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Laser Spectroscopy Studies in the Neutron-Rich Sn Region

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Summary
We propose to use the powerful laser spectroscopy method to determine the magnetic moment μ and the variation of the mean square charge radius ($\delta\langle r_c^2\rangle$) for ground and long-lived isomeric states of the Sn isotopes from A=125 to the doubly-magic ^{132}Sn isotope and beyond. For these neutron-rich Sn nuclei, numerous $\delta\langle r_c^2\rangle$ curves have already been calculated and the predictions depend upon the effective interactions used. Therefore, a study of the effect of the shell closure N=82 on the $\delta\langle r_c^2\rangle$ values in the Z=50 magic nuclei is of great interest, especially because ^{132}Sn is located far from the stability valley. It will help to improve the parameters of the effective interactions and make them more suitable to predict the properties of exotic nuclei.
The neutron-rich Sn isotopes produced with an uranium carbide target, are ionized using either a hot plasma ion source or the resonant ionization laser ion source RILIS. In both cases the purity of the ion beam is not perfect. Then, getting accurate results beyond A=132 is a challenge. Therefore, we will use the most suitable method depending on the experimental conditions : collinear laser spectroscopy on fast beam or resonant ionisation spectroscopy on laser desorbed beam using the COLLAPS and COMPLIS setup respectively. For Sn heavier than ^{134}Sn, performing measurements directly on the ion beam delivered by RILIS is planned as a later step, now under investigation. This method will enable us to extend measurements, that are impossible otherwise, to other elements for both neutron-rich and neutron-deficient isotopes very far from stability.

1. Physics motivation

The variation of the mean square charge radius ($\delta\langle r_c^2\rangle$) and static moments of nuclei have been studied in detail, via laser spectroscopy of the isotope shift and hyperfine structure in atomic transitions. Drastic changes in the slope of $\delta\langle r_c^2\rangle$ curves have been observed at neutron shell closure for N= 20, 28, 50, 82 and 126 and finer details of the nuclear shape have been revealed by the static moments μ_I and Q_s. For the proton magic elements, this slope change has been seen in the Pb (Z=82) isotope chain at N=126 [Th83] and in the Ca (Z=20) isotope chain at N=28. The behaviour of the $\delta\langle r_c^2\rangle$ curve at the shell closure N=82 has not yet been studied for the proton magic Sn isotopes.

The doubly-magic nuclei are of great interest in nuclear physics because their properties (binding energy, radius...) serve to perform parametrization of effective interactions used for mean-field calculations [Va72, De80]. For the last two decades, these calculations successfully described global properties of the nuclear ground states [Qu78, Gi83, Gi89, Pa99]. In the same time, the relativistic mean-field theory [Wa74] was getting success for describing nuclear ground state properties [Re89, B194, Pa99]. In parallel, numerous new and accurate experimental results were obtained making systematic data available along isotopic series from light to heavy nuclei. More recently, it appeared that the mean-field models had to be improved to correctly reproduce these precise results. This motivated many theoretical works in particular to improve the parameters of the effective interactions currently used.

For example, the $\delta\langle r_c^2\rangle$ curve extracted from isotope shift measurements in the Pb isotopes from A=190 to A=214 [Th83, An86, Di87, Du91] exhibits a slope change at the doubly-magic ^{208}Pb. All the mean-field calculations performed with the usual effective interactions (Skyrme forces, D1S force) failed to describe this slope change [Ta93] whereas the relativistic mean-field model could reproduce it especially when the NL-SH force is used [Sh93] (see fig. 1a). On the other hand, the latter failed to describe the Ca results [Re95, Pa99]. The $\delta\langle r_c^2\rangle$ curve of Pb isotopes has then been used to study a new pairing treatment [Ta93] and new parameters of the Skyrme force [Re95, Ch97, Ch98]. Thus, a better description was obtained (see fig. 1).

The goal of these theoretical studies is to define an effective interaction valid not only along the valley of stability but also for exotic nuclei.

We propose to measure the isotope shift from ^{125}Sn to ^{132}Sn and beyond in order to study the effect of the shell closure at N=82 on the $\delta\langle r_c^2\rangle$. This will provide a set of precise data on neutron-rich nuclei to study the effective interactions as suggested in [Re95].

One of the most important questions is : will the $\delta\langle r_c^2\rangle$ curve of Sn exhibit a slope change for ^{132}Sn as that of Pb does for ^{208}Pb ? To get a qualitative answer to this question we are comparing, in fig. 2, the behaviour of the $\delta\langle r_c^2\rangle$ curves of Ra, Fr, Rn and Pb (left hand side) with those of Ba, Cs, Xe and Sn (right hand side). All these curves exhibit a slope change for the N=126 and N=82 magic numbers. At the bottom of fig. 2, we show the evolution of the $\delta\langle r_c^2\rangle$ slopes just below (B) and above (A) the magic number. We can see that the slope change decreases when Z diminishes. From a rough extrapolation performed for Sn the slope is expected to change at N=82.

On the other hand, $\delta\langle r_c^2\rangle$ curves for neutron-rich Sn have also been calculated [Re97, Gi98] and the predictions depend on the type of calculation (see fig. 3).

2. Experimental methods

To clarify the above question we propose to measure hyperfine structure (HFS) and isotope shift (IS) by laser spectroscopy. This technique is indeed a powerful tool to get precise data on ground and long-lived isomeric states. The nuclear moments are extracted from the HFS while the IS provides the $\delta\langle r_c^2\rangle$ values along an isotopic chain. Getting good results beyond A=132

is a challenge. We will thus use the most suitable setup depending on the experimental circumstances : collinear laser spectroscopy on fast beam (COLLAPS), resonant ionisation spectroscopy on laser desorbed beam (COMPLIS) or even direct measurements at the Resonant Ionization Laser Ion Source (RILIS).
The neutron-rich Sn isotopes are produced by bombarding an uranium carbide target with the proton beam. The hot plasma ion source (HPIS) and the RILIS allow the ionization of Sn atoms. In 1999, we measured the yields of the elements produced by these two types of ion source. By use of HPIS, Cd, In, Sn, Sb, Te, I and Cs are also ionized (fig. 4). As an example for A=132, the Sn yield represents 0.24 % of the nuclei produced. Using RILIS a better purity is obtained : the Cd, In, Sb, Te and I are ionized only slightly, or not at all while the amount of Cs strongly increases; for A=132 Sn represents around 2.4 % of Cs. Unfortunately Cs which is very easily ionized, is expected to be much more perturbing than the other contaminants. This is why it is extremely difficult to decide what is the best laser spectroscopy method to use before testing them in actual experimental circumstances.

COLLAPS

Collinear laser spectroscopy has been used for the study of the atomic hyperfine structure and the isotope shift in many elements throughout the periodic table. It is the main advantage of this method that it can be used for any beam from ISOLDE, provided there are suitable spectral lines existing for excitation by a narrow-band cw laser. Such spectral lines can usually be reached by charge-transfer neutralization of the ion beam into a long-lived atomic state. Using this scheme, Eberz et al. [Eb87] investigated the radioactive isotopes $^{108\text{-}111}$Sn at the GSI on-line mass separator. Two transitions from the metastable $5p^2\ ^1S_0$ level, either to 5s6p $^1P_1$ (452 nm) or to 5s6p $^3P_1$ (563 nm) can be used, both decaying by fluorescence in the ultraviolet to the ground state.
At ISOLDE, the heavy Sn isotopes are produced in a UC target as fission products and the mass separated beams are strongly contaminated by isobars from heavier elements. This has been studied in detail for targets coupled to a hot plasma ion-source and to a laser ion-source.
First tests at the collinear setup at ISOLDE would have to clarify the competitive advantages of either transition from the sensitivity point of view. The existing apparatus for collinear laser spectroscopy is nowadays mostly used in combination with sophisticated high-sensitivity detection schemes or in combination with a β-NMR setup, both for light elements [Kl96,Ke95]. However, as the fluorescence detection is usually available in parallel, there will be no serious interference with the experimental programme planned to succeed IS304. The only concern will be about the long-lived radioactivity collected in the apparatus during experiments on Sn isotopes. This will make a careful beam time planning necessary.
As a rule of thumb, one can expect that yields of about 10^6 to 10^7 atoms per second will be necessary for the envisaged detection of optical transitions. The resolution will be generally superior to the other methods.
It is known from yield measurements that the hot plasma ion source may give huge isobaric contamination on the Sn masses of interest. This will not directly disturb the selective optical measurement, but it may involve background light produced by collisions of the abundant isobars either in the charge-exchange cell or in the residual gas. Again the main concern about the isobars is the radioactivity, not only contaminating the apparatus, but also giving rise to background in the photon counting system. It may therefore be necessary to use the laser ion source.
In order not to spoil the narrow energy distribution of the beam - which directly affects the resolution and sensitivity of collinear laser spectroscopy - the laser ion source should be

constructed without any special device for fast and more efficient extraction of the ions, just as an ordinary surface ion source.

COMPLIS

The COMPLIS setup: It has been designed to perform Resonance Ionization Spectroscopy (RIS) on a pulsed secondary atomic beam produced by laser desorption. The radioactive isotopes produced by ISOLDE enter the COMPLIS beam line where they are guided by electrostatic elements and a magnet, are slowed from 60 kV down to 1 kV and implanted into the first atomic layers of a graphite collecting disk (see fig. 5). Then, the atoms are desorbed using a pulsed, frequency-doubled Nd : YAG laser beam. This produces the pulsed secondary atomic cloud. Some microseconds later the desorbed atoms are ionized in a two or three step RIS process (inset, fig. 5). The resulting photoions are then accelerated by the 59 kV high voltage of the retardation lens. They are deflected in a symmetrical way relative to that of the incident ions by the magnet. Then, they are guided to a microchannel plate (MCP) detector and mass-identified by their time of flight. For each frequency step, the ion signal is integrated using a digital oscilloscope and the data are sent into a multitask SUN workstation that also controls the motion of the collecting disk, the firing of the laser and the frequency scan. An injector (an auxiliary ion source coupled to a small mass spectrometer) allows us to send stable ion beams into the COMPLIS incident beam line before the experiment, in order to optimize the ionization and desorption efficiencies (see fig. 5).
To obtain a hyperfine spectrum, the first excitation step of the RIS scheme is scanned. To produce the required single-mode pulses, a dye cell pumped by a second frequency-doubled Nd : YAG laser is inserted into the cavity of a commercial cw single mode tunable dye laser (Coherent model 599) [Pi77]. The resulting pulses are further amplified in two additional dye cells. The ionization step is obtained using a Lambdaphysik dye laser pumped by the same Nd : YAG laser. The two laser beams cross at right angles in the interaction region to reduce Doppler line width broadening. The time synchronization of the pulses is insured by adjustment of an optical delay line. The cw radiation is analysed by a fixed 10 cm spacing confocal Fabry-Perot interferometer, which provides the frequency-scale.
With the COMPLIS setup, good frequency resolution is obtained but at the expense of efficiency ; the overall efficiency is typically 10^{-5} for a frequency resolution around 300 MHz.

Results obtained: Up to now, this setup has been used to study the isotopes obtained by radioactive decay of Hg ions available at ISOLDE, namely: Au, Pt and Ir. A delay between collection and laser desorption was then chosen to optimize the amount of the studied atoms. For nuclei with a half-life long enough ($T_{1/2}$>1s), we could accumulate the number of collected ions but the sensitivity of the setup was then limited by the progressive increase of the background during the collecting time and the delay.
Numerous new results have however been obtained on nuclear moments (μ, Q_s) and change in the mean square charge radius $\delta < r_c^2 >$for Au, Pt and Ir isotopes[Le97, Le99, Ve99]. To illustrate the quality in frequency resolution we can obtain with the COMPLIS setup we show, in fig. 6, the hyperfine spectrum recorded for the ^{184}Au isomeric and ground states. To identify the two isomers, different collecting times have been used [Le97] .

In fig. 7 are shown the $\delta < r_c^2 >$ values we have determined with COMPLIS for Au, Pt and Ir isotopes together with those previously measured for Hg [Ul86], Au [Wa89, Sa90, Kr88] and Pt [Hi92, Du89]. A progressive decrease of the change in the mean square charge radius as the neutron number diminishes, corresponds to an increase in deformation. So, for the even Pt nuclei, we can see in fig. 7 that the deformation increases from N=110 to N=102 and starts to decrease at N=100. Thus, the maximum deformation is found for N=102. Furthermore, in addition to a strong inverted odd-even staggering that appears around the neutron mid-shell in the Pt isotopes, a deformation change is indicated between isomeric and ground states of the ^{184}Au, ^{183,185}Pt and ^{186}Ir nuclei. These results show that the nuclear deformation is highly influenced by the coupling of one or two single particles to the core, illustrating the softness of these exotic nuclei. In the case of the Pt isotopes, the comparison of the measured $\delta < r_c^2 >$ values with those predicted in the framework of microscopic Hartree-Fock-Bogoliubov (HFB) calculations using the Gogny force suggests that the odd-even staggering observed around N=104 is due to shape changes : the even Pt isotopes have a triaxial shape with an asymmetry parameter γ around 15°, and the odd Pt nuclei a prolate shape as also suggested by the nuclear moment values [Le99].

Furthermore, in fig. 7, one can see that the odd-proton Ir and Au isotopes have a similar behavior. A sudden deformation increase observed between A=187 and A=186 can be associated with the change of the proton state. The proton occupies indeed the $3/2^+$ [402] or $1/2^+$ [400] state for $A \geq 186$ and the 5/2 $1/2^-$ [541] or 3/2 $3/2^-$ [532] intruder state arising from the $h_{9/2}$ subshell for $A \leq 186$ [Ve99]. We have to note that the coupling of a neutron to the single proton has little or no influence on the nuclear deformation in both Au and Ir isotopes. On the other hand, for the even-proton Pt isotopes with A<186, the coupling of a neutron to an even-even core highly influences the nuclear deformation, whatever the involved neutron state may be (fig. 7). This behavior is similar to that already observed for the coupling of the $1/2^-$ [521] neutron state, in the Hg isotopes [Ul86]. Moreover, for this $1/2^-$ [521] neutron state, the odd-even staggering increases as A decreases for both the Hg and Pt isotopes [Ul86, Ro98] (fig. 7).

Nevertheless, in general, the nuclear deformation changes observed below A=186 are less and less pronounced as the proton number drops below Z=82. This rather high instability in deformation could be due to the presence of the neutron midshell located very far from the β stability valley for these elements. The beginning of a deformation instability has also been observed around the neutron midshell N=66 for the Ba and Cs isotopes located also far from stability [Sa93].

The COMPLIS setup for Sn studies :

- The first excitation step of the RIS process we will use corresponds to the $5s^2 5p^2\ ^3P_0 \Rightarrow 5s^2 5p6s\ ^3P_1$ transition at 286.4 nm. The single mode laser pulses will be obtained from frequency doubling. For the ionization, a frequency doubled laser beam at 410 nm will be used. This optical scheme has already been tested.
- A rather good frequency resolution (~250 MHz) can be achieved as shown in fig. 6.
- The collected ions can be accumulated for isotopes with a half-life larger than 1s. This allows i) an increase of the amount of the studied atoms and ii) the identification of the

resonant lines that belong either to the isomeric state or to the ground state, which is not possible with the other methods. Such an identification will be necessary for the 127-130 masses.

- The yields from A=125 to A=132 are high enough to perform measurements, provided the Cs ionization efficiency remains at a low level.
- No delay between collection and desorption is necessary since the Sn isotopes are directly produced. So, for the isotopes with a short half-life (< 2s), the collection and desorption can be simultaneously performed, which should prevent from background accumulation and most probably should improve the COMPLIS efficiency. This could enable us to measure the ^{133}Sn and ^{134}Sn.

Direct measurements on the RILIS

For Sn isotopes heavier than A=134, the Sn yield is not high enough to perform laser spectroscopy measurements using both the COLLAPS and COMPLIS setup. Therefore, such measurements should be done directly on the RILIS ion beam. To get accurate results the frequency resolution of the RILIS laser setup must be improved. We are discussing what is the best way to solve this resolution problem. This method, in spite of a frequency resolution rather worse, will enable us to perform laser spectroscopy measurements on other elements for both neutron-rich and neutron-deficient isotopes that are located very far from stability and that cannot be studied using the two other methods.

3. Beam time request

We plan to carry out the measurements of Sn isotopes up to A=134 before the end of 2001. At first, it is necessary to test the two first methods, namely COLLAPS and COMPLIS and then to realize the experiment using the method having the strongest sensitivity. Then, we ask for:

• testing the use of COLLAPS	8 shifts
• testing the use of COMPLIS	8 shifts
• performing the experiment	20 shifts
This represents in total	36 shifts

In the present proposal no shift is asked for performing measurements directly on the RILIS ion beam since the precise experimental procedure is not yet defined. This procedure can depend on the results we will obtain using the COLLAPS and/or COMPLIS setup.

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Figure captions

Fig. 1 Comparison of the calculated $\delta < r_c^2 >$ curves with the experimental results.
a) relativistic mean field theory with the NL-SH and NL1 forces and mean field calculations with the SkM* Skyrme force, b) mean field calculations with the new Skyrme force Sly4, c) same as b) but with Sly7 that takes into account both the spin gradient and the two-body center of mass contributions, d) same as c) but with also a new spin-orbit term.

Fig. 2 Slopes of $\delta < r_c^2 >$

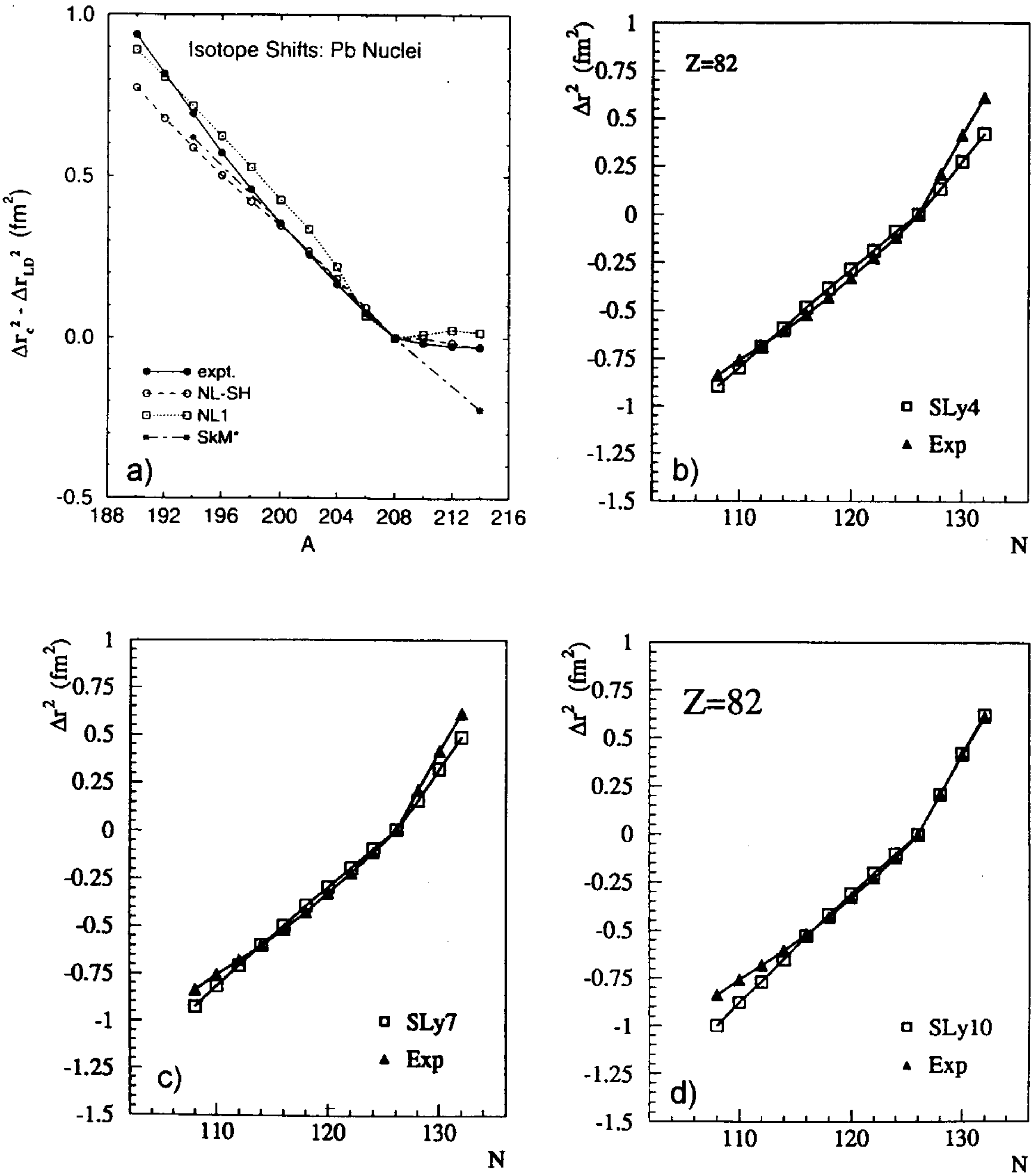
Fig. 3 $\delta < r_c^2 >$ calculated for mean field theory (HFB Gogny, SkyrmeI and SkI4 forces) and relativistic mean field model (NL3 and NL-2 forces)[Re97, Gi98]. The curves have been normalized for A=122.

Fig. 4 Mean number of neutron-rich nuclei per second obtained with a collecting time from 10 to 50 ms performed immediately after a proton pulse of 1μC bombarding an uranium carbide target at 2070 degrees coupled to a hot plasma ion source. The mean number of Sn nuclei per second measured in the same way using the same target at 2100 degrees coupled to RILIS are reported as points linked by dotted line. The values not connected by lines correspond to Sn isomeric states. The values of isomeric states of the other elements have also been determined but they are not reported.

Fig. 5 The COMPLIS setup. The insert shows the ionization scheme used for platinum atoms.

Fig. 6 Hyperfine spectrum of $^{184}Au^{g+m}$ (the ground state lines have been magnified by a factor of 5). The two spectra above the experimental one have been calculated with the extracted hyperfine constants A and B and the isomeric shift.

Fig. 7 $\delta < r_c^2 >$ values for Hg [Ul86], Au [Wa89, Sa90, Kr88, Le97] and Pt nuclei [Hi92, Du89, Le99]. The preliminary values displayed for $^{182-189,191,193}Ir$ have been estimated using the F factor deduced from a measured λ value [Sa89]. The values not connected by lines correspond to isomeric states.



Isotope Shifts: Pb Nuclei
expt.
NL-SH
NL1
SkM*
a)
A
Z=82
SLy4
Exp
b)
N
SLy7
Exp
c)
N
Z=82
SLy10
Exp
d)
N

fig. 1

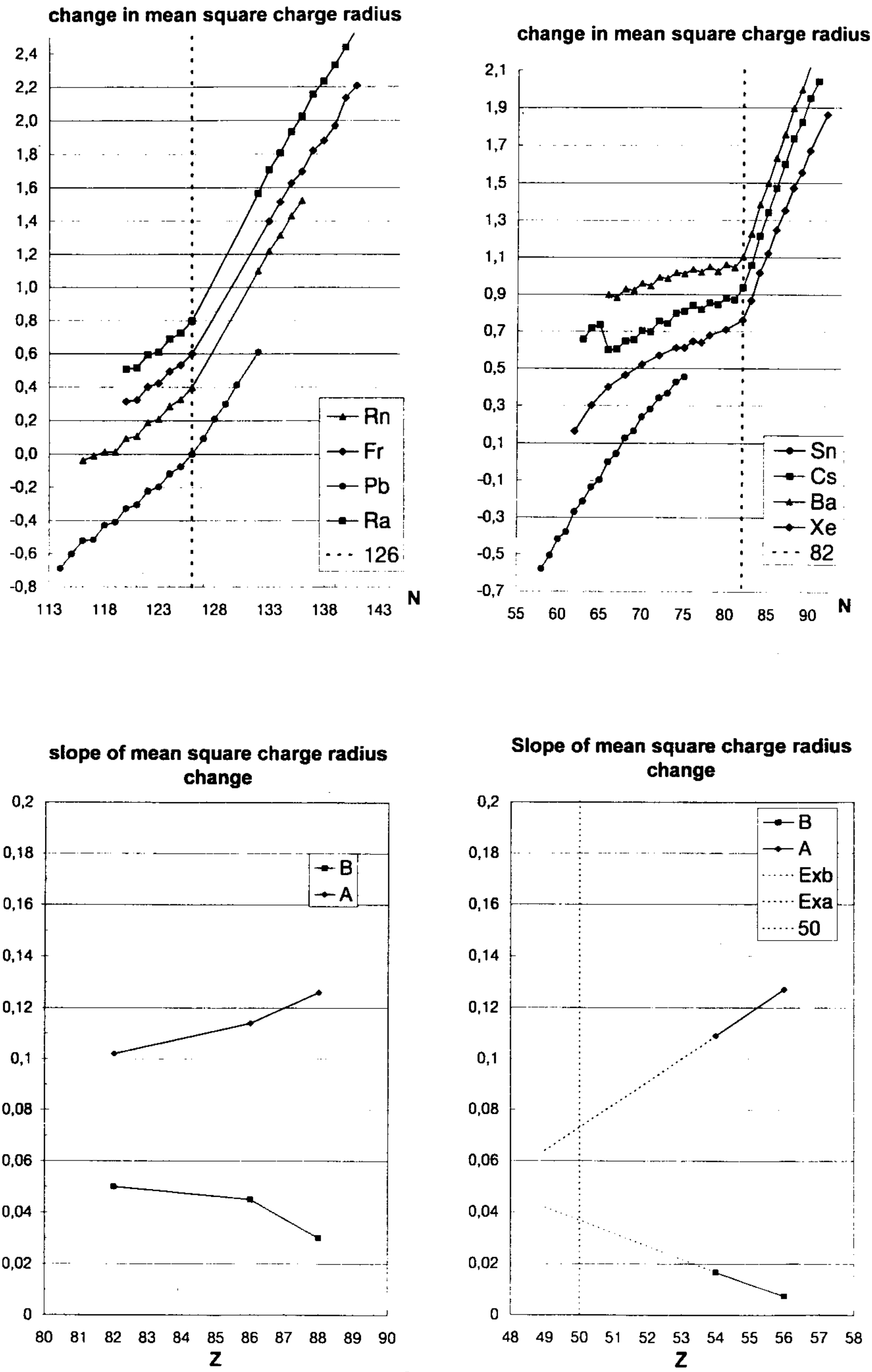

change in mean square charge radius
Rn
Fr
Pb
Ra
126
N
change in mean square charge radius
Sn
Cs
Ba
Xe
82
N
slope of mean square charge radius change
B
A
Z
Slope of mean square charge radius change
B
A
Exb
Exa
50
Z

fig. 2

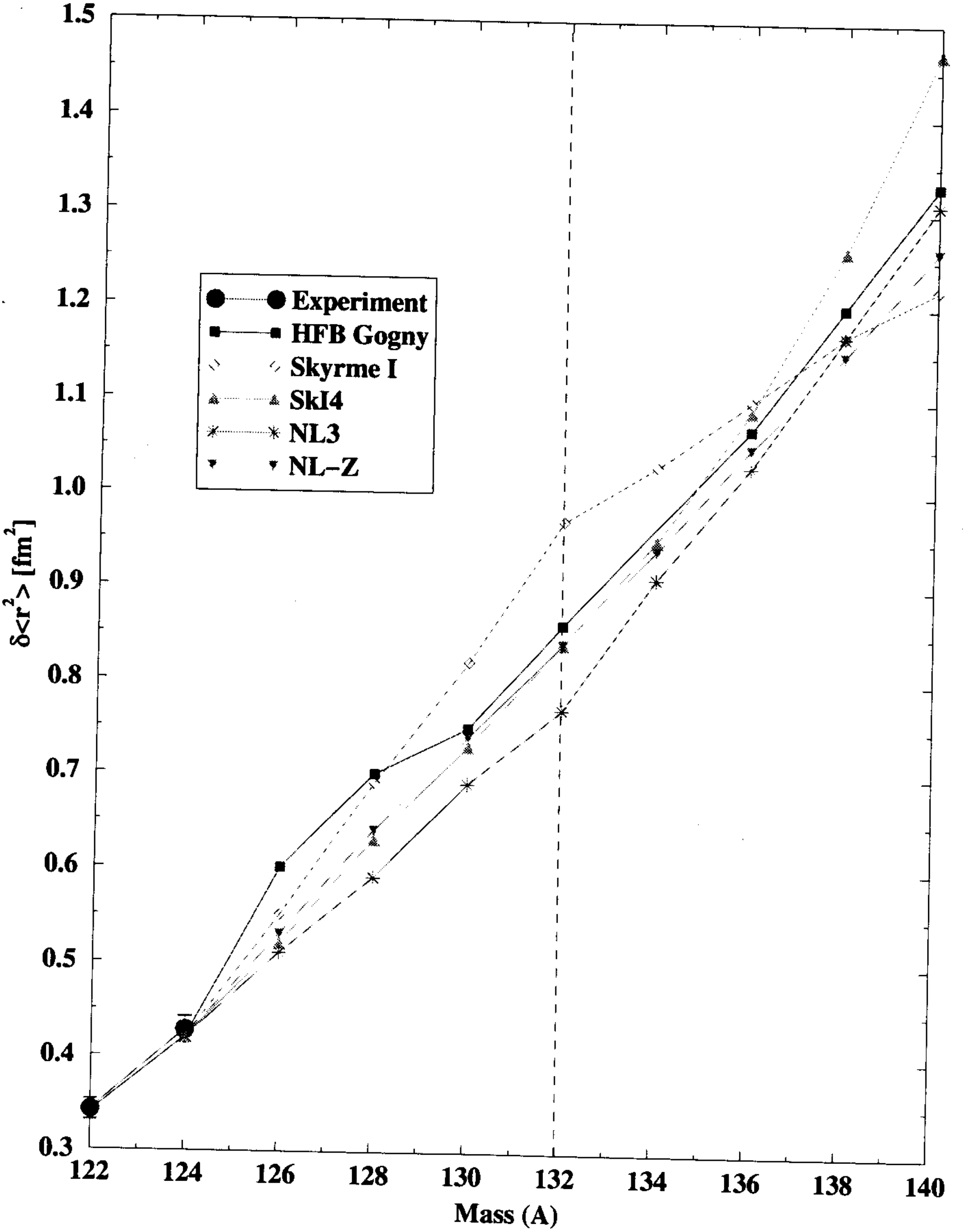

Experiment
HFB Gogny
Skyrme I
SkI4
NL3
NL-Z
δ<r²> [fm²]
Mass (A)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
122
124
126
128
130
132
134
136
138
140

fig. 3

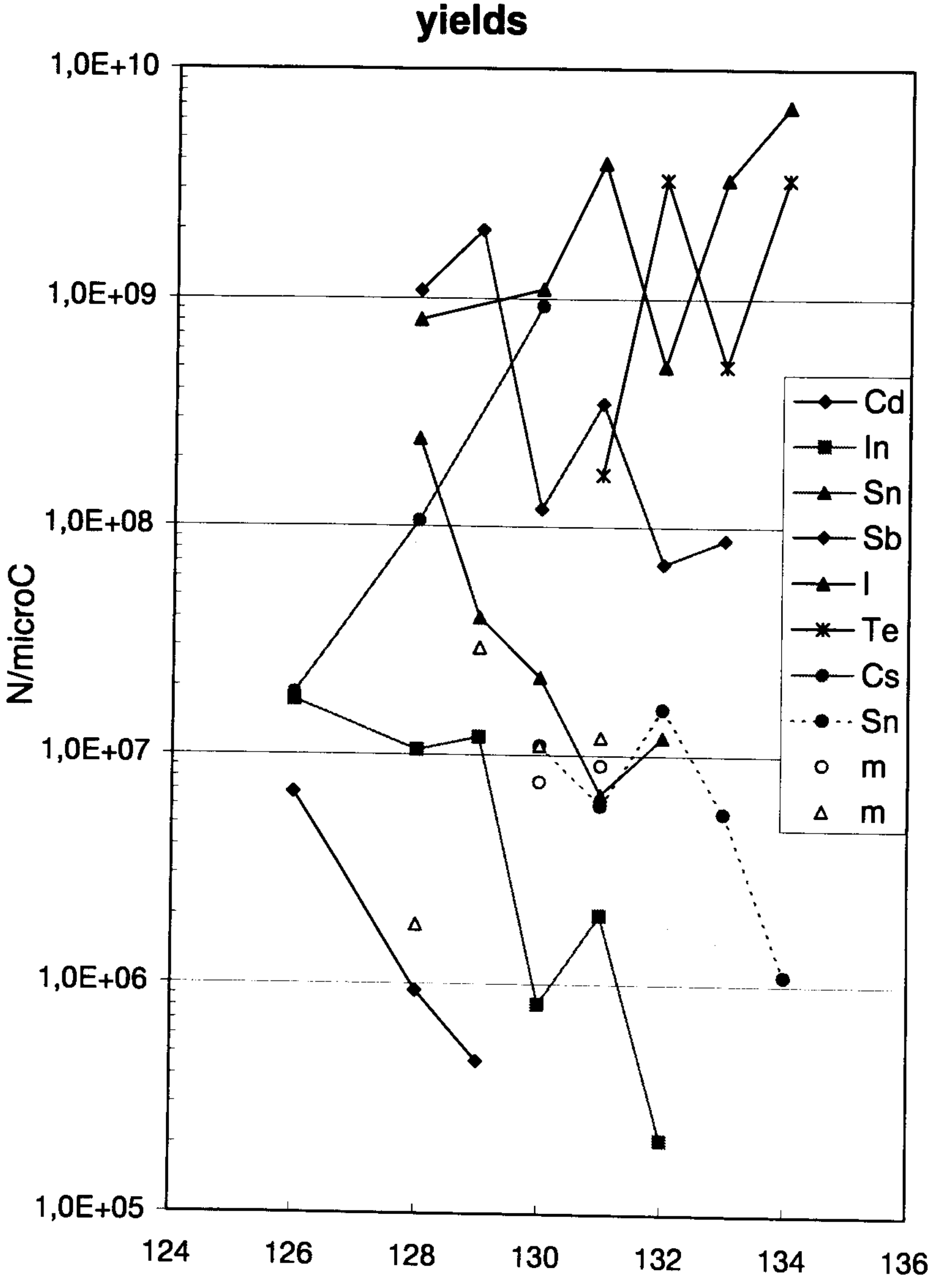

yields
1,0E+10
1,0E+09
1,0E+08
1,0E+07
1,0E+06
1,0E+05
N/microC
124
126
128
130
132
134
136
A
Cd
In
Sn
Sb
I
Te
Cs
Sn
m
m

fig. 4

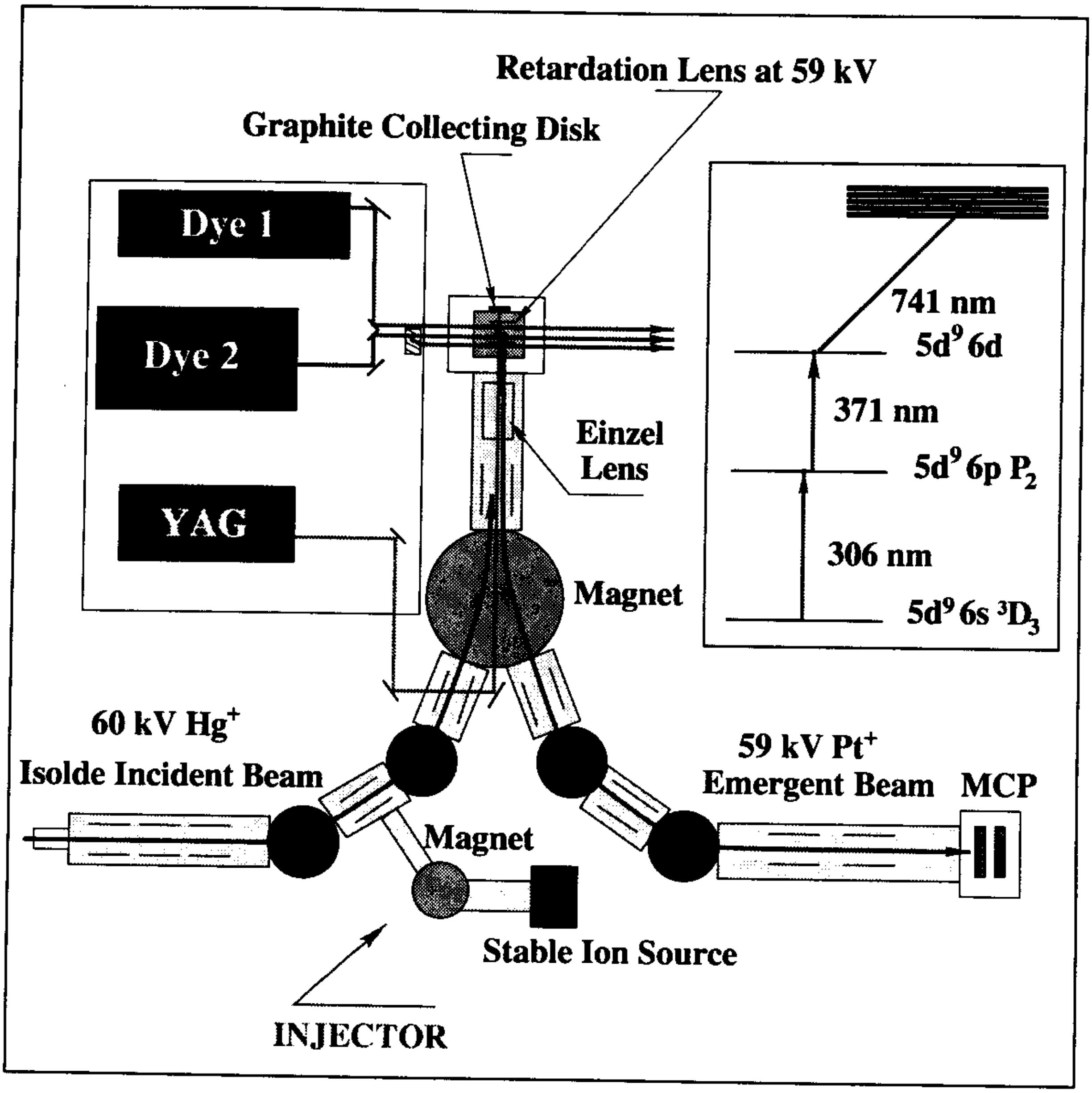

Retardation Lens at 59 kV
Graphite Collecting Disk
Dye 1
Dye 2
YAG
Einzel Lens
Magnet
741 nm
5d⁹ 6d
371 nm
5d⁹ 6p P₂
306 nm
5d⁹ 6s ³D₃
60 kV Hg⁺
Isolde Incident Beam
59 kV Pt⁺
Emergent Beam
MCP
Magnet
Stable Ion Source
INJECTOR

fig. 5

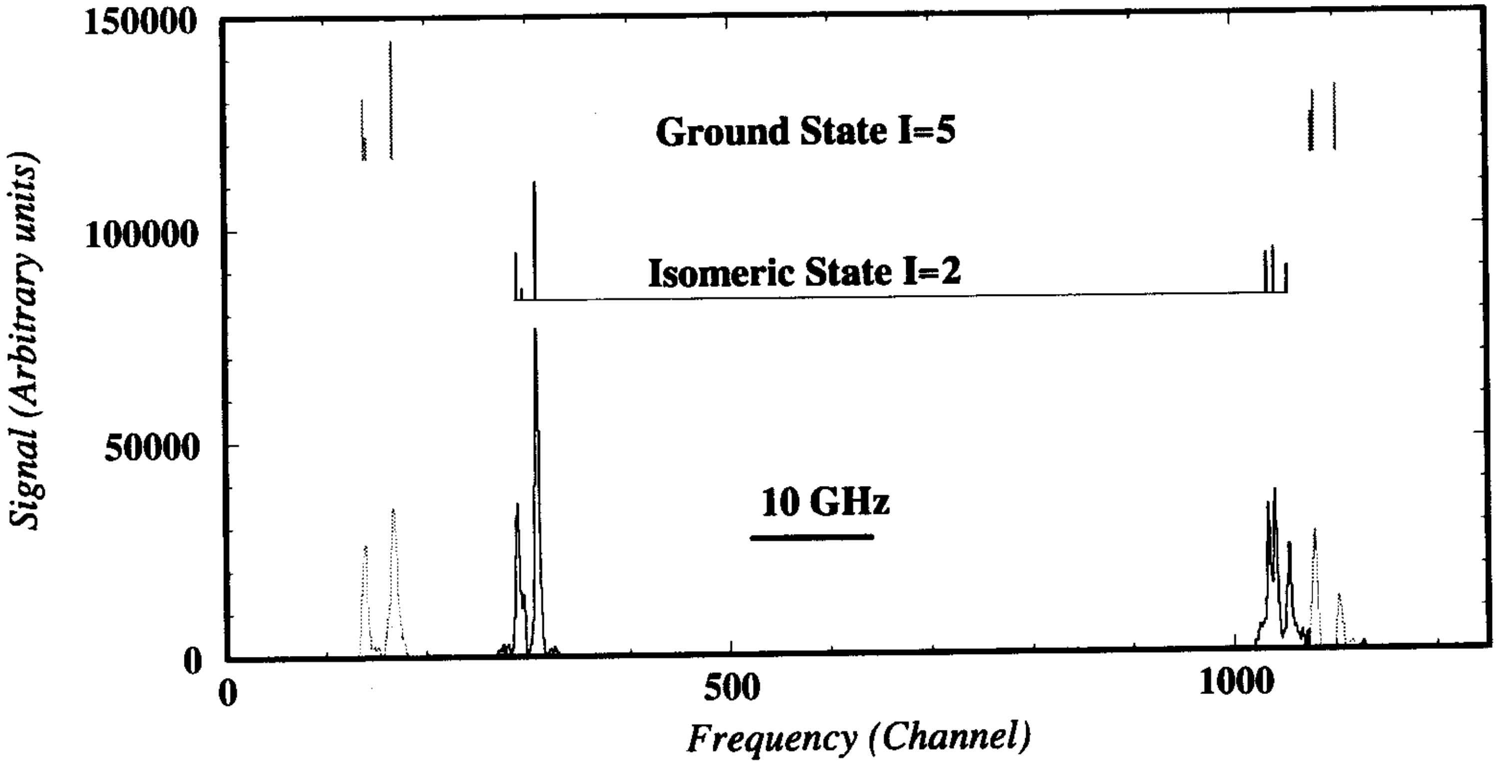
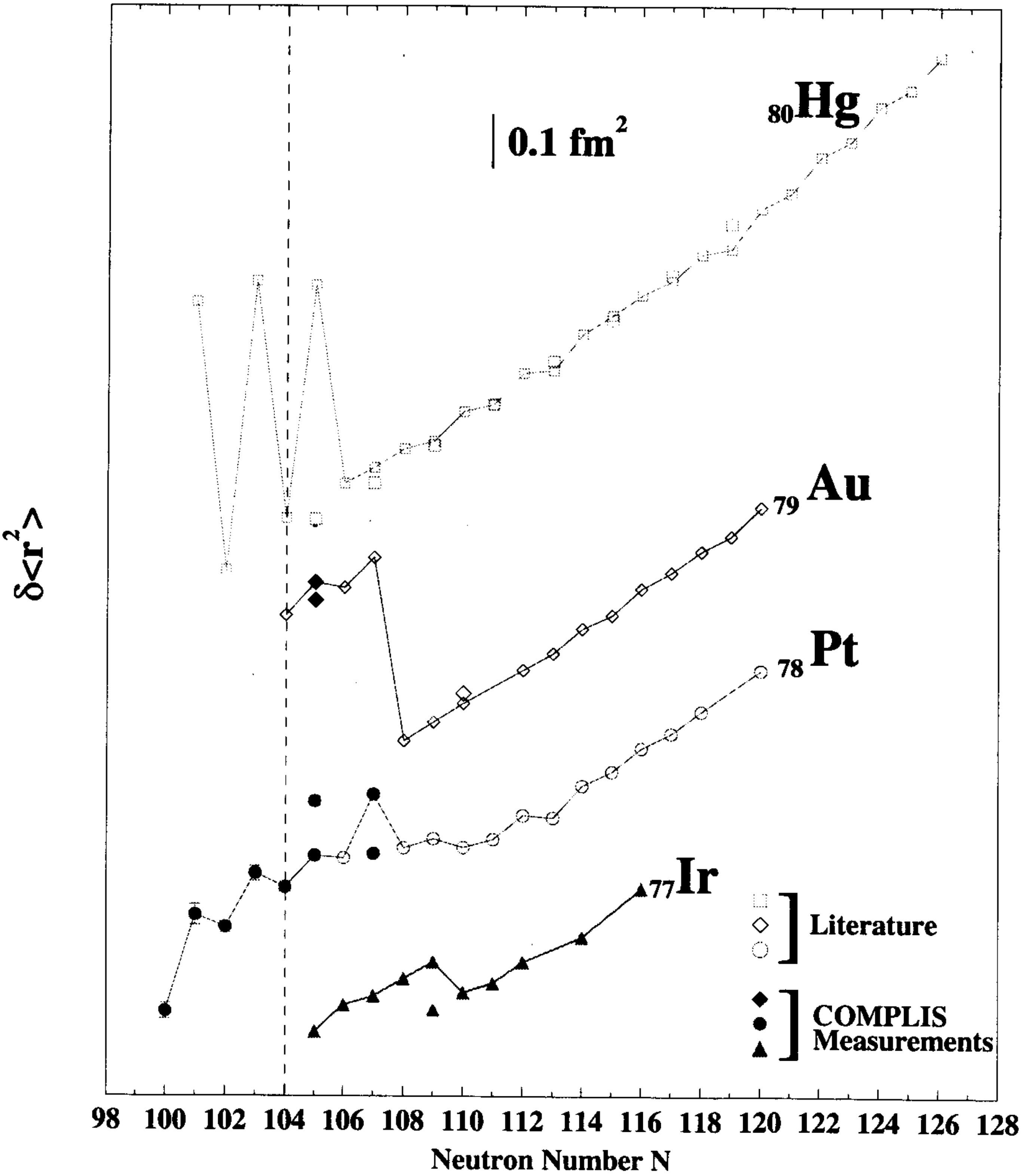

150000
100000
50000
0
Signal (Arbitrary units)
Ground State I=5
Isomeric State I=2
10 GHz
0
500
1000
Frequency (Channel)

fig. 6



80Hg
0.1 fm2
79 Au
78 Pt
77Ir
Literature
COMPLIS
Measurements
δ<r2>
98 100 102 104 106 108 110 112 114 116 118 120 122 124 126 128
Neutron Number N

fig. 7