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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 using the COMPLIS experimental set-up which allows Resonant Ionization Spectroscopy (RIS) on laser desorbed atoms. 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. 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 lying beyond the neutron shell closure at N = 82. The neutron-deficient Te isotopes will be obtained by radioactive decay of Xe (Xe $\rightarrow$ I $\rightarrow$ Te) which are produced using a cerium oxide target. The neutron-rich Te 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 $^{116-121}$Te and $^{129-136}$Te ground states and on the ^{129,131,133}Te isomeric states. It is worth noting that, for the neutron-deficient Te isotopes which are not produced as ISOLDE ion beams, COMPLIS is absolutely necessary to perform laser spectroscopy measurements. But even for the neutron-rich Te isotopes directly produced by ISOLDE, COMPLIS presents some advantages: *i)* it works even if the ISOLDE ion beam is not pure, which is the case for Te and *ii)* it allows the discrimination between the hyperfine lines corresponding to the ground state and those associated with the isomeric state.

The change in the mean square charge radius through the Te isotopes will bring information about:

- the role played by the neutron shell closure at N = 82 for isotopes close to the magic number Z = 50; the $\delta <r_c^2>$ have been measured for the even-Z (Z $\geq$ 54) isotope series and the Te series will allow the study of the variation of the kink at N = 82 from Z = 62 down to Z = 52.
- the role played by the dynamic degrees of freedom in the nuclei near Z = 50.

The determination of the nuclear moments in the odd Te nuclei will provide information on the structure of the states. Moreover the measurement of the isomeric shift in ^{129,131,133}Te will bring indication on the influence of the single particle coupled to the core on the deformation of the nucleus.

1 Physics motivations

The tellurium isotopes belong to the region of shape instability located just above the Z = 50 shell closure. Coexistence between spherical and deformed intruder states has 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 $\frac{9}{2}^+$ state corresponding to the excitation of a $1g_{9/2}$ proton hole have been observed. This $\frac{9}{2}^+$ proton state ($\frac{9}{2}^+$[404] Nilsson state) corresponds to a large nuclear deformation that increases with Z moving away from Z = 50 and N going close to the middle of the neutron shell (N = 66). Moreover, for N $\sim$ 66 in each isotopic series, this $\frac{9}{2}^+$ state exhibits an energy minimum and 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. The negative parity states originate from the $h_{11/2}$ subshell : from Te to Xe and Ba, the character of the negative parity band is changed from a decoupled ΔI = 2 to a ΔI = 1 sequence [9]. The structure observed for this band is strongly correlated with the triaxiality of these nuclei [9-11]. However the softness of the nucleus increases when Z decreases down to 50 [9]. The positive parity states arise from the $s_{1/2}$, $d_{3/2}$, $d_{5/2}$ and $g_{7/2}$ subshells. Here again, the nuclei appear to exhibit a large softness in the γ direction and the dynamical deformation becomes important [9, 12]. Moreover near the neutron mid-shell, the nuclei exhibit prolate-shaped states corresponding to larger β deformation, for instance the strongly deformed $\frac{5}{2}^+$[413] ground state in $^{121}_{56}Ba_{65}$ [13], the slightly deformed $\frac{5}{2}^+$[402] and $\frac{7}{2}^+$[404] states located at low energy (E < 450 keV) in $^{117,119}_{52}Te_{65,67}$ and $^{121}_{52}Te_{69}$ [14].

Laser spectroscopy is a powerful tool to study the deformation properties of the ground and isomeric states. Using this technique in a region of shape instability provides a deep understanding of the coupling mode of the odd particle(s) to the core and of the influence of the particle coupled to the core on the deformation of the nucleus as shown by numerous studies in the Hg-Au-Pt-Ir region [15-25]. Laser spectroscopy has also provided very interesting results in the isotope series near Z = 50. One can mention the following features :

- at N = 65 in Ba and Cs, an abrupt change in the mean square charge radii has been

interpreted as a shape transition with the appearance of strongly deformed configuration for the ground state ($\pi\frac{9}{2}^+[404]$ in ^{119}Cs and $\nu\frac{5}{2}^+[413]$ in ^{121}Ba) [13, 26].
- a kink is observed at the N = 82 shell closure in all the isotope series studied above Z = 50 [26-28]. The recent results obtained on neutron-rich tin isotopes up to 132 [29, 30] show that the slope of the $\delta <r_c^2>$ curves decreases before N = 82 from Sn to Sm (see fig. 1).
- a parabolic behaviour of the change in the mean square charge radius between the two neutron shell closures N = 50 and N = 82 has been founded for Cd, In and Sn [31-34]. It has been interpreted as the signature of important dynamical deformation in these Z $\sim$ 50 nuclei. In tin nuclei, this $\delta <r_c^2>$ parabolic behaviour has been confirmed up to 132 by the recent COMPLIS measurements [29, 30]. The tin charge radii have been calculated in the frame of various microscopic approaches : *i)* the relativistic mean-field theory with the NL3 effective interaction, *ii)* the Hartree-Fock-Bogolyubov calculations using the Gogny force and *iii)* a dynamical approach using a Bohr hamiltonian for which the deformation energy potential and the inertia tensor are deduced from constrained Hartree-Fock-Bogolyubov calculations. The comparison between the theoretical and experimental charge radius (fig. 2) sustains the role of the dynamical deformation in the tin nuclei.
In this context of a nuclear region rich in phenomena related to deformation, we propose to extend the laser spectroscopy measurements in the Z > 50 nuclei to the Te isotopes. This would allow us to extend significantly the data available in this isotope series. Indeed, up to now, the nuclear charge radii have been measured from muonic atoms [39], 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 [40]. The nuclear moments known for the ground and isomeric states of Te [41, 42] are presented in table 1, one can note that :
- the μ values are available for isotopes with $119 \leq A \leq 133$ but the sign of μ is not known for the $\frac{3}{2}^+$ ground state in ^{127,129,131}Te, the $\frac{11}{2}^-$ isomeric state in ^{119,121,133}Te and the $\frac{1}{2}^+$ ground state in ^{119}Te;
- Q_S has been measured only for the $\frac{3}{2}^+$ ground state in ^{129}Te and for the $\frac{11}{2}^-$ isomeric state in ^{125}Te.
ISOLDE offers the opportunity for studying this isotope series over a wide mass range from the neutron-deficient nuclei located at the N = 66 neutron mid-shell to the neutron-rich ones lying beyond the neutron shell closure at N = 82.
The $\delta <r_c^2>$ in Te through the N = 82 neutron shell is the last missing link among the even-Z isotopes above Z = 50 and will allow us to study the variation of the kink at N = 82 when going away from the Z = 50 proton shell closure. It appears from figure 3 that the slopes of the $\delta <r_c^2>$ curves before and after N = 82 depends strongly on Z : the more Z differs from the Z = 50 magic number, the stronger the slope difference is, indicating that it becomes easier for the nucleus to be deformed. Moreover, 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, which indicates that the ability of a nucleus for having deformation depends on the occupied neutron shell. Deformation is a global, collective property of the nucleus. It results from the coherent interaction of the pairs in the proton and neutron valence shell and then, for these Z$\sim$50

nuclei, the deformation depends not only on the number of proton valence pairs but also on the neutron shell involved. The experimental data in Te are required for confirming this behaviour close to the magic number Z = 50.
In even-even nuclei, the energy of the first 2^+ excited state is strongly related to the deformation of the nucleus. Fig. 4 shows the energy of the 2_1^+ state in the even-Z nuclei from Mo (Z =42) to Ce (Z =58). Up to N = 68, the energy of the 2_1^+ state is very similar in Cd and Te which have respectively two protons less and more than tin. But from N = 70 to 80, the energy of the 2_1^+ state in Cd remains almost constant, similar to the case in tin, whereas in Te the 2_1^+ state energy increases smoothly up to N = 82. Thus we can wonder whether, in Cd and Te, other collective properties could show that pattern of first similarities and then discrepancies when N increases. For instance, does the $\delta <r_c^2>$ exhibit a parabolic behaviour in Te and, if it exists, does this pattern persist up to N = 82? The proposed experiment in Te will allow us to answer this question.
Concerning now the odd-N Te isotopes, in addition to the $\delta <r_c^2>$, this experiment will give access to the static moments: the magnetic moment (μ) and, when the nuclear spin differs from $\frac{1}{2}$, the spectroscopic quadrupole moment (Q_S). The value and the sign of μ will yield information on the structure of the state. This will be the case for the $\frac{1}{2}^+$ ground state in $^{125-117}$Te. Indeed such a $\frac{1}{2}^+$ state is present in Ba, Xe and Sn, but depending on its structure, the μ values are different: large and negative in $^{113-119}$Sn, ^{123,125}Te, ^{129}Xe and ^{131,133}Ba where the $\frac{1}{2}^+$ state is interpreted as a quasispherical $s_{1/2}$ state or a slightly deformed $\frac{1}{2}$[400] state, then small and positive in ^{125}Ba where the $\frac{1}{2}^+$ ground state appears to be described by the $\frac{1}{2}$[411] deformed state.
Moreover, from A = 115 to 133, all the odd-A Te isotopes exhibit an isomeric state. The measurement of the isomeric shift will give us a direct indication on the influence of the single particle coupled to the core on the deformation of the nucleus.

2 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 $\frac{1}{2}$) and changes in the mean square charge radius. The COMPLIS set-up has been designed to perform good resolution Resonance Ionization Spectroscopy (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 used in particular when the studied isotopes have a low yield and $T_{1/2} >$ 2s. 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 with different delay

times 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. These various COMPLIS characteristics will be used in the study of the tellurium isotopes.
The neutron-rich Te isotopes are 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 [45]. Thus, with this target and ion-source system, we plan to measure the Te isotopes from A = 129 to 136. For the A = 129, 131 and 133 odd isotopes, COMPLIS will allow us to discriminate between the hyperfine lines corresponding to the ground and isomeric states.
The neutron-deficient Te isotopes are obtained by radioactive decay of Xe (Xe $\rightarrow$ I $\rightarrow$ Te) which are produced by irradiating, with the PS-Booster 1 GeV proton beam, a cerium oxide target associated with a plasma ion source having a cooled transfer line. In this case, as the Te isotopes are not available as ISOLDE beams, COMPLIS will be used according to its initial purpose. The yields are equal to 10^8 atoms/μC for ^{125}Xe to ^{119}Xe and then decreases down to 2.5×10^5 atoms/μC for ^{115}Xe. We plan to perform the laser spectroscopy measurements on $^{121-116}$Te. For the 121, 119 and 117 odd masses, only the ground state will be studied because the $\frac{11}{2}^-$ isomeric state is not populated by the β^+/EC decay of I isotopes.
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 Te study, we will use the 5p^4 $^3P_2$ $\rightarrow$ 5p^{3}6s $^5S_2$ optical transition at 225.97 nm. The single mode laser pulses will be obtained from frequency tripling. For the ionization, a frequency doubled laser beam at 345 nm will be used. Since the atomic states involved in the first excitation step have both J = 2, the hyperfine structures are expected to be very complex. Another optical transition (5p^4 $^3P_2$ $\rightarrow$ 5p^{3}6s $^3S_1$) at 214.35 nm can be used for the Te study. In order to determine what is the most suitable one, both optical transitions will be used to investigate the Te stable ion beams delivered by the injector linked to the COMPLIS incident beam line. These tests with the stable beams will also allow us to determine the optimal conditions for the desorption and ionization of Te.

3 Beam time request

We consider that, on average, 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 = 129 m+g, 131 m+g, 133 m+g, 132, 134, 135, 136) which need an uranium carbide target with a hot plasma ion-source.
• **9 shifts** for the study of the neutron-deficient Te isotopes (A = 116-121) which require a cerium oxide target associated with a plasma ion-source having a cooled transfer line.
In total, our beam time request is : **26 shifts**.

References

[1] G. Wenes *et al.*, Phys. Rev. **C23** (1981) 2291.
[2] J. Rikowska *et al.*, Nucl. Phys. **A505** (1989) 145.
[3] J.L. Wood *et al.*, Phys. Rep. **215** (1992) 101.
[4] W.D. Fromm *et al.*, Nucl. Phys. **A243** (1975) 9.
[5] A.K. Gaigalas *et al.*, Phys. Rev. Let. **35** (1975) 555.
[6] D.B. Fossan *et al.*, Phys. Rev. **C15** (1977) 1732.
[7] V. Garg *et al.*, Phys. Rev. Let. **40** (1978) 831.
[8] K. Heyde *et al.*, Phys. Rep. **102** (1983) 291.
[9] U. Hagemann *et al.*, Nucl. Phys. **A329** (1979) 157.
[10] J. Gizon and A. Gizon, Z. Phys. **A285** (1978) 259.
[11] A. Gade *et al.*, Nucl. Phys. **A686** (2001) 3.
[12] F. Dönau *et al.*, J. Phys. **G7** (1981) 1379.
[13] S.A. Wells *et al.*, Phys. Let. **B211** (1988) 272.
[14] U. Hagemann *et al.*, Z. Phys. **A290** (1979) 399.
[15] J. Bonn *et al.*, Z. Phys. **A276** (1976) 203.
[16] G. Ulm *et al.*, Z. Phys. **A325** (1986) 247.
[17] K. Wallmeroth *et al.*, Nucl. Phys. **A493** (1989) 224.
[18] G. Passler *et al.*, Nucl. Phys. **A580** (1994) 173.
[19] G. Savard *et al.*, Nucl. Phys. **A512** (1990) 241.
[20] F. Le Blanc *et al.*, Phys. Rev. Let. **79** (1997) 2213.
[21] J.K.P. Lee *et al.*, Phys. Rev **C38** (1988) 2985.
[22] H.T. Duong *et al.*, Phys. Let. **B217** (1989) 401.
[23] T. Hilberath *et al.*, Z. Phys. **A342** (1992) 1.
[24] F. Le Blanc *et al.*, Phys. Rev. **C60** (1999) 054310.
[25] D. Verney, Thèse de Doctorat de l'Université Joseph Fourier, Grenoble I.
D. Verney *et al.*, to be published.
[26] C. Thibault *et al.*, Nucl. Phys. **A367** (1981) 1.
[27] A.C. Mueller *et al.*, Nucl. Phys. **A403** (1983) 234.
[28] W. Borchers *et al.*, Phys. Let. **B216** (1989) 7.
[29] F. Le Blanc *et al.*, Int. Conf. on Exotic Nuclei and Atomic Masses, ENAM 2001.
[30] B. Roussière *et al.*, Int. Workshop "Prospects for the development of laser methods in the study of nuclear matter", Poznań, Poland, May 28-31 2001.
[31] F. Buchinger *et al.*, Nucl. Phys. **A462** (1987) 305.
[32] J. Eberz *et al.*, Nucl. Phys. **A464** (1987) 9.
[33] M. Anselment *et al.*, Phys. Rev. **C34** (1986) 1052.
[34] J. Eberz *et al.*, Z. Phys. **A326** (1987) 121.
[35] C. Piller *et al.*, Phys. Rev. **C42** (1990) 182.
[36] G.A. Lalazissis *et al.*, At. and Nucl. Data Tables **71** (1999) 1.
[37] S. Péru, private communication.
[38] J. Libert, private communication.
[39] E.B. Shera *et al.*, Phys. Rev. **C39** (1989) 195.
[40] R. Lecordier and J.M. Helbert, Physica **94C** (1978) 125.
R. Lecordier, Phys. Let. **72A** (1979) 327.
[41] P. Raghavan, At. and Nucl. Data Tables **42** (1989) 189.

[42] G. White *et al.*, Nucl. Phys. **A640** (1998) 323.
[43] *Tables of isotopes*, R.B. Firestone and V.S. Shirley editors, 1996, John Wiley and Sons, Inc, New York.
[44] K.L. Kratz, Proc. of the Int. Conf. on Exotic Nuclei and Atomic Masses, AIP Conference Proceedings **455** (1998) 827.
[45] *http://isolde.web.cern.ch/ISOLDE/*.

Table 1: Nuclear moments known for the ground and isomeric states in Te

A	$T_{1/2}$	I^{π}	E(keV)	$\mu(\mu_N)$	Q_S(b)
133m	55.4m	$\frac{11}{2}^-$	334	1.129(7)*	
131m	30h	$\frac{11}{2}^-$	182	-1.04(4)	
				1.123(7)*	
131g	25.0m	$\frac{3}{2}^+$	0	0.696(9)*	
129m	33.6d	$\frac{11}{2}^-$	106	-1.091(7)	
129g	69.6m	$\frac{3}{2}^+$	0	0.702(4)*	0.055(13)
127m	109d	$\frac{11}{2}^-$	88	-1.041(6)	
127g	9.35h	$\frac{3}{2}^+$	0	0.635(4)*	
125m	57.4d	$\frac{11}{2}^-$	145	-0.985(6)	-0.06(2)
125g	stable	$\frac{1}{2}^+$	0	-0.885051(4)	
123m	119.7d	$\frac{11}{2}^-$	247	-0.927(8)	
123g	$> 10^{13}$y	$\frac{1}{2}^+$	0	-0.7369478(8)	
121m	154d	$\frac{11}{2}^-$	294	0.895(10)*	
119m	4.70d	$\frac{11}{2}^-$	300	0.894(6)*	
119g	16.03h	$\frac{1}{2}^+$	0	0.25(5)*	

* the sign of μ is not known

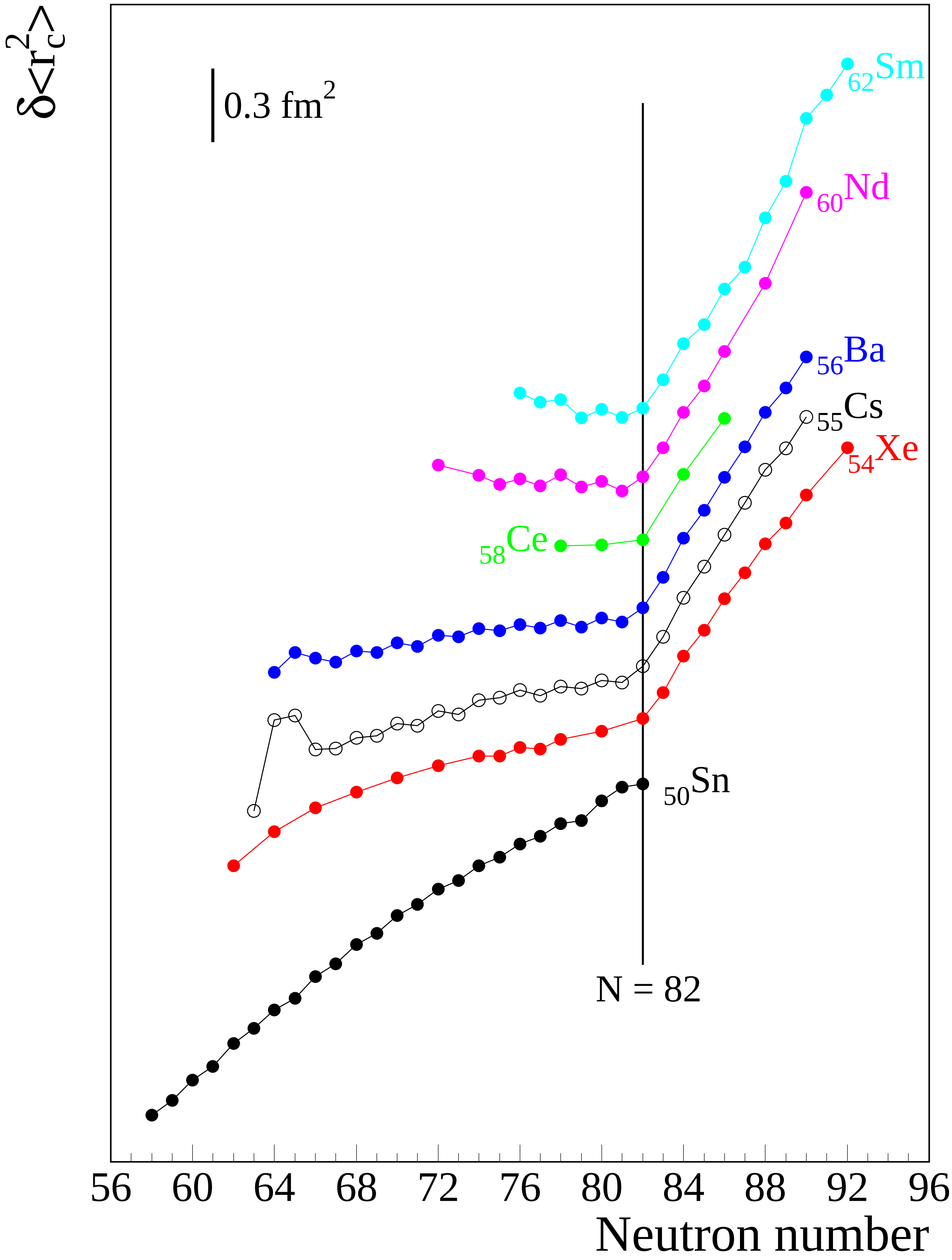

Figure 1: Changes in the mean square charge radius near N = 82.

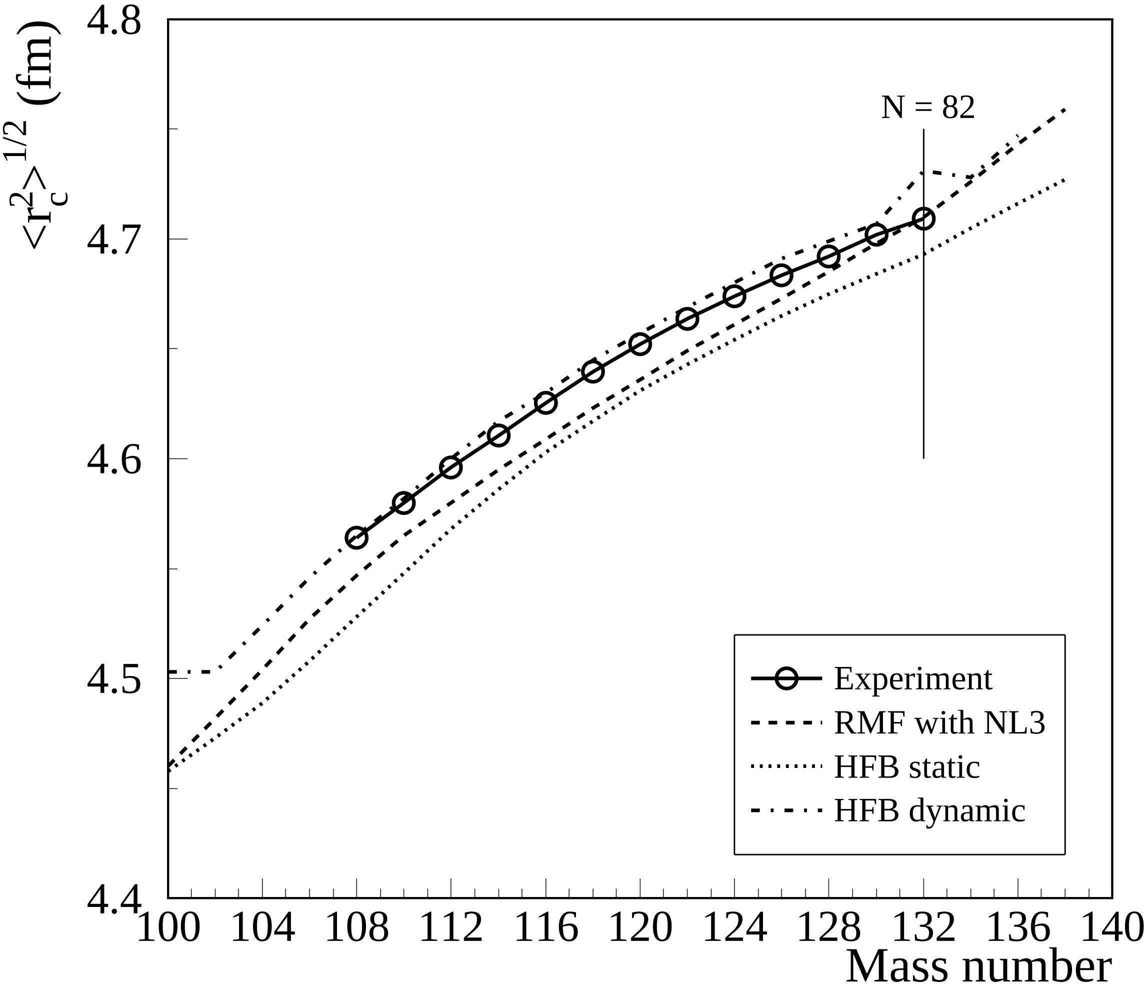

Figure 2: Experimental and theoretical charge radius for even tin isotopes. Experimental values have been obtained from the $\delta <r_c^2>$ values [29,30] taking as reference the charge radius of ^{120}Sn [35]. Theoretical values are from refs. [36-38].

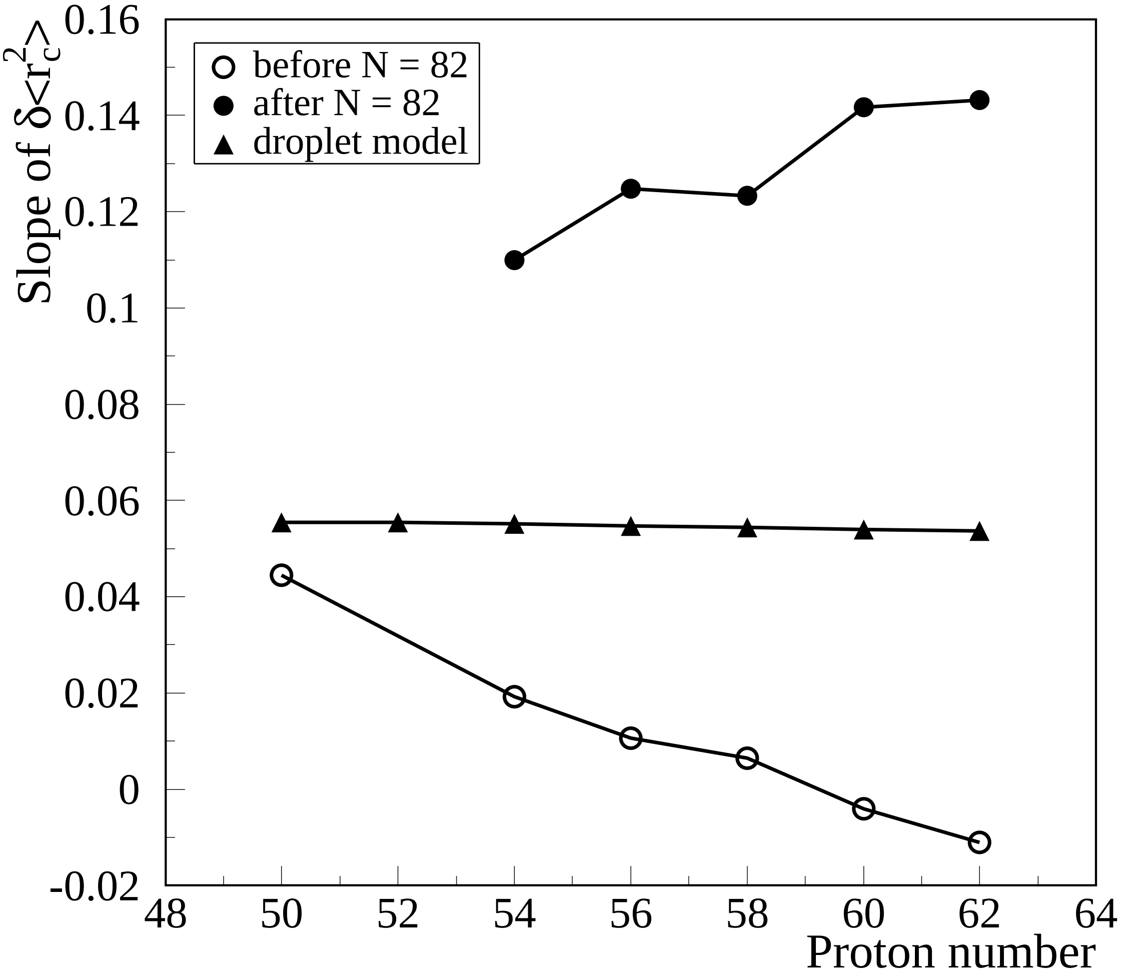

Figure 3: Slope of the $\delta < r_c^2 >$ curve for the even-Z nuclei around N = 82. The experimental values have been calculated from the experimental $\delta < r_c^2 >$ values of the even-even nuclei (from N $\geq$ 70 up to 82, and from N = 82 up to 86 $\leq$ N $\leq$ 92).

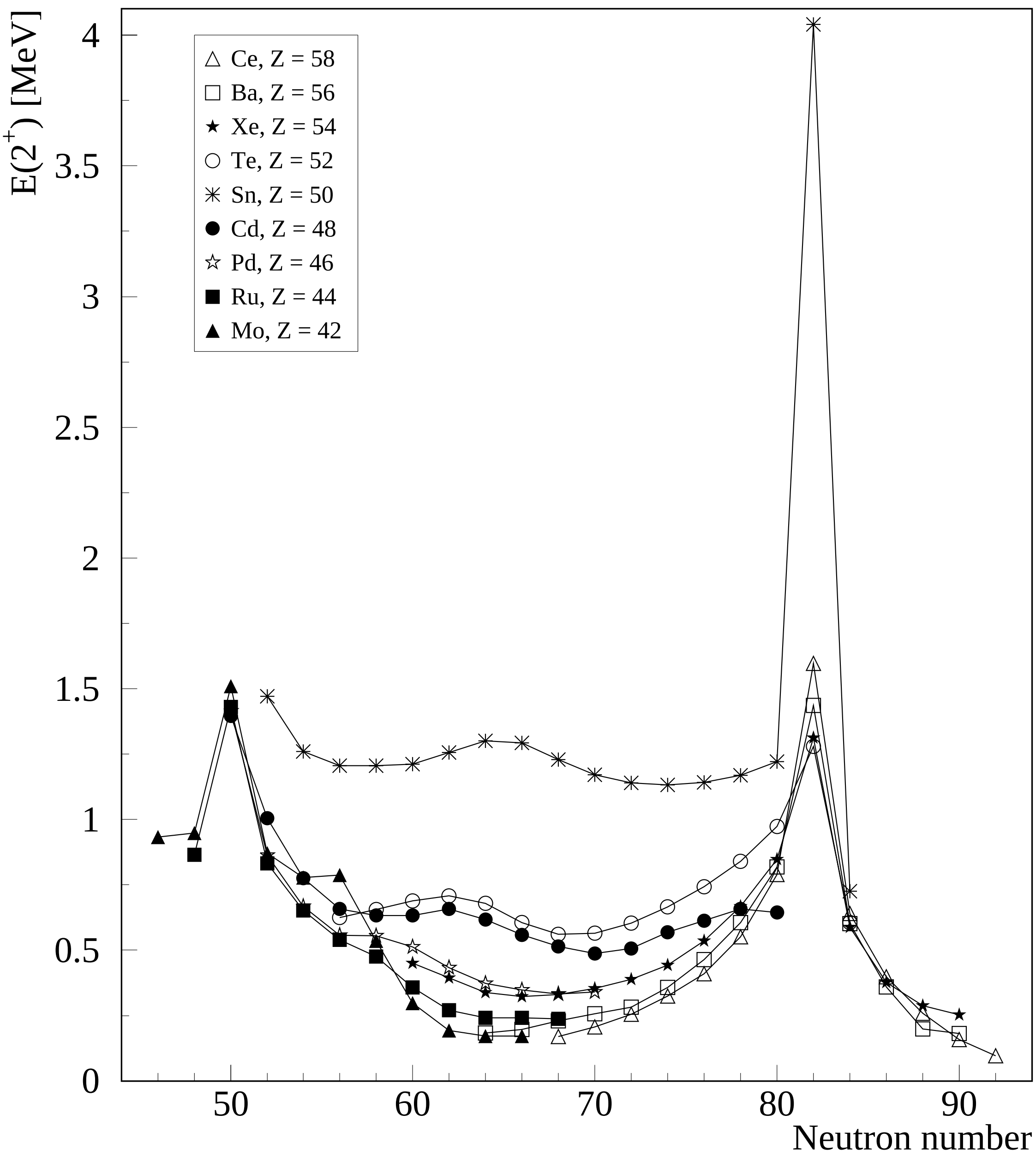

Figure 4: Energy of the first excited 2^+ state in the even-even nuclei near Z = 50. The data are taken from refs. [43,44].