ionization Spectroscopy (RIS) on laser desorbed atoms. The $5p^4\ ^3P_2 \rightarrow 5p^3\ 6s\ ^3S_1$ and $5p^4\ ^3P_2 \rightarrow 5p^3\ 6s\ ^5S_2$ optical transitions have been used to perform, on the stable Te isotopes, the tests required by the INTC committee. For this purpose stable-ion sources have been built and Te isotopes have been delivered as stable beams by the injector coupled to the COMPLIS setup.

ISOLDE offers the opportunity for studying the Te isotope series over a wide mass range, from the nuclei located near the N = 66 neutron mid-shell to the neutron-rich ones beyond the neutron shell closure at N = 82. The neutron-deficient Te isotopes will be obtained either directly as ion beams or by the radioactive decay of Xe (Xe $\rightarrow$ I $\rightarrow$ Te), using a cerium oxide target associated in the first case with a hot plasma ion source and in the second case with a plasma ion source having a cold transfer line. The neutron-rich isotopes will be obtained from the ^{238}U fission in a uranium carbide target associated with

a hot plasma ion source. We expect to carry out the measurements on the $^{112-121}$Te and $^{129,121-136}$Te ground states and on the ^{115,119,121,129,131,133}Te isomeric states. It is worth noting that, when the neutron-deficient isotopes are obtained by radioactive decay of Xe, COMPLIS is absolutely necessary to perform laser spectroscopy measurements. But even for the Te isotopes produced as ISOLDE ion beams, COMPLIS presents some advantages: i) it works even if the ISOLDE ion beam is not pure provided that the ions that we want to study represent more than 0.1 % of the total ion beam, which is the case for Te, ii) it allows the discrimination between the hyperfine lines corresponding to the ground state and those associated with the isomeric state provided that the half-lives are rather different, in other cases provided that the γ-lines observed in the radioactive decay of the ground and isomeric states are different, SIINODE (Séparation Isomérique et Isobarique de NOyaux DEscendants, an upgrade of the COMPLIS experimental setup) can be used. The change in the mean square charge radius through the Te isotopes will bring information about:
- the variation of the kink at N = 82 when coming nearer the magic number Z = 50 ;
- the role played by the dynamic degrees of freedom in the nuclei near Z = 50 ;
- the influence of the coupling of the single particle to the core on the deformation of the nucleus. Moreover the determination of the nuclear moments in the odd Te nuclei will provide information on the structure of the states.

1 Physics motivations

Laser spectroscopy is a powerful tool to determine the global properties of the ground and isomeric states of nuclei far from stability. It enables the determination of i) the change in the mean square charge radius ($\delta <r_c^2>$) from the isotope shift and ii) the magnetic (μ) and spectroscopic quadrupole (Q_S) moments from the hyperfine structure. These nuclear data give information on the deformation of the nucleus and on the stucture of the ground and isomeric states. It is important to measure these data whatever nuclei we consider since they belong to the fundamental properties that any nuclear structure model has to reproduce. Indeed having a right description of a nucleus implies that nuclear models are able to predict the properties of the nucleus in its simplest states, i.e. the ground and isomeric states. In that respect, the change in the mean square charge radius and the nuclear moments can be considered as stringent tests of nuclear models.
The tellurium isotopes belong to the region of shape instability located just above the Z = 50 shell closure. Coexistences between spherical and deformed intruder states have been observed in the even-even Sn, Cd and Te nuclei especially around the neutron mid-shell [1-3].
In the odd-A Sb (Z = 51), I (Z = 53) and Cs (Z = 55) nuclei [4-8], collective structures built on a 9/2+ proton state (9/2+[404] Nilsson state) correspond to a nuclear deformation that increases with Z moving away from Z = 50 and N going close to the middle of the neutron shell (N = 66). In each isotopic series, this 9/2+ exhibits an energy minimum for N $\sim$ 66 and even becomes the ground state in ^{119}Cs. In the odd-A Te (Z = 52), Xe (Z = 54) and Ba (Z = 56) nuclei, the situation is more complex. States arising from $s_{1/2}$, $d_{3/2}$, $d_{5/2}$, $g_{7/2}$ and $h_{11/2}$ neutron subshells have been observed. In these states, the nuclei

appear to exhibit a large softness in the γ direction and the dynamical deformation can become important [9-12]. Moreover the nuclear softness increases when Z decreases down to 50 [9]. However near the neutron mid-shell, the nuclei exhibit prolate-shaped states corresponding to larger β deformation. Indeed in $^{121}_{56}Ba_{65}$ the ground state corresponds to deformed 5/2+[413] state [13]. In Te nuclei, even though they are close to the Z = 50 magic proton number, the 5/2+[402] and 7/2+[404] deformed states are located at low energy (E < 450 keV) in $^{117,119,121}_{52}Te_{65,67,69}$ [14].
In this context of a nuclear region rich in phenomena related to deformation, we propose to extend the laser spectroscopy measurement in the Z > 50 nuclei to the Te isotopes. Moreover, it is worth noting the revival of interest for the Te isotopes as demonstrated by the recent experimental and theoretical results published on the B(E2) transition probability in these nuclei [15-17] and by the experiment proposed recently on the g factor measurement in ^{132,134,136}Te [18]. Laser spectroscopy measurements would allow us to extend significantly the data (μ, Q_S, $\delta <r_c^2>$) available in the Te isotope series, which will provide direct information on the shape and deformation of these isotopes. Moreover, from A = 115 to 133, all the odd-A Te isotopes exhibit an isomeric state and the measurement of the isomeric shift will give us a direct indication of the influence of the coupled neutron state on the deformation of the nucleus. ISOLDE offers the opportunity for studying this isotopic series over a wide mass range from the neutron-deficient nuclei located near the N = 66 neutron mid-shell to the neutron-rich ones lying beyond the neutron shell closure at N = 82. The study of this isotopic series will provide the μ value in seven cases, the sign of μ in six other cases and the Q_S value in ten cases (see table 1). The value and the sign of μ will give information on the structure of the state. For example, different μ values are measured depending on the deformation and structure of the 1/2+ state present also in Ba, Xe and Sn : $\sim -0.8\ \mu_N$ for a quasi-spherical $s_{1/2}$ state or a slightly deformed 1/2+[400] state or $\sim +0.1\ \mu_N$ for the 1/2[411] deformed state.
Up to now, the nuclear charge radii have been measured from muonic atoms [19], thus they are known only for the stable isotopes. It is the same for the optical isotope shift studies that have been performed only on the stable isotopes [20, 21]. The change in the mean square charge radius obtained in the isotope series with Z $\geq$ 50 [13, 22-30] is shown in fig. 1. A slope change of the $\delta <r_c^2>$ curve is observed when the N = 82 subshell is crossed. This kink is especially strong when Z differs from the Z = 50 magic number. Figure 2 is another representation of this phenomenon. The $\delta <r_c^2>$ slopes obtained before N =82 and after N = 82 are plotted as a function of Z, as well as the slopes calculated from the spherical droplet model [31] and from the relativistic mean field model [32] (which was the first model able to reproduce the kink in the Pb isotopes). It results from figure 2 that, in the frame of the spherical droplet model, no slope change is expected at N = 82. Thus the slope change shows the deformation ability of the nucleus when the neutron number goes away from the N = 82 magic number. Moreover the more Z differs from the Z = 50 magic number, the stronger the slope difference (between before and after N = 82) is, indicating that it becomes easier for the nucleus to be deformed. Furthermore, for each Z value, the gap between the droplet model slope (corresponding to spherical nuclei) and the experimental slope is larger after N = 82 than before N = 82, this suggests that the ability of a nucleus for having deformation depends on the number of available neutron states in the major shell. The experimental data in Te are required

for confirming this behaviour close to the magic numbers Z = 50 and N = 82. On the other hand, it appears from figure 2 that the RMF model reproduces the behaviour of the $\delta <r_c^2>$ slopes before N = 82 better than the spherical droplet model. However the predicted slopes are over-estimated for Z $\leq$ 56 and under-estimated for Z > 56. After N = 82, the RMF model under-estimates the values for Z $\geq$ 60 and over-estimates them for Z $\leq$ 58. In the same way, contrary to the spherical droplet model, the RMF calculations predict a kink at N = 82 in the tin nuclei. The tellurium isotopes with Z = 52 are the isotope series nearest Z = 50, thus the determination of $\delta <r_c^2>$ through the neutron-rich Te isotopes around N = 82 will allow us to study the variation of the kink at N = 82 when coming nearer Z = 50.
Concerning now the isotopes with N < 82, the parabolic behaviour of the $\delta <r_c^2>$ curve observed in the Cd (Z = 48), In (Z = 49) and Sn (Z = 50) isotopes has been associated to important dynamical effects [25, 33, 34]. On the other hand, such a parabolic behaviour has not been observed in the isotopic series with Z $\geq$ 54. Looking for a parabolic behaviour of the $\delta <r_c^2>$ in the Te isotopes will allow us to answer the following questions: do the dynamical effects exist systematically in the isotope series near Z = 50, in other words, do these effects appear so long that the other types of deformation (in particular the quadrupole one) remain weak, or do they appear only in the nuclei located below the Z = 50 proton-closed shell ?

2 Experimental procedures

2.1 Production of Te isotopes at ISOLDE

The neutron-rich Te isotopes will be obtained at ISOLDE from the ^{238}U fission by using an uranium carbide target associated with a hot plasma ion source. The Te yields vary from 10^8 atoms/μC for ^{131g}Te to 4×10^7 atoms/μC for ^{136}Te [35]. With this hot plasma ion source, many other elements are ionized in particular the Cs nuclei that are highly produced. In order to eliminate the Cs isotopes, a target+ion source supplied with a polarization system can be used : tests have shown that, in these conditions, the yields decrease by a factor of 10 for Cs and by a factor of 2 for the other isotopes. With this target and ion source system, we plan to measure the Te isotopes from A = 129 to 136.
To obtain the neutron-deficient Te isotopes, a Ce_2O target will be used. This target can be associated with a plasma ion source having a cooled transfer line. In this case, ISOLDE delivers Xe beams and the neutron-deficient Te isotopes are obtained by radioactive decay of Xe (Xe $\rightarrow$ I $\rightarrow$ Te). The yields are equal to 10^8 atoms/μC from ^{125}Xe to ^{119}Xe and then decrease to 2.5×10^5 atoms/μC for ^{115}Xe. This target+ion source system could be used to perform the laser spectroscopy measurements on $^{121-116}$Te. For the 121, 119 and 117 odd masses, only the ground state is populated by the β^+/EC decay of I isotopes. Therefore, if this target+ion source is used, laser spectroscopy measurement cannot be performed on the $11/2^-$ isomeric state of ^{121,119,117}Te. However U. Koster has proposed to associate the Ce_2O target with a hot plasma ion source. In that case, the Te isotopes, and for the odd-A ones in their ground and isomeric states, will be obtained as ion beams. The yields of Te expected using this hot plasma ion source range from $\sim10^8$ atoms/μC

for ^{121}Te to $\sim 4 \times 10^6$ atoms/μC for ^{112}Te. Besides obtaining the hyperfine spectrum of the $11/2^-$ isomeric state of the odd isotopes, this configuration will allow us to perform the laser spectroscopy measurements down to A = 112.

2.2 The COMPLIS setup

At ISOLDE, three laser spectroscopy setup are available : RILIS [36], COLLAPS [37] and COMPLIS. RILIS has an excellent efficiency due to its high laser repetition rate (10 kHz), the optical resolution (some GHz) gives selectivity for most elements but it is not high enough to perform isotope shift measurements in the medium-mass nuclei, in particular in the Te isotopes. COLLAPS, designed to perform collinear laser spectroscopy on fast atomic beams, has an excellent resolution (65 MHz) but works better with isobar-free beams. In case of Te, with the hot plasma ion source, the great amount of Cs isobars could give rise to fluorescent light and thus to a continuous background noise reducing the detector sensitivity. In these conditions, COMPLIS has proved to be competitive since pure beams are not needed. For example, the tin isotopes, obtained with a UC_x target associated with a hot plasma ion source are much less produced than the Cs isotopes at A = 132 but they have been studied with COMPLIS up to A = 132.
The COMPLIS experimental setup has been designed to perform Resonant Ionization Spectroscopy (RIS) on a pulsed secondary atomic beam produced by laser desorption. COMPLIS and its precursors [38, 39] have opened a new field to laser spectroscopy since they allow the study of the isotopes that are not delivered as ion beams but that can be obtained by radioactive decay.
The COMPLIS experimental setup is shown in figure 3. The ions delivered at 60 keV by ISOLDE enter the COMPLIS incident beam line, are decelerated to 1 keV and deposited in the first atomic layers of a graphite disk. The atoms that we want to study, either directly delivered by ISOLDE or obtained by radioactive decay, are desorbed by a focused pulsed Nd:YAG laser at 532 nm. Some ten microseconds later, two synchronized lasers are fired to selectively ionize the atoms in two or three laser excitation steps. Spectroscopic information is obtained by scanning the first laser excitation step supplied by a single mode continuously tunable dye laser [40]. The frequency of this laser is monitored using a lambdameter to have an absolute frequency calibration. The last excitation allows to reach the ionization continuum. When the frequency of the first excitation step corresponds to a resonant transition, the atoms are excited and ionized. Then the ions are accelerated, deflected to the COMPLIS emergent line by a magnet and finally detected by microchannel plates with a time-of-flight mass-analysis. The frequency spectrum of the isotope under study is recorded simultaneously with that of a stable or long-lived isotope previously collected on the graphite disk and used as a reference for the optical isotope shift determination. The stable ions are provided by the stable-beam injector linked to the COMPLIS incident beam line. Two running modes are available with COMPLIS: the collection-desorption mode suitable for the long-lived isotopes ($T_{1/2} \geq 5$ m) and the step-by-step mode for the short-lived isotopes. In the collection-desorption mode, the measurement starts by the collection of the mass we want to study. During about a quarter of an hour, the ions delivered by ISOLDE are collected on the slowly rotating graphite disk. Then, after a suitable waiting time allowing the decay of the collected atoms in the

element that we are interested in, the disk turns back to its initial position and starts rotating again with the same velocity as during the collection while the Nd:YAG pulses desorb the surface-implanted ions. The frequency scan is performed during the desorption. In the step-by-step mode, the ion collection is performed at a fixed position of the graphite disk during one or several PS-Booster macrocycles. Then, in order to optimize the overlap between the collection spot (width $\sim$ 1 mm) and the desorption spot (width $\sim$ 50 μm), the disk turns around this position to explore the whole implanted spot during the measurement, i.e. the desorption and the ionization at a given frequency of the excitation step. After the frequency is changed and the collection-measurement cycle is repeated to scan the whole chosen frequency range. This second running mode is also used for the isotopes with low yield since it allows the accumulation of the nuclei under study before the laser measurement.
An upgrade of the COMPLIS setup has been installed recently in order to determine in what extent COMPLIS can be used as an isobaric or isomeric separator. In this new working mode, called SIINODE, the aim is not to record hyperfine spectra but to produce pure secondary radioactive beams. SIINODE adds to the high selectivity obtained by resonant ionization the power in the isotope identification given by γ-spectroscopy. It can be considered as a good tool to solve specific problems of atomic spectroscopy (such as the attribution of hyperfine lines to the ground or isomeric nuclear state) or of nuclear spectroscopy (identification of transitions belonging to the decay of the isomeric or ground state, measurement of the half-life of the ground state in the case of this half-life is shorter than that of the isomeric state...). In this new working mode, the frequency of the laser used for the excitation step is not scanned but is set to a value corresponding to a resonant transition of the chosen element. Figure 3 shows the modifications brought to the COMPLIS experimental setup. Firstly, a little microchannel plate detector that can be moved horizontally and vertically has been added in the detection chamber: it is used to determine and optimize the shape of the photoion beam. Secondly, a mylar-aluminum tape can now be introduced in the detection chamber: it is used to produce, by collecting the photoions, radioactive sources that are then transported in front of a γ-detector in order to determine their radioactive components. Thirdly, a pulsed high voltage and a screen have been added to deviate and intercept the ions directly created by the desorption laser in order to keep in the beam only the ions obtained by resonant ionization.

2.3 Results already obtained with COMPLIS

The first COMPLIS results have been obtained in the Z $\leq$ 80 region, well known for its shape instabilities [41-48], on the Au, Pt and Ir isotopes obtained from the radioactive decay of Hg delivered by ISOLDE [49-51]. These studies have provided a deep understanding of the coupling mode of the odd particle(s) to the core and of the influence of the particle(s) coupled to the core on the deformation of the nucleus.
More recently we have investigated the neutron-rich tin isotopes which are delivered as ion beams by ISOLDE. The change in the mean square charge radius has been obtained from A = 125 up to 132. The isomeric shifts measured for ^{125,127,129,130,131}Sn are rather small and lead to $\delta<r_c^2>$ relative to A = 120 very similar for the ground and isomeric states [22, 23]. Using results from muonic atom experiments [52] we have determined the

absolute charge radius of all the neutron-rich tin isotopes up to 132, in particular the charge radius of ^{132}Sn, neutron-rich and doubly-magic nucleus located far from stability, whose properties are important for the test of the parameters of the effective interactions. Figure 4 presents the experimental charge radius from A = 108 up to 132 and the values calculated within various microscopic models : the relativistic mean-field theory (RMF) with the NL3 effective interaction [32] and the Hartree-Fock Bogolyubov (HFB) calculations assuming spherical nuclei or including dynamical degrees of freedom [53, 54]. It is worth noting that the charge radius, predicted for ^{132}Sn by Beiner and Lombard thirty years ago [55] in the frame of an extension of the Brueckner formulation of the energy density formalism taking into account shell structure effects, is in perfect agreement with the experimental value. It results from figure 4 that dynamical effects are very important in the tin nuclei up to A = 132. These effects have been pointed out previously in the mid-shell tin isotopes from the significant difference observed between the deformation parameters obtained from the B(E2) values (sensitive to the static deformation) and from the $\delta<r_c^2>$ values (sensitive to the static and dynamical deformation) [25]. As regards the RMF calculation results, the ^{132}Sn theoretical charge radius reproduces quite well the experimental value. But the shape of the radius curve and in particular the slope of this curve before N = 82 differs from what is observed experimentally. This is an important point because the RMF model was the first one able to reproduce the kink observed in the $\delta<r_c^2>$ at N = 126 in the Z-magic (Z = 82) Pb isotopes. This success was attributed to the exact calculation of the spin-orbit contribution. Since we have not succeeded in measuring the isotope shift for ^{134}Sn, the question of a kink at N = 82 in the tin isotopes remains open.

The experiment performed on ^{129}Sn has allowed us to show that SIINODE works well (however quantitative measurements remain to do) and also to solve the puzzle set by the hyperfine spectra obtained for the odd tin isotopes. For ^{125,127,129,131}Sn, the hyperfine spectra indeed exhibit five hyperfine lines instead of the six expected (three for the ground state and three for the isomeric state) from the spin values (3/2 and 11/2) proposed for the ground and isomeric states. Either one of the hyperfine lines is a doublet and belongs to both ground or isomeric states or the spin value is not 3/2 but 1/2, the only spin value leading to two hyperfine transitions. This 1/2 spin value would imply that the nucleus is strongly deformed in this state, which would be very surprising in the proton-magic tin isotopes expected to be spherical and stiff against deformation. To settle this question, we have performed two measurements. The frequency of the excitation laser has been fixed in the first case to a value corresponding to a hyperfine transition attributed to ^{129m}Sn, and in the second case to the value assumed to be the doublet. In each case, the photoions created have been collected on the tape and moved in front of the γ-detector. The results obtained are shown in figure 5. The γ-spectrum obtained in the first case exhibits the γ-lines characteristic of the ^{129m}Sn decay, proving that only tin atoms in the isomeric state have been ionized. On the contrary, the γ-spectrum obtained in the second case shows not only the γ-lines associated to the ^{129m}Sn decay but also the γ-line signing the ^{129g}Sn decay. This confirms the hyperfine doublet hypothesis and consequently the 3/2 spin value proposed to ^{129g}Sn.

2.4 Atomic transitions for the study of tellurium

In a COMPLIS experiment, the spectroscopic information (isotope shift and hyperfine spectrum) is obtained by scanning the first excitation step of the RIS scheme. For the tellurium study, two optical transitions are available: the $5p^4\ ^3P_2 \rightarrow 5p^3\ 6s\ ^5S_2$ transition at 225.97 nm or the $5p^4\ ^3P_2 \rightarrow 5p^3\ 6s\ ^3S_1$ one at 214.35 nm. In both cases, the single mode laser pulses will be obtained from frequency tripling. For the ionization, a laser beam at 352 or 384 nm has to be used respectively. Figure 6 shows the hyperfine spectrum expected for the I = 1/2, 3/2 and 11/2 spin values. The hyperfine constants for the magnetic interaction have been evaluated from refs. [56, 57] using the known experimental μ values whereas the hyperfine constants for the electrostatic interaction have been neglected. Moreover, we have assumed a 375 MHz FWHM for the resonant lines, which is the resolution obtained when frequency tripling is used. One can note that, for both transitions, the calculated hypefine spectra for I = 3/2 and 11/2 exhibit mixed lines.
In order to obtain the mean square charge radius from the isotope shift, the atomic parameters F_i related to the electron density at the origin and the specific mass shift have to be determined. The F_i factor can be either evaluated using MCDF calculations or extracted, as well as the specific mass shift, from a modified King plot analysis. Such an analysis will be done using the optical isotope shifts obtained for the stable Te isotopes with these transitions and the muonic $\delta\langle r_c^2\rangle$ values [19]. If the precision obtained for the optical isotope shifts is not good enough, the King plot analysis will be used only for the specific mass shift determination, taking for the F_i parameter the calculated value.

2.5 Tests on stable Te isotopes

In this section, we report on the tests required by the Committee when this proposal was presented for the first time. The aim of these tests was i) to produce stable beams of Te and ii) to prove our ability to perform laser spectroscopy measurements on Te with COMPLIS, which includes the determination of the optimal conditions for the desorption and ionization of Te.
The stable-beam injector linked to the COMPLIS incident beam line (see figure 3) allows us to determine these optimal conditions, before the experiment, by simulating an on-line experiment. Indeed the ion beam delivered at 12 kV by the injector is decelerated to 1 kV before being collected on the graphite disk. Then the value of the deceleration/acceleration high voltage as well as the value of the COMPLIS magnetic field are changed and the laser measurement (desorption, ionization and detection) is carried out in exactly the same experimental conditions as during the on-line experiments. In particular, measurements with about 10^8 atoms by frequency step are realized, which corresponds to the amount of atoms proved to be necessary in the previous on-line experiments on Au, Pt, Ir and Sn. This requires to produce stable beams of the element that we want to study.

2.5.1 Tests for producing stable Te ion beams

For the Te study, two stable-ion sources have been built. In the first one, tellurium is compressed and put into a graphite crucible. In the second one, a Ni-Te alloy is used,

the melting point of this alloy is 900°C instead of 452°C for Te. The two ion sources work well. However we prefer to use the second one, because, the melting point of the Ni-Te alloy being higher, the working mode of this ion source is more regular, steadier as a function of time and consequently the ion-source lifetime is expected to be longer. Figure 7 shows a photograph of this ion source as well as a beam profile obtained in the focal plane of the first dipole of the COMPLIS injector.

2.5.2 Tests of laser spectroscopy on Te

As above-mentioned, two optical transitions can be used for the first excitation step of the RIS scheme for tellurium. We have first tested the $5p^4\ ^3P_2 \rightarrow 5p^3\ 6s\ ^3S_1$ transition at 214.35 nm because, the atomic angular momentum of the excited state being equal to 1, the number of hyperfine transitions is smaller. This transition belongs to the UV spectrum, we could fear an important absorption by air since the laser beams travel over about fifteen meters from the laser room to the ionization point. However the power transmitted at the entrance of the ionization chamber proved to be sufficient to perform the first excitation step. For the second step, the ionization one, a scan around the theoretical value necessary to ionize has allowed us to find the maximum of ionization at 387 nm. An overall efficiency of 5×10^{-9} has been measured with implanted sources of stable Te. Then the second optical scheme has been used (in this case the maximum of ionization has been found at 353.85 nm) but without any improvement in efficiency.
The obtained efficiency is very low and under these conditions measurements can be performed only on $^{116-118}$Te for the neutron-deficient nuclei and on $^{131-134}$Te for the neutron-rich isotopes. Measurements on ^{136}Te, located beyond the neutron shell-closure at N = 82, require an overall efficiency equal to 1.5×10^{-7}. The aim of the next tests on the stable Te isotopes is to obtain at least this efficiency value. A scan of the ionizing laser frequency in the vincinity of the ionization threshold has shown no auto-ionizing level, as it was in the tin experiments, so to enhance the ionization cross-section and reach the saturation, we will use a more intense laser beam at 355 nm provided directly by the frequency tripling of a Nd:YAG laser. These tests achieved last week (week 16) were successful since the efficiency has been measured to be 5×10^{-7}.

3 Proposed experiment

We propose to use COMPLIS to measure isotope shifts and hyperfine structures in Te, which allows direct determination of magnetic moments, spectroscopic quadrupole moments (when $I \neq 0$ and 1/2) and changes in the mean square charge radius.
The COMPLIS setup has been designed to perform good resolution RIS on a pulsed secondary atomic beam produced by laser desorption. It is well suited to study elements which are not available as ISOLDE ion beams but can be obtained by radioactive decay of an element delivered by ISOLDE. However, even when the element under study is produced by ISOLDE as an ion beam, COMPLIS can offer some advantages over the other laser spectroscopy methods. Firstly, the collected ions can be accumulated, thereby increasing the amount of atoms available for the laser measurement. This is useful in particular when the studied isotopes have a low yield and $T_{1/2} > 2$ s. Secondly, when the isotope under study has an isomeric state and provided that the half-lives of the isomeric

and ground states are different, the resonant lines that belong to the isomeric state can be distinguished from that belonging to the ground state by comparing the intensities of the hyperfine lines on spectra obtained using the two COMPLIS running modes (see section 2.2), which amounts to changing the delay time between the collection of the ions and the laser measurement. Furthermore, it is worth noting that pure beams are not needed to use the COMPLIS setup as we have proved it by studying the Sn isotopes.
We plan to measure the neutron-rich Te isotopes from A = 129 to 136 using an uranium carbide target associated with a hot plasma ion source. For the A = 129, 131 and 133 odd idotopes, COMPLIS will allow us to discriminate between the hyperfine lines corresponding to the ground and isomeric states since the half-lives are rather different. In this case, by changing the delay between the collection and the laser measurement, we can favour the hyperfine spectrum corresponding to the ground or isomeric state.
For the study of the neutron-deficient Te isotopes, we will use a Ce_2O target associated with a hot plasma ion source, since with this configuration the Te yields are high enough to plan laser spectroscopy measurements from A = 121 down to 112. Moreover, for the odd nuclei with A = 121, 119 and 115, the hyperfine spectrum will be obtained not only for the ground state but also for the isomeric state. However, it will not be possible to distinguish the hyperfine lines corresponding to the ground state from those corresponding to the isomeric state using the method applied for the neutron-rich Te isotopes since for A = 121, 119 and 115 the half-lives of the ground and isomeric states are either both long or very similar. But with the SIINODE working mode, the hyperfine lines will be attributed unambiguously to the ground or isomeric state. Indeed, for each mass, there are γ-rays with strong intensity and observed only in the ^{g}Te or ^{m}Te decay (see table 2). As it appears from figure 6, the hyperfine spectrum expected from the 11/2 state is very complex, exhibiting 9 hyperfine lines at least. Moreover, the resonant lines corresponding to the 1/2 state can be mixed to those corresponding to the 11/2 state depending on the value of the isomeric shift. If the SIINODE method fails the attribution of the hyperfine lines to the ground or isomeric state, we plan to perform measurements using the plasma ion source having a cooled transfer line that delivers Xe beams. As the 11/2 isomeric state is not populated in the I decay, this source offers a means to obtain pure collections of Te in its ground state, and consequently a pure hyperfine spectrum corresponding to the ground state.

4 Beam time request

The beam time necessary to perform these experiments is not easy to determine. If the experimental conditions are optimal, some hours are needed to complete the hyperfine spectrum of one isotope. But to obtain these optimal conditions, and this point concerns all the technics involved in the experiment (the ion beam transport, its deceleration, collection and desorption, the geometry for the crossing of the laser beams, the stability of the lasers, the resolution obtained for the first excitation step...), time is necessary at the beginning of the experiment, even when tests have been realized just before the on-line experiment. However this time is not only devoted to adjustments, measurements can be performed but with a weaker efficiency or with a lower resolution. Moreover, it is worth noting that these laser spectroscopy measurements are difficult to perform. We

measure, as a function of the first-step-laser frequency, the number of ions detected. This is a quantitative measurement and all the parameters playing a role in the amount of detected ions must not vary during the measurement, in particular the proton beam, the ISOLDE ion beam and the laser beams. For this reason, we have to record many spectra for each isotope.
The experience that we gained during the previous experiments leads us to consider that, on average (i.e. distributing this adjustment time over all the isotopes studied in one experiment), one shift is necessary to perform the laser spectroscopy measurement for an even isotope and two shifts for an odd isotope, since the number of hyperfine transitions is higher. When the measurement is performed not only on the ground state but also on the isomeric state, two shifts more are needed to attribute each hyperfine transition to one state. Thus we ask for:
- 17 shifts for the study of the neutron-rich Te isotopes (A = 129m+g, 131m+g, 133m+g, 132, 134, 135, 136) which needs an uranium carbide target with a hot plasma ion-source.
- 21 shifts for the study of the neutron-deficient Te isotopes (A = 121m+g, 120, 119m+g, 118, 117g, 116, 115m+g, 114, 113 et 112) which requires a cerium oxide target associated with a hot plasma.
- in case of problem in the attribution of the hyperfine lines to the ground and isomeric states, 4 shifts more in order to obtain the pure hyperfine spectrum of ^{121g}Te and ^{119g}Te, which requires a cerium oxide target too, but associated with a plasma ion source having a cooled transfer line.
In total, our beam time request is: 38(+4) shifts.

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Table 1: Nuclear moments of the ground and isomeric states in $^{135-113}$Te isotopes [58, 59].
• indicates the isotopes that we request to study
$*$ indicates that the sign of μ is not known
? indicates that the moments is not known

A		$T_{1/2}$	I^π	E [keV]	μ [μ_N]		Q_S [b]
135	•	19.0 s	(7/2−)	0	?		?
133 g	•	12.5 m	(3/2+)	0	?		?
133 m	•	55.4 m	(11/2−)	334	1.129(7)	*	?
131 g	•	25.0 m	3/2+	0	0.696(9)	*	?
131 m	•	30 h	11/2−	182	−1.04(4)		?
129 g	•	69.6 m	3/2+	0	0.702(4)	*	0.055(13)
129 m	•	33.6 d	11/2−	105	−1.091(7)		?
127 g		9.35 h	3/2+	0	+0.635(4)		?
127 m		109 d	11/2−	88	−1.041(6)		
125 g		stable	1/2+	0	−0.8885051(4)		
125 m		57.4 d	11/2−	145	−0.985(6)		−0.06(2)
123 g		$>10^{13}$ y	1/2+	0	−0.7369478(8)		
123 m		119.7 d	11/2−	247	−0.927(8)		?
121 g	•	16.78 d	1/2+	0	?		
121 m	•	154 d	11/2−	293	0.895(10)	*	?
119 g	•	16.03 h	1/2+	0	0.25(5)	*	
119 m	•	4.7 d	11/2−	261	0.894(6)	*	?
117 g	•	62 m	1/2+	0	?		
117 m		103 ms	(11/2−)	296+x	?		?
115 g	•	5.8 m	7/2+	0	?		?
115 m	•	6.7 m	(1/2+)	<20	?		
113	•	1.7 m	(7/2+)	0	?		?

Table 2: γ-rays observed only in the decay of the ground or isomeric state.

	ground state		isomeric state	
A	E_γ [keV]	I_γ [%]	E_γ [keV]	I_γ [%]
115	724	30	770	33
119	644	84	154	66
			1213	66
121	573	100	82	IT 80
			212	IT 80

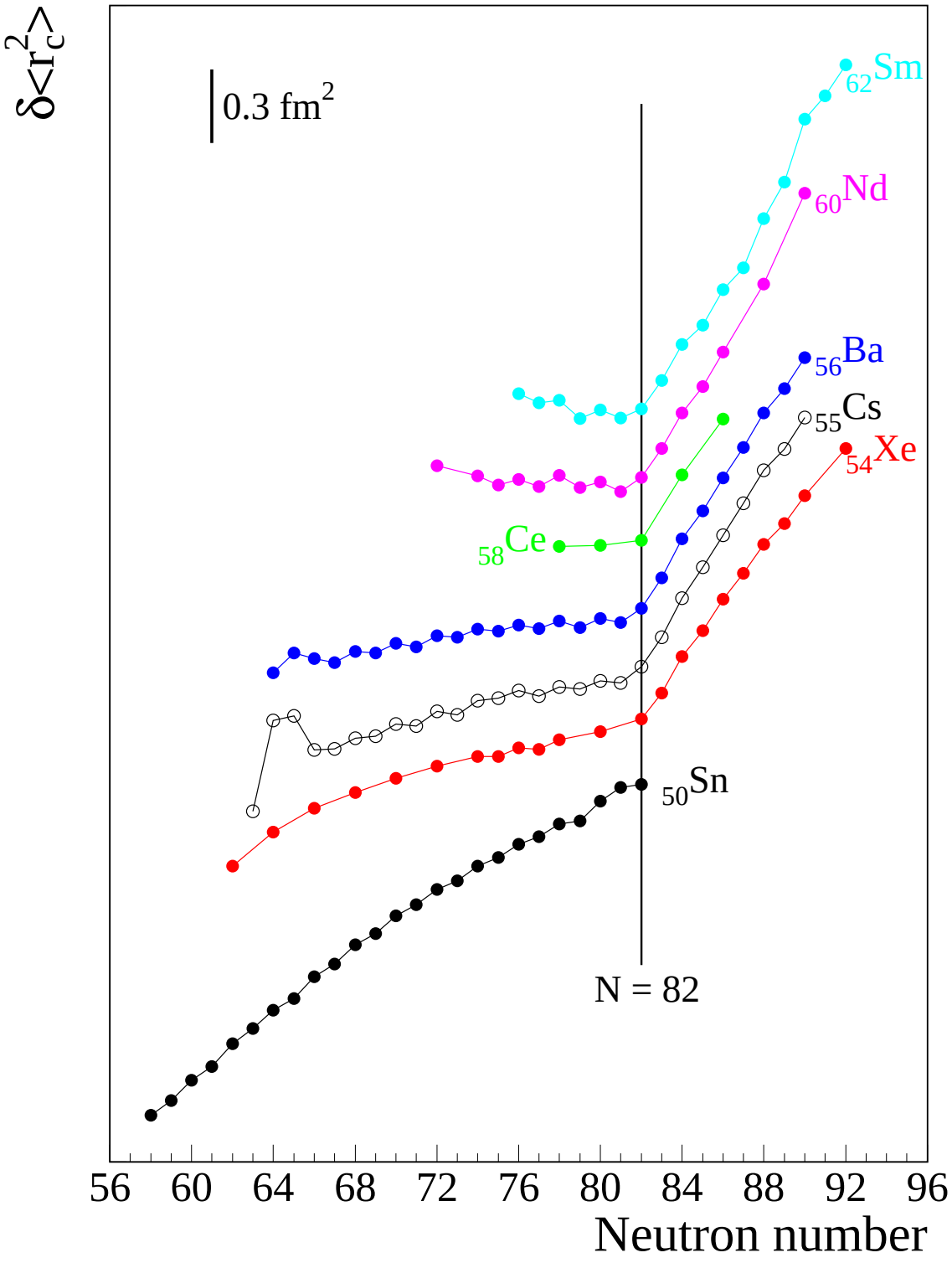

Figure 1: Changes in the mean square charge radius near N = 82.

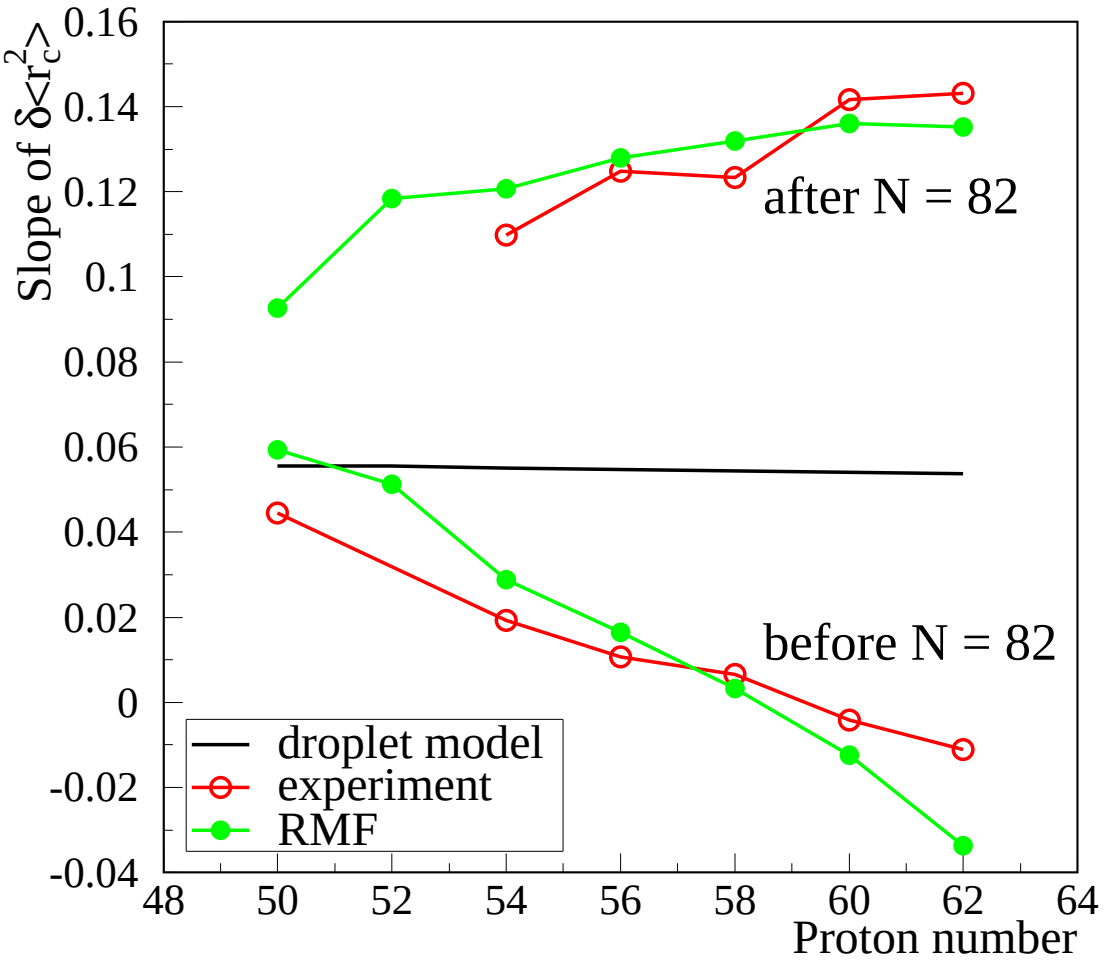

Figure 2: Slope of the $\delta <r_c^2>$ curve for the even-Z nuclei around N = 82. The experimental values have been calculated from the experimental $\delta <r_c^2>$ values of the even-even nuclei (from N $\geq$ 70 up to 82, and from N = 82 up to 86 $\leq$ N $\leq$ 92).

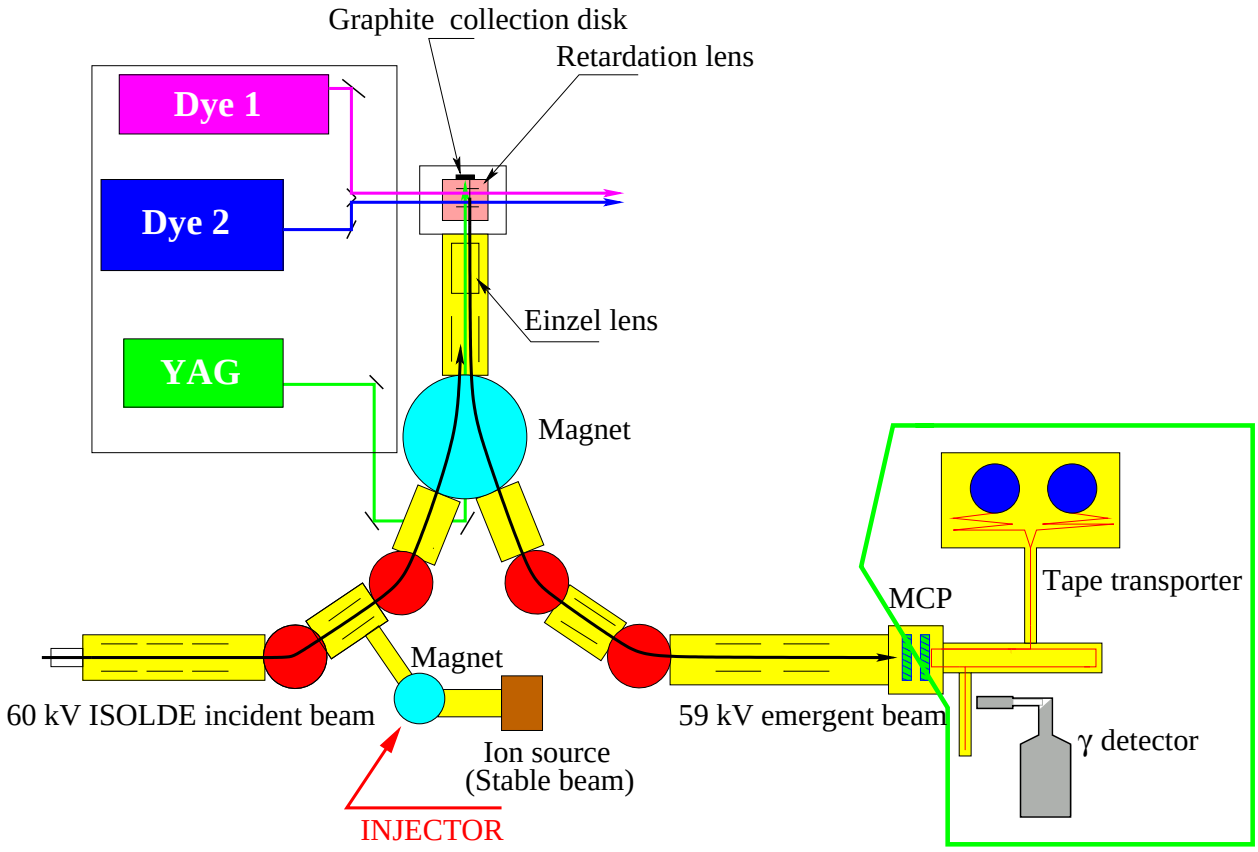

Figure 3: Schematic view of the COMPLIS experimental set up. The modifications brought to work in the SIINODE mode are framed by a green line.

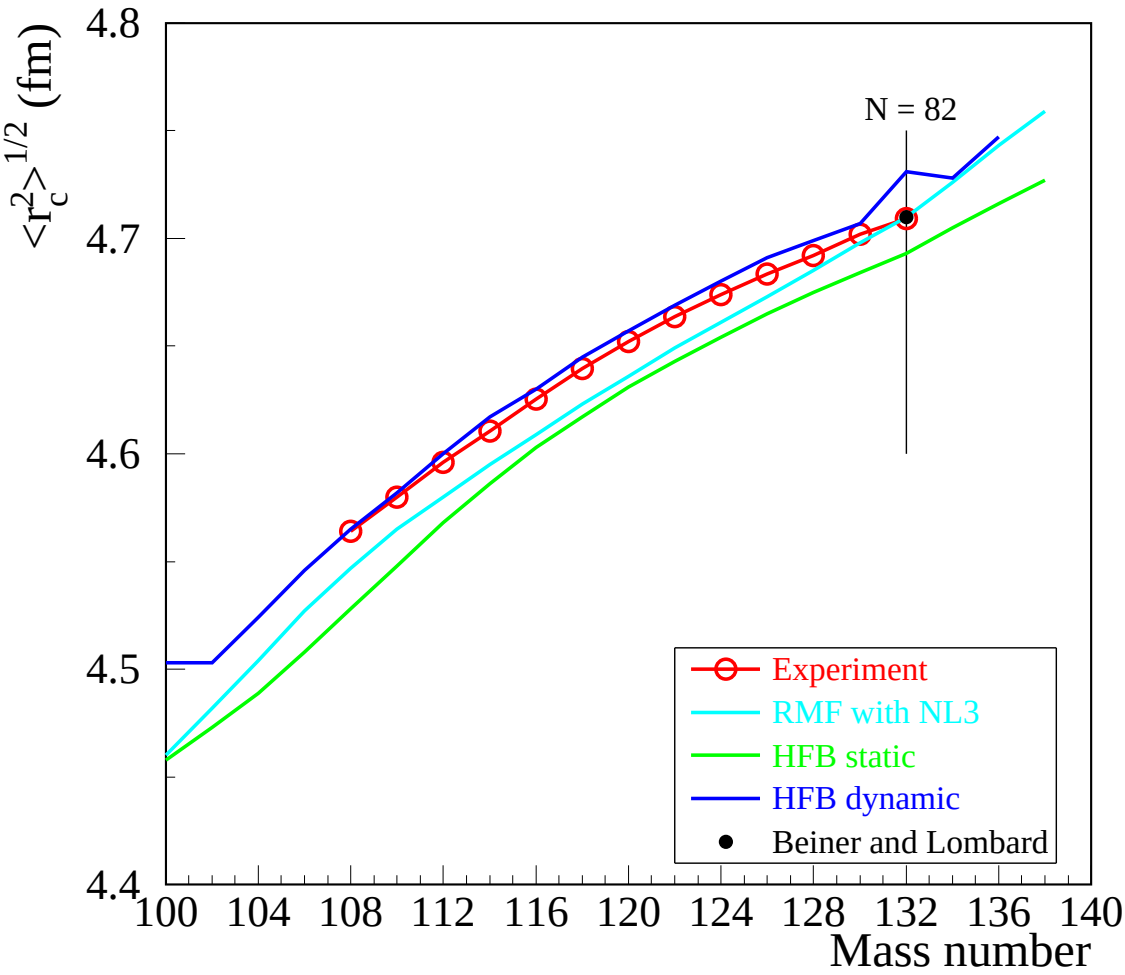

Figure 4: Experimental and theoretical charge radius for even tin isotopes.

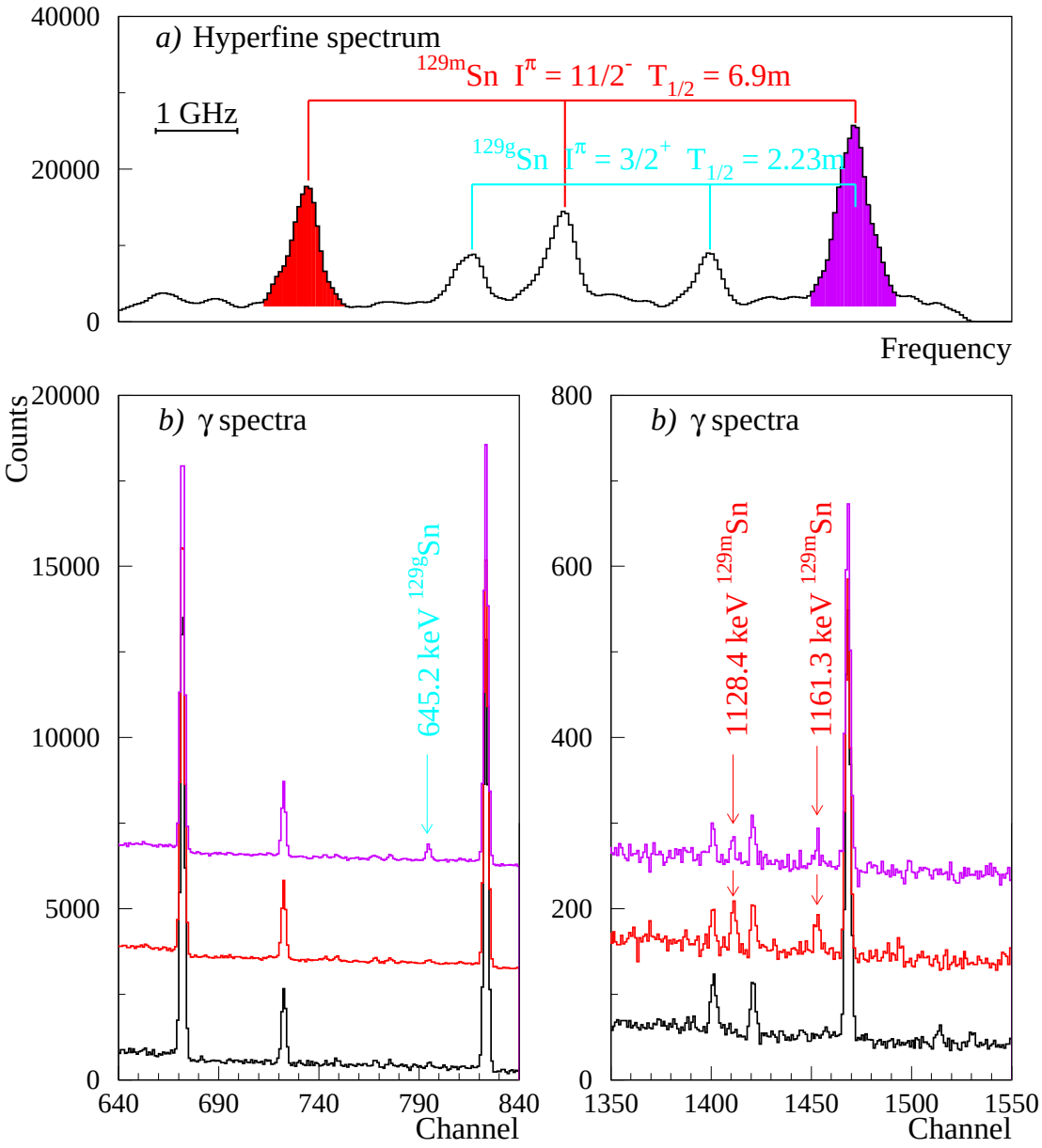

Figure 5: (a) Hyperfine spectrum obtained with COMPLIS on ^{129}Sn
(b)γ spectra obtained with SIINODE :
- in red, when the frequency of the excitation laser is set to a value corresponding to a hyperfine transition belonging to ^{129m}Sn
- in purple, when the frequency of the excitation laser is set to a value corresponding to a hyperfine transition belonging to both ^{129m}Sn and ^{129g}Sn
- in black, a background spectrum shown as a reference.

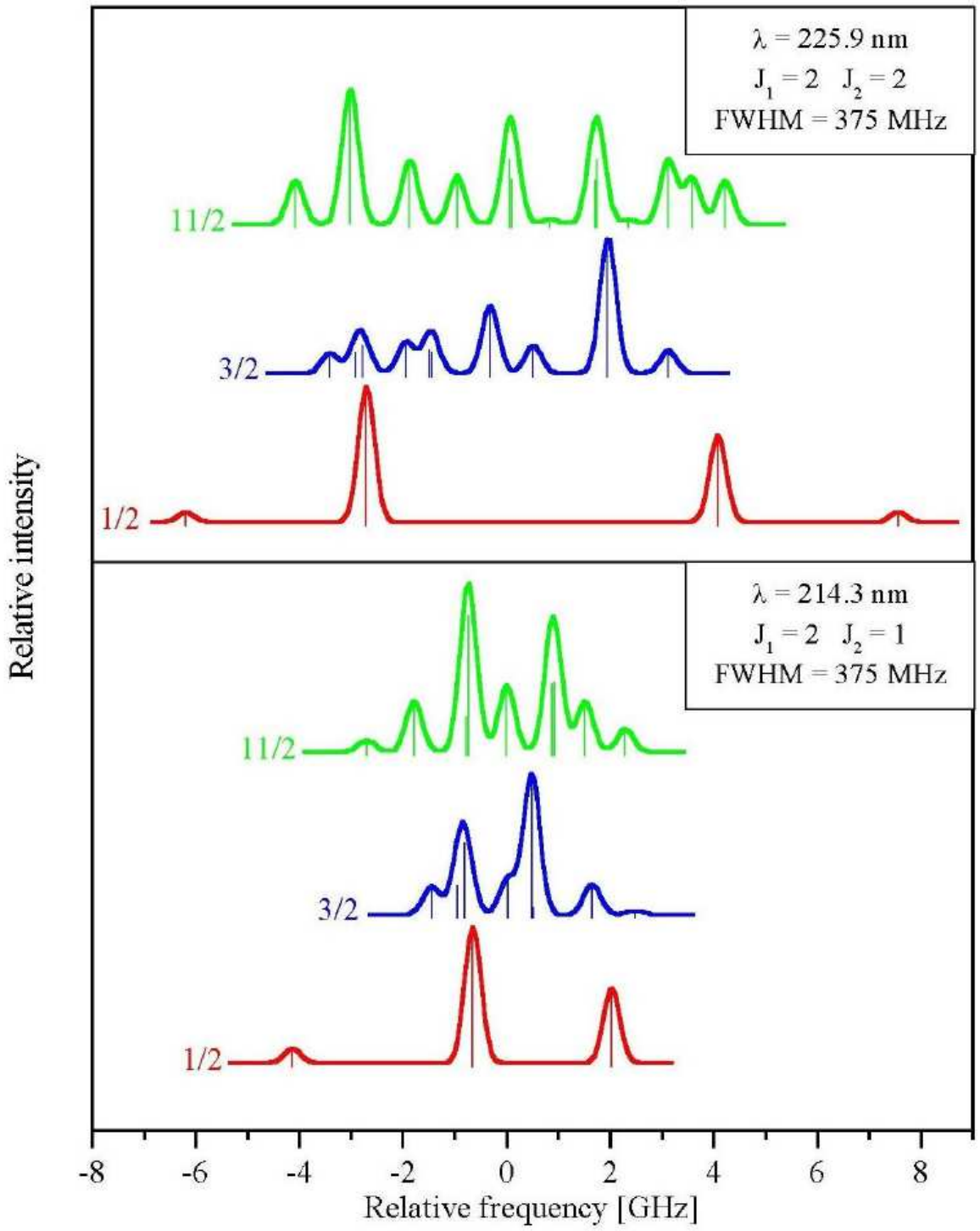

Figure 6: Expected hyperfine spectra for I = 1/2, 3/2 or 11/2.

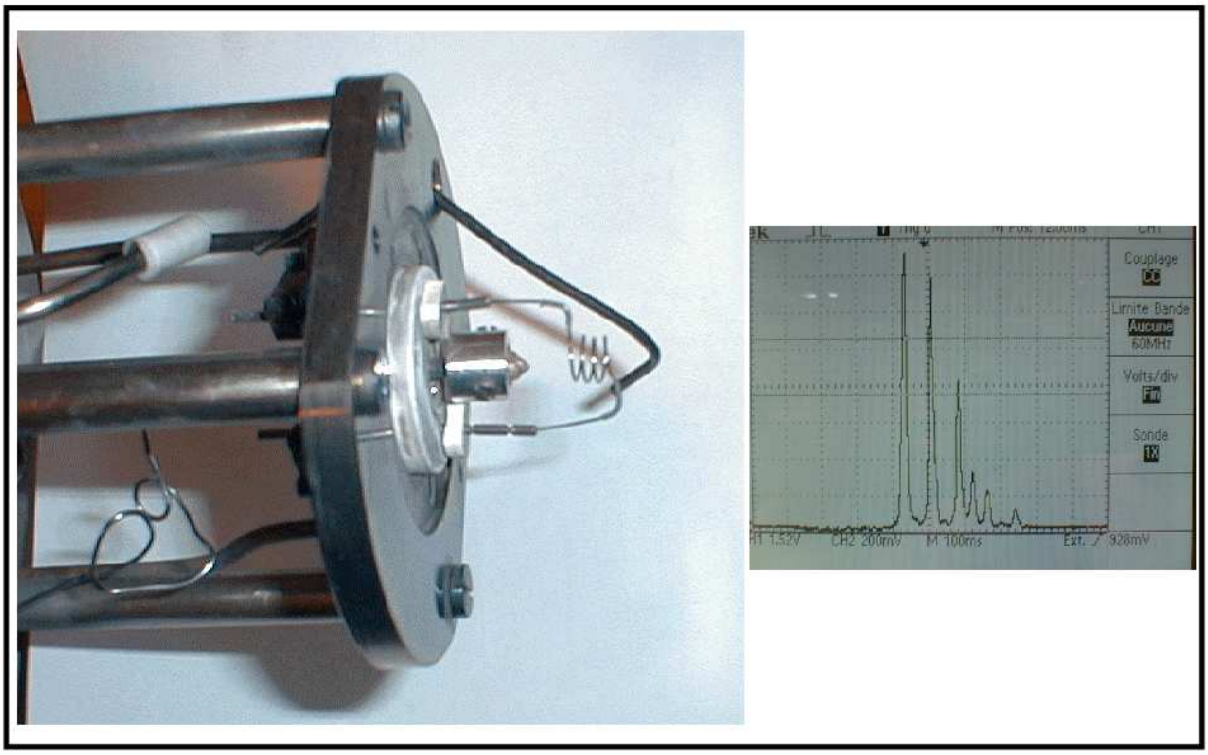

Figure 7: Ion source producing the Te stable beams from a NiTe alloy and the beam profile, showing the 130, 128, 126, 125, 124 and 122 masses, obtained in the focal plane of the first dipole of the injector.