

Nuclear magnetic moments in the lead region: Recent results and perspectives

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Magnetic moments in the lead region

1. Hyperfine structure anomaly and the method of HFA study far from stability.
Example: Au
2. g factor and nonaxiality: $^{179}, ^{177}\text{Au}$
3. Spins and magnetic moments as a fingerprint of shell evolution:
 $^{179}, ^{177}\text{Hg}$
4. Shell effect in $\pi h_{9/2}$ magnetic moments at $N = 126$ and core-polarization corrections
5. Striking regularity in the g -factor behaviour:
 $\pi h_{9/2}$ at $N > 126$;
 $\pi h_{11/2}$ at $82 < N < 126$

Hyperfine structure anomaly

HFA:

$$^{A_1} \Delta ^{A_2} = \frac{a_1 \cdot I_1}{\mu_1} \cdot \frac{\mu_2}{a_2 \cdot I_2} - 1$$

high accuracy independent μ measurement is needed → data was obtained only close to stability

$$a = a_{point} (1 + \varepsilon) \longrightarrow ^{A_1} \Delta ^{A_2} \approx (\varepsilon_{A_1} - \varepsilon_{A_2})$$

$$\mu_A = \mu_{A_0} \cdot \frac{I_A}{I_{A_0}} \cdot \frac{a_A}{a_{A_0}}$$

usually $\Delta \sim 10^{-3} \div 10^{-4}$

however, ~1% at large spin change:
Tl, Fr, Ra; up to ~20% for Au!

Theory:

factorization:

atomic part: independent on A

$$\varepsilon(A) = b \langle r^2 \rangle_m (A) \cdot d(A)$$

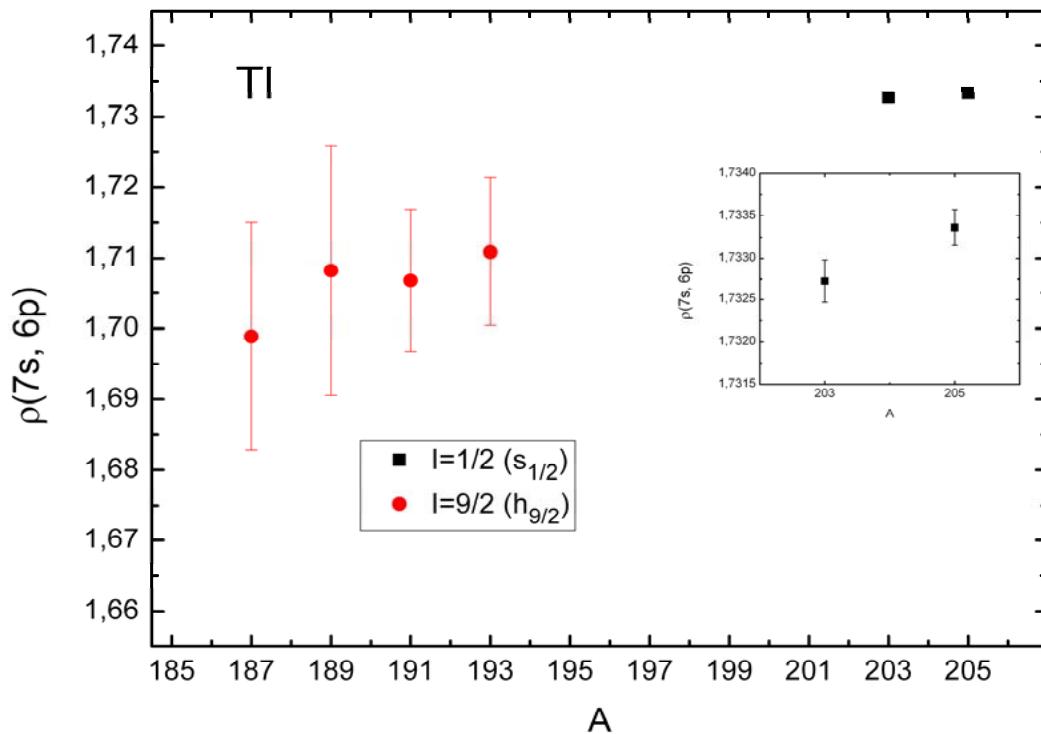
nuclear configuration part

A.-M. Mårtensson-Pendrill, Phys. Rev. Lett. **74**, 2184 (1995)

Differential hyperfine structure anomaly

$$\rho_{n_1 l_1, n_2 l_2}^A = \frac{a_{n_1 l_1}^A}{a_{n_2 l_2}^A}$$

Ratio $\rho_{n_1 l_1, n_2 l_2}^A$ may have a different value for different isotopes because the atomic states with different n, l have different sensitivity to the nuclear magnetization distribution.



DHFA \rightarrow RHFA \rightarrow μ correction

$${}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{n_2 l_2} \equiv \frac{\rho_{n_1 l_1, n_2 l_2}^{A_1}}{\rho_{n_1 l_1, n_2 l_2}^{A_2}} - 1 = {}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}(n_1 l_1) - {}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}(n_2 l_2)$$

$$\eta(n_1 l_1, n_2 l_2) \equiv \frac{{}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}(n_1 l_1)}{{}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}(n_2 l_2)}$$

$${}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}(n_2 l_2) = \frac{{}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{n_2 l_2}}{{}_{A_1}^{n_1 l_1} \Delta {}_{A_2}^{A_2}}$$



pure atomic value!
Independent on A
due to factorization

determination of HFA without
independent high-accuracy μ
measurements

V. J. Ehlers et al., PR. **176**, 25 (1968)
J. R. Persson, EPJ. A **2**, 3 (1998)

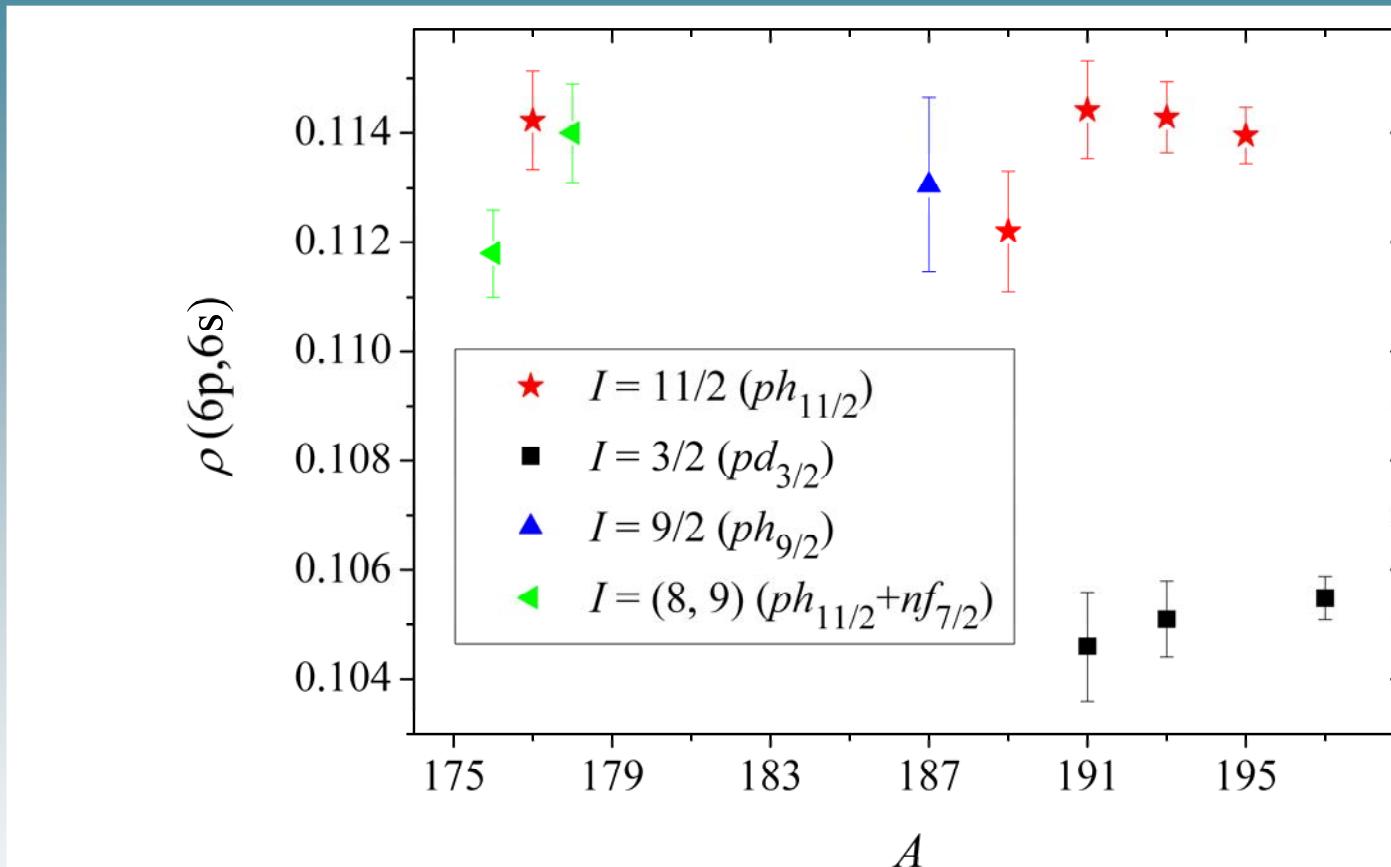
This approach was used for short-lived Tl and Bi isotopes:

A. E. Barzakh et al. Phys. Rev. C **86**, 014311 (2012)

S. Schmidt et. al., Phys. Lett. B **779**, 324 (2018)

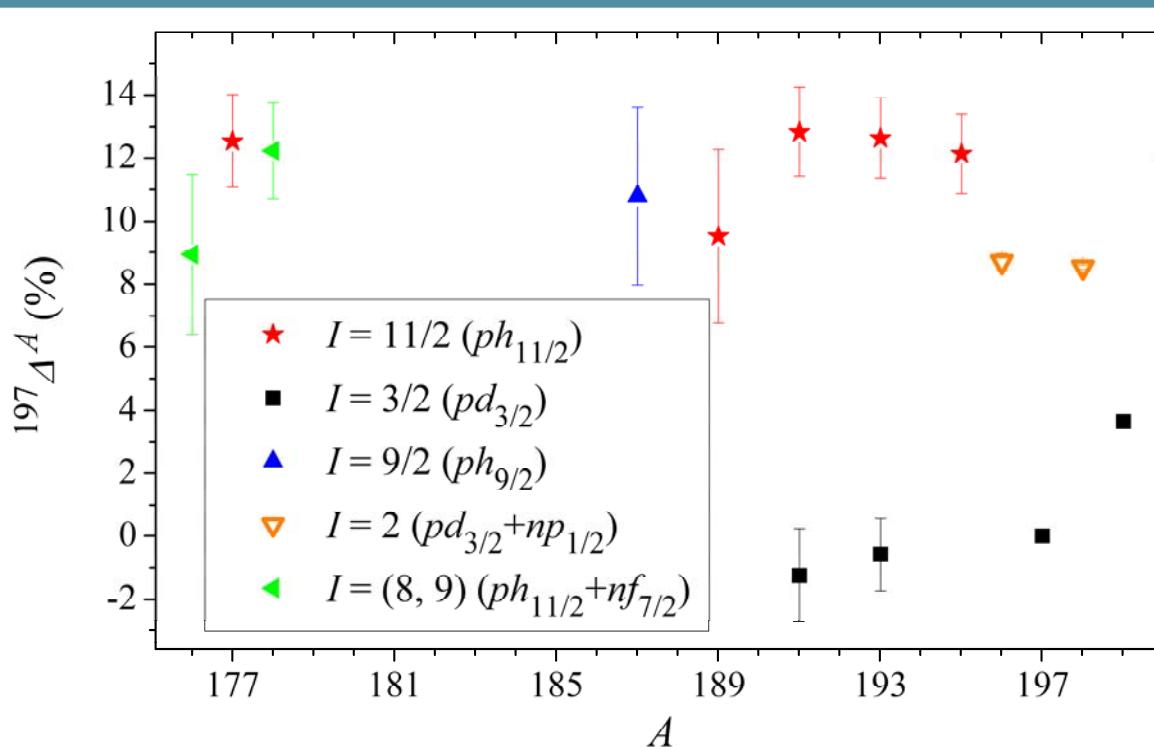
(Cf. also the “method of specific difference” which yield a conclusive test of QED in strong magnetic fields: V.M. Shabaev et al., PRL 86 (2001) 3959)

DHFA in Au



$$\frac{n_1 l_1}{A_1} \Delta_{A_2}^{n_2 l_2} \equiv \frac{\rho_{n_1 l_1, n_2 l_2}^{A_1} - 1}{\rho_{n_1 l_1, n_2 l_2}^{A_2}} \quad \longrightarrow \quad {}^{A_1} \Delta^{A_2} (n_2 l_2) = \frac{\frac{n_1 l_1}{A_1} \Delta_{A_2}^{n_2 l_2}}{\eta - 1} \text{ with } 1/\eta \text{ (Au)}_{\text{theor}} = 3.2(6)$$

RHFA in Au

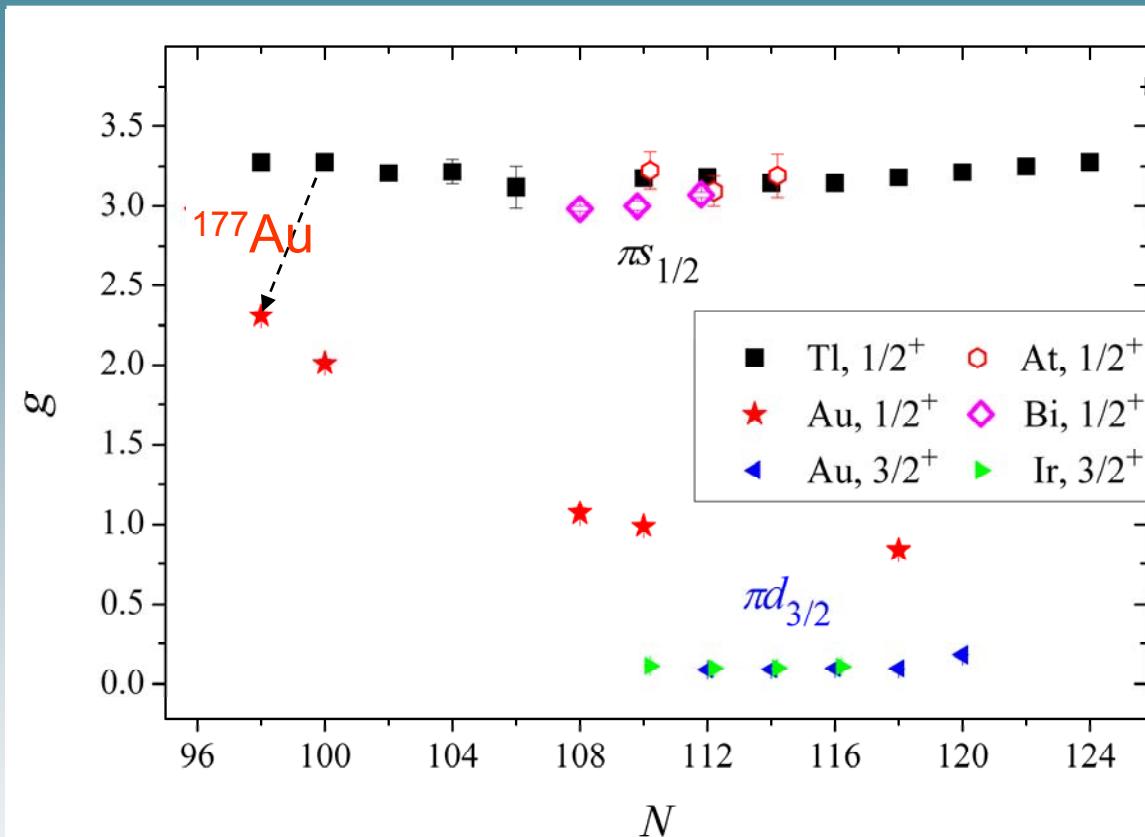


$${}_{A_1} \Delta {}_{A_2} (n_2 l_2) = \frac{n_1 l_1 \Delta {}_{A_2}^{n_2 l_2}}{\eta - 1}$$

$$1/\eta (\text{Au})_{\text{theor}} = 3.2(6)$$

RHFA in Au is larger than 10%. To extract μ properly one needs in calculation/measurement of η factor. Measurement of η is possible for $^{196,198,199}\text{Au}$ where precise independent μ values are available.

g factor for $1/2^+$ and $3/2^+$ states at $N < 126$



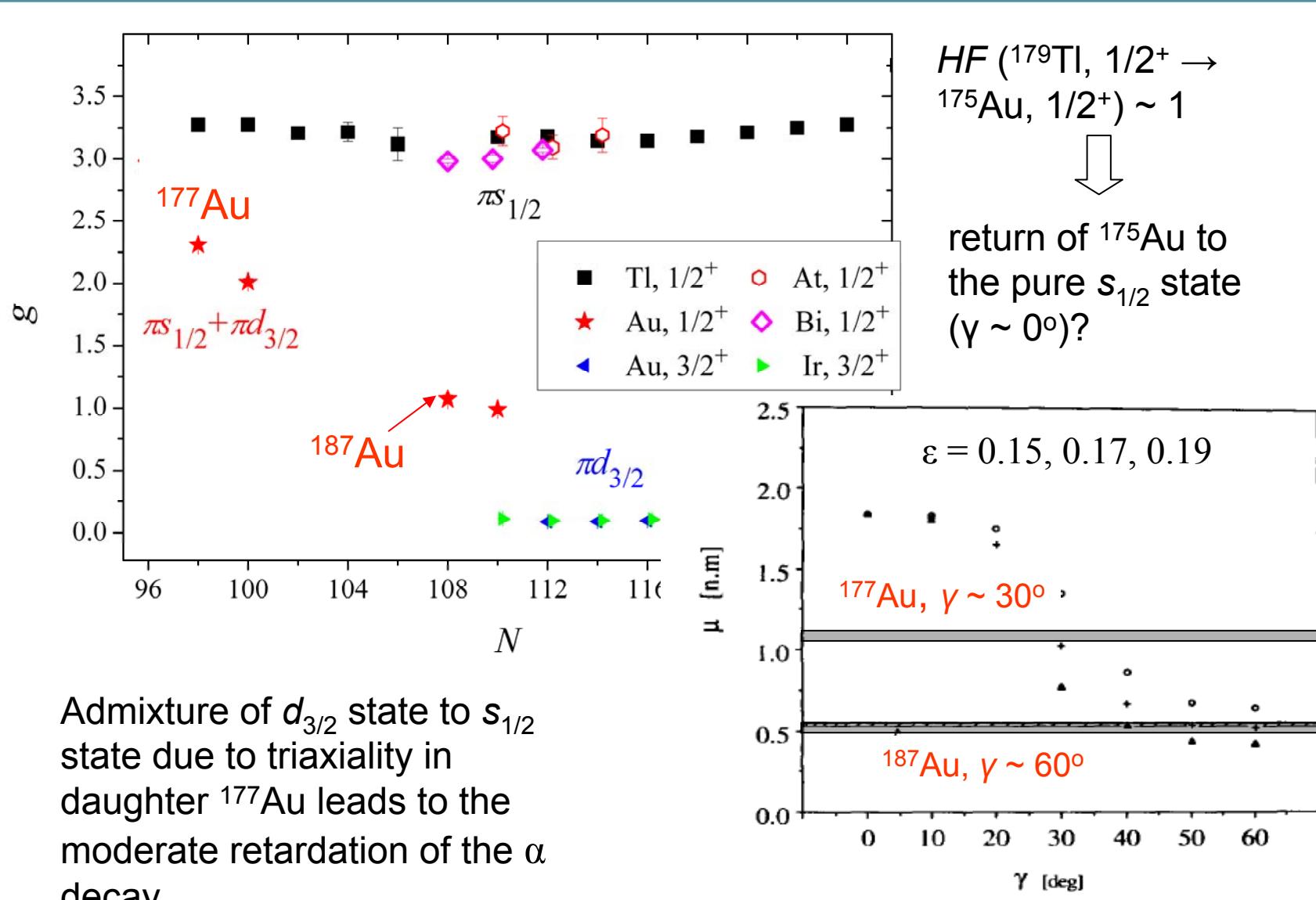
$g(1/2^+)$ is practically independent on Z although $1/2^+$ states have different nature for Tl and Bi or At isotopes (“normal” spherical vs intruder deformed)

$$HF\left({}^{181}\text{Tl}, 1/2^+ \rightarrow {}^{177}\text{Au}, 1/2^+\right) \sim 4$$

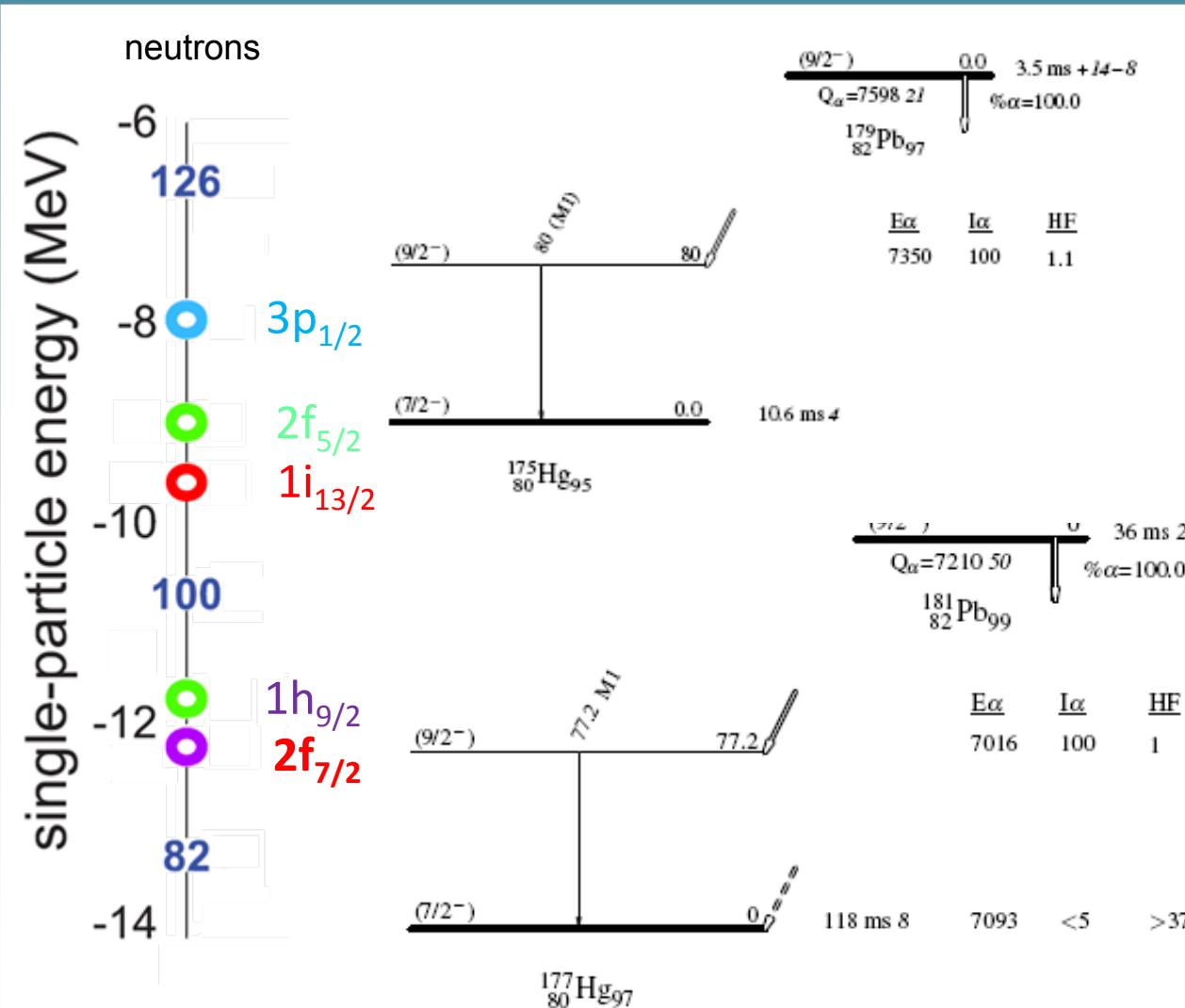
For all other α decays in these region (At \rightarrow Bi, Bi \rightarrow Tl, Tl \rightarrow Au)
 $HF(\dots, 1/2^+ \rightarrow \dots, 1/2^+) \sim 1$ ($s_{1/2} \rightarrow s_{1/2}$)

g factor for $1/2^+$ and $3/2^+$ states at $N < 126$

g factor as a fingerprint of triaxiality

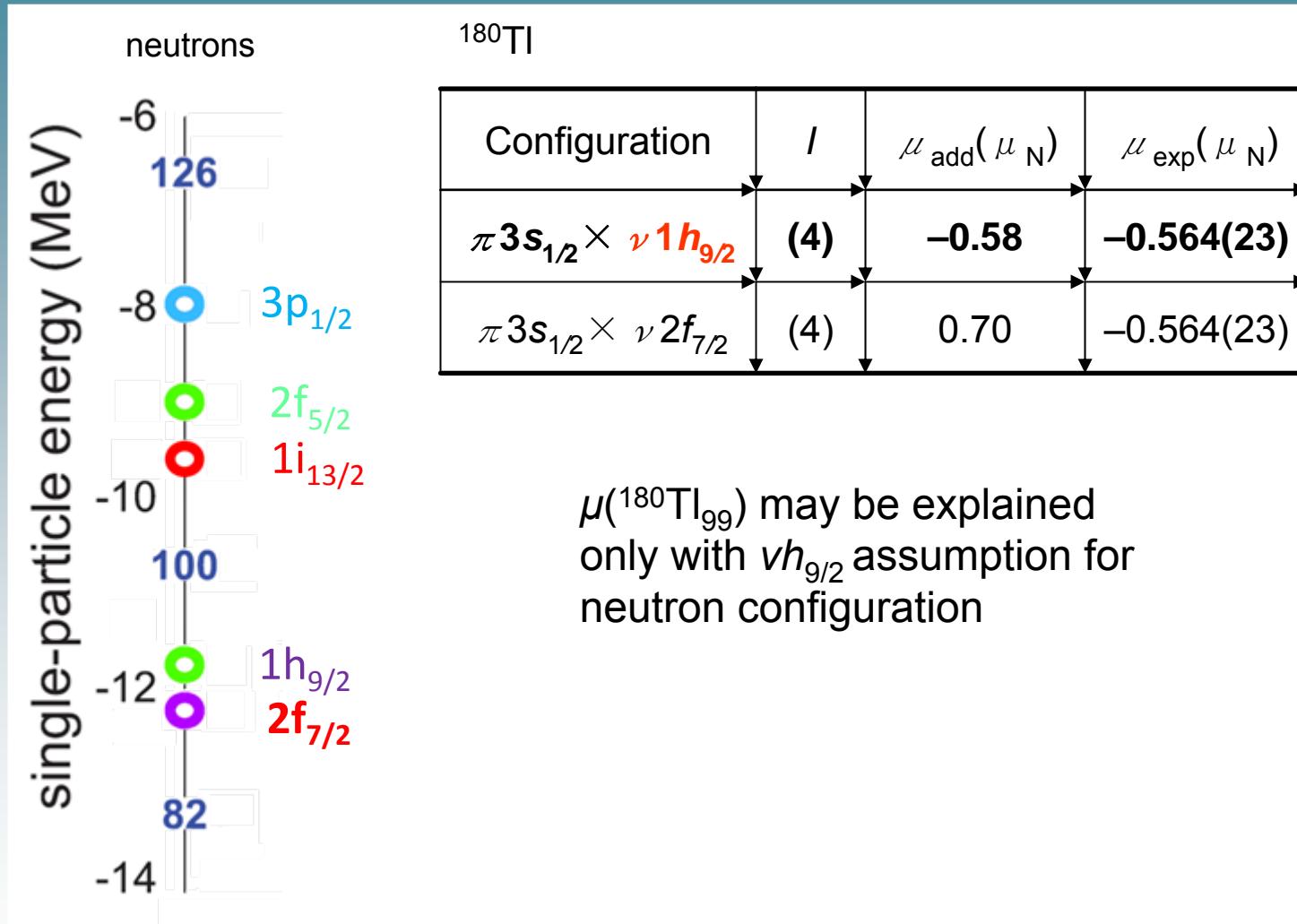


$\nu h_{9/2}$ vs $\nu f_{7/2}$ at $N < 100$: shell evolution

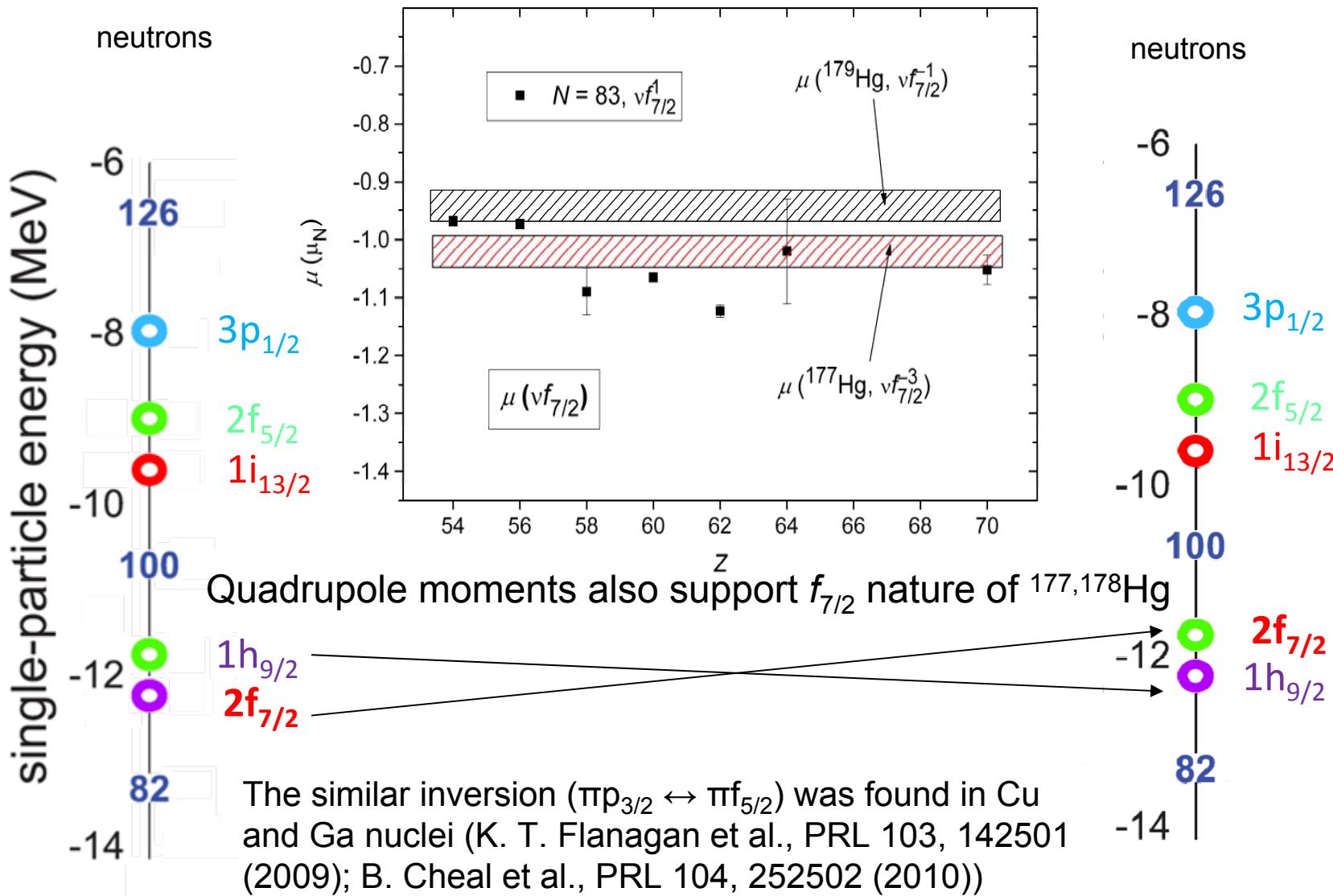


Ground states of $^{181, 179}\text{Pb}$ are presumably $9/2^-$ ($\nu h_{9/2}$). To confirm, μ measurement is needed

$\nu h_{9/2}$ vs $\nu f_{7/2}$ at $N < 100$: shell evolution



$\nu h_{9/2}$ vs $\nu f_{7/2}$ at $N < 100$: shell evolution



Au vs Tl isotopes: shell swap

^{176}Au

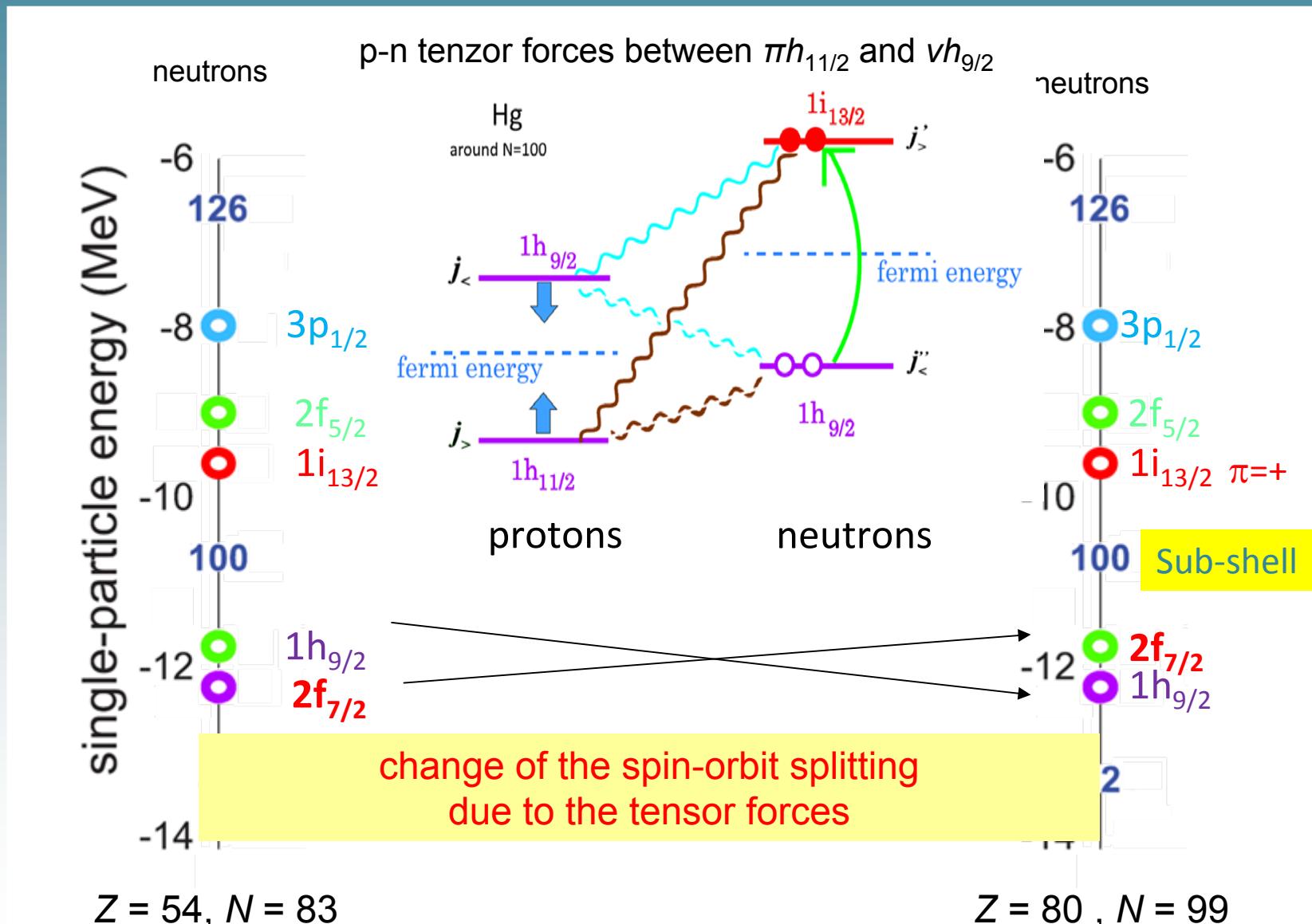
Configuration	I	$\mu_{\text{add}}(\mu_N)$	$\mu_{\text{exp}}(\mu_N)$
$\pi d_{3/2} \times \nu 2f_{7/2}$	(4)	-0.84	-0.834(9)
$\pi s_{1/2} \times \nu 1h_{9/2}$	(4)	-0.20	-0.834(9)
$\pi d_{3/2} \times \nu 1h_{9/2}$	(4)	0.66	-0.834(9)

$\mu(^{176}\text{Au}_{97})$ is explained only with $\nu f_{7/2}$ assumption for neutron configuration (additivity relation)

$I^\pi (^{181, 179}\text{Pb}_{99, 97}) = 9/2^-$:
 $\nu h_{9/2}$ configuration?

$\mu(^{180}\text{Tl}_{99})$ is explained only with $\nu h_{9/2}$ assumption for neutron configuration

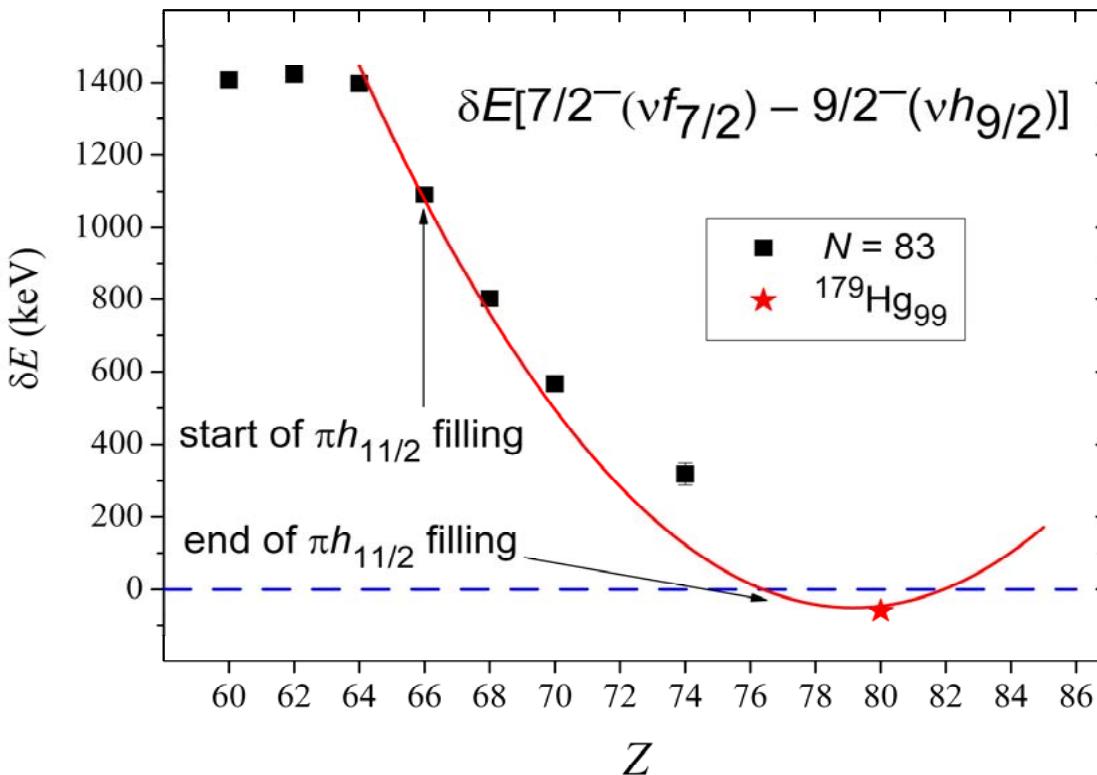
Hg isotopes: shell swap, μ



$Z = 54, N = 83$

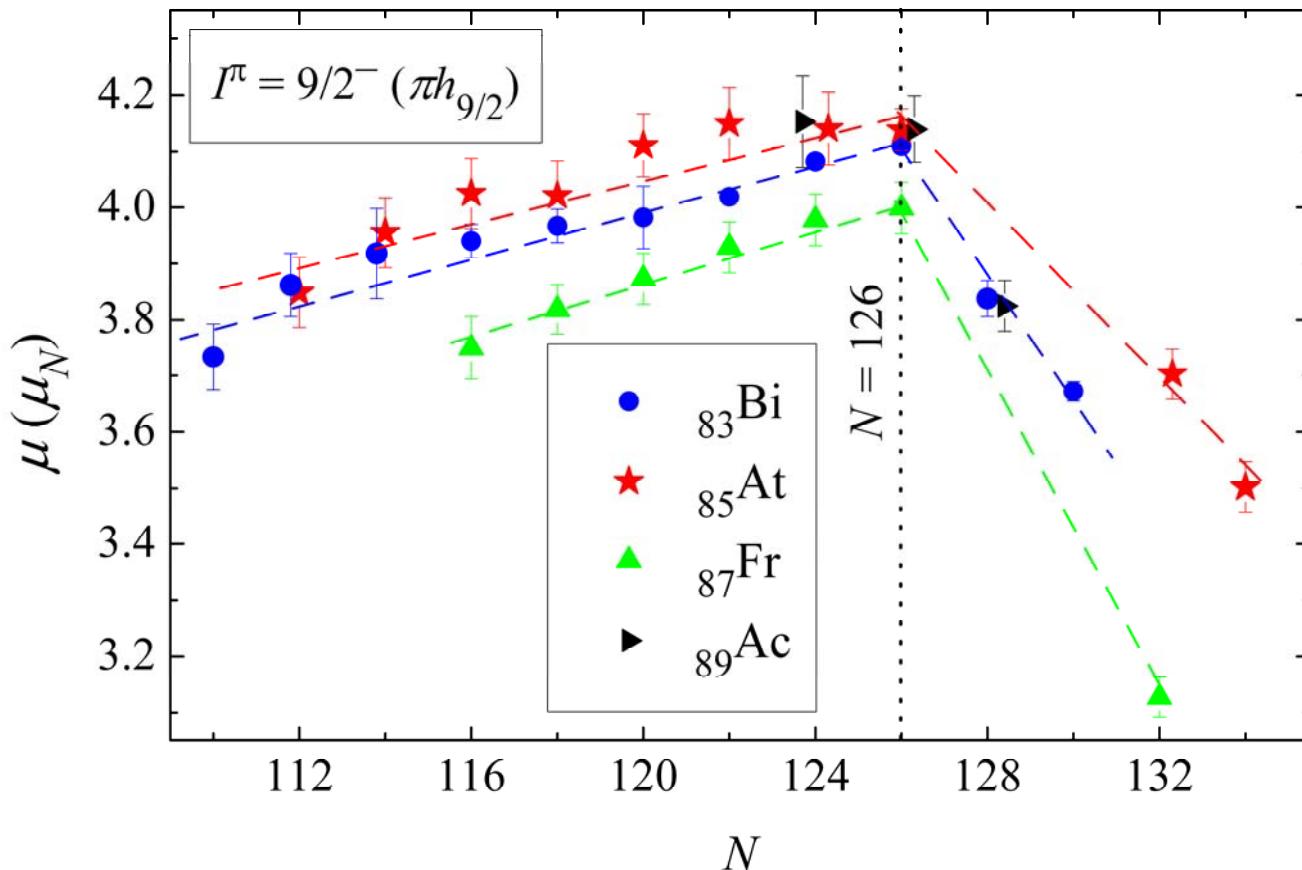
$Z = 80, N = 99$

Au vs Tl isotopes: shell swap



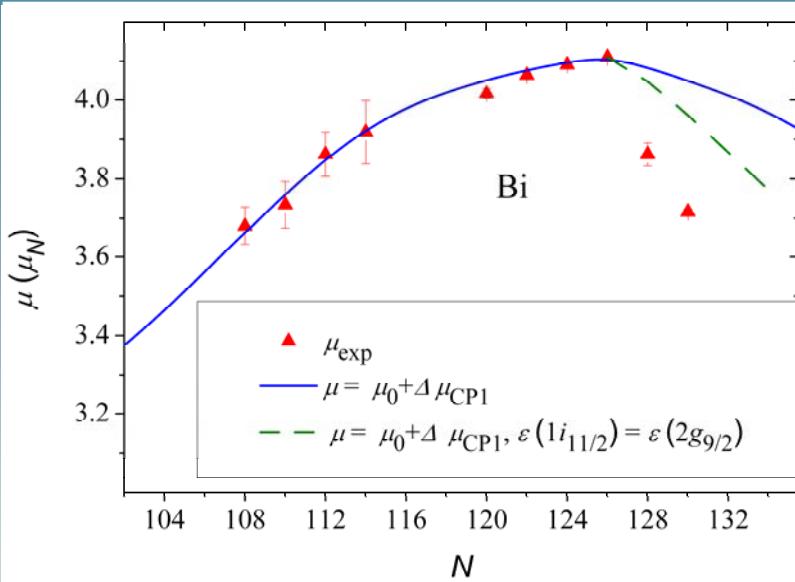
Subshells return to the
“normal” ordering at $Z > 80$

$\pi h_{9/2}$ g factor: systematics at $N \sim 126$



The same slope of the isotopic dependencies of $\mu(\pi h_{9/2})$
The same kink at $N = 126$

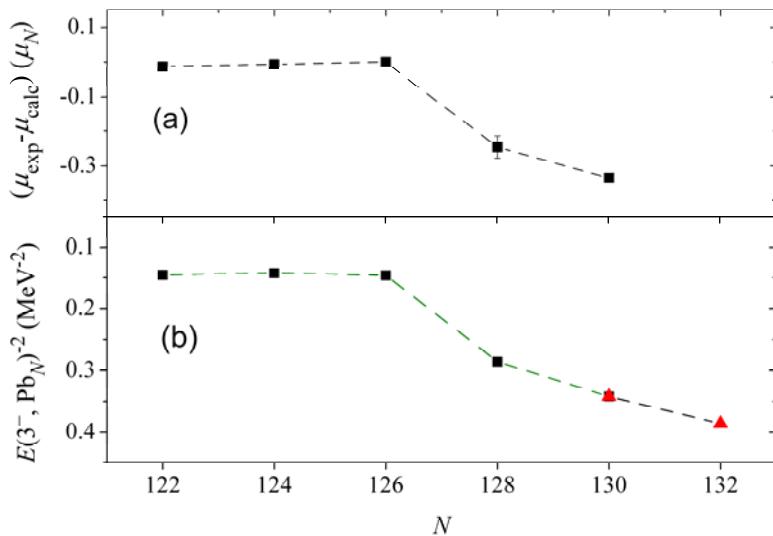
1st order core-polarization correction: Bi



$$\Delta \mu_{\text{CM1}}(N) = C \cdot [(2j_1 + 1)v_j^2(N)][(2j_2 + 1)u_j^2(N)]$$

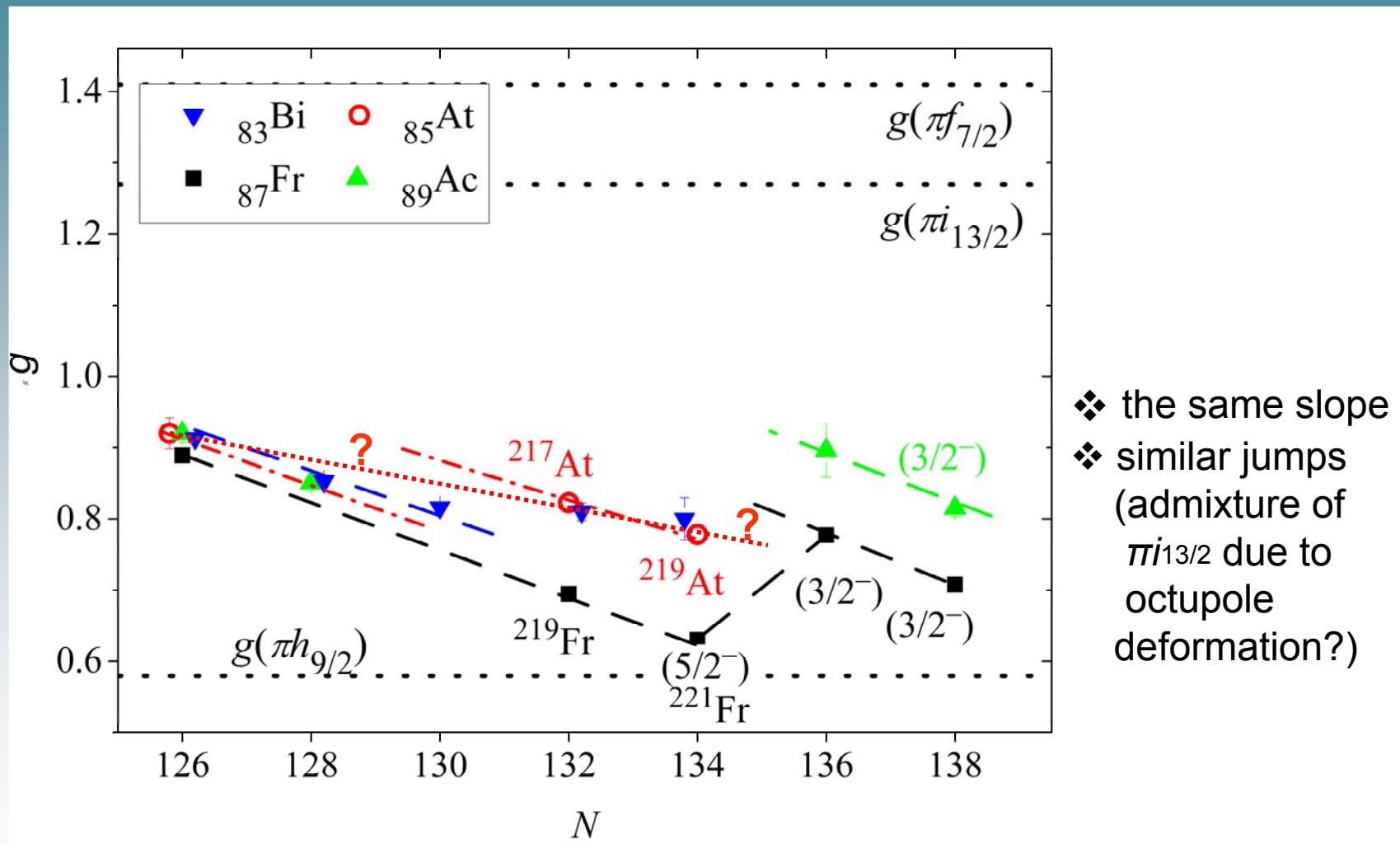
$$v_j^2 = \frac{1}{2} \left[1 - \frac{\varepsilon_j - \lambda}{\sqrt{(\varepsilon_j - \lambda)^2 + \Delta^2}} \right], \quad v_j^2 + u_j^2 = 1$$

$$N = N_0 + \sum_n (2j_n + 1)v_{j_n}^2 \quad j_1 = 13/2, j_2 = 11/2$$



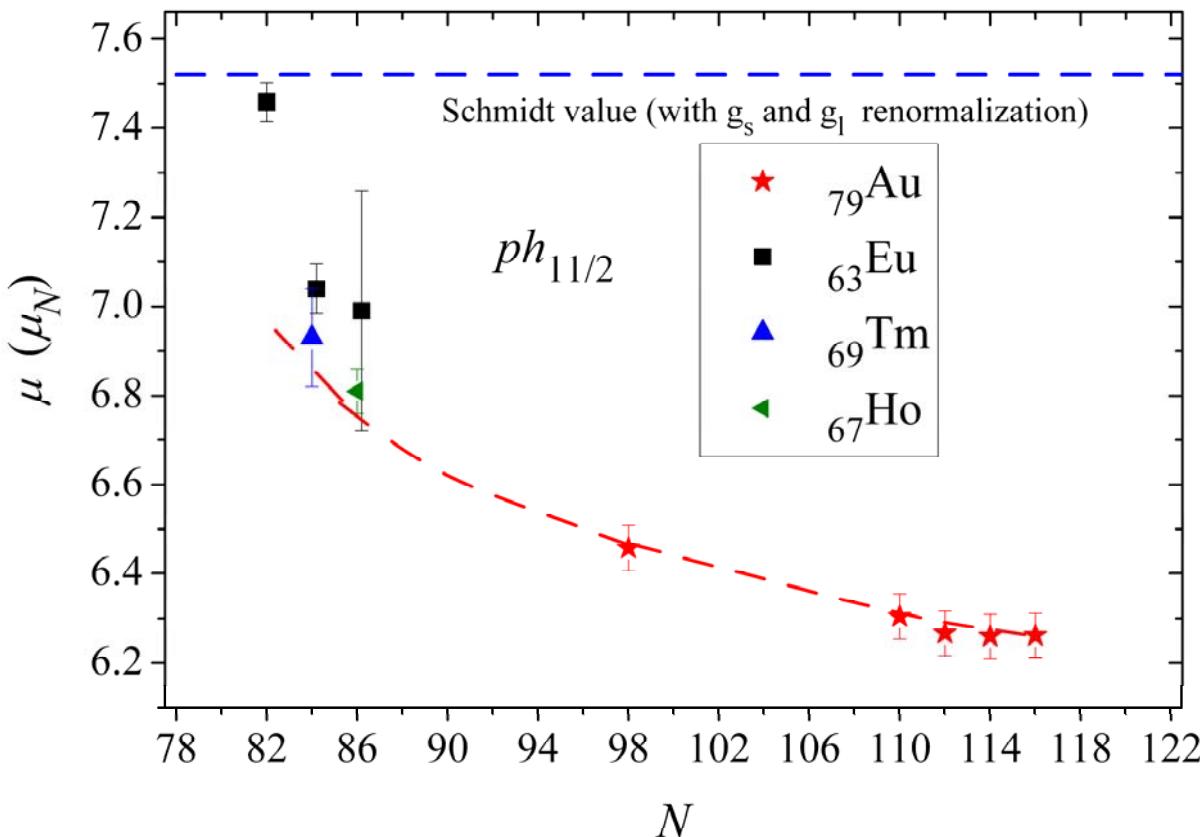
$$\Delta \mu_{CP2} \propto 1/E(3^-)^2$$

$\pi h_{9/2}$ g factor: systematics for $N > 126$



missing points: $^{213}, ^{215}\text{At}$, $^{215}, ^{217}\text{Fr}$, ^{219}Ac (short lived), $^{221}, ^{223}\text{Ac}$

$\pi h_{11/2}$ g factor: systematics



Weak Z-dependence; first-order core polarization?

missing points: $^{171, 173, 175, 199, 201, 203, 205}\text{Au}^m$
(some of them very short lived)

Outlook

1. HFA: systematic study of the a -constants ratio with the accuracy ~0.1%:
 - Correction of the μ values;
 - Configuration mixing;
 - Deformation and HFA
2. Striking regularity of the $g(\pi h_{9/2})$ and $g(\pi h_{11/2})$ isotopic behaviour:
 - Systematics should be extended to short-lived isotopes;
 - Underlining mechanisms should be revealed
3. Evolution of nonaxiality in odd- A Au isotopes:
 - Whether ^{175}Au “returns” to the pure $s_{1/2}$ configuration?
4. Shell swap at $Z \sim 80$, $N \sim 100$:
 - Do $^{179}, ^{181}\text{Pb}^g$ belong to the pure $\nu h_{9/2}$ configuration?