Probing isospin-symmetry breaking and mapping the proton drip-line

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Shenzhen, May 11, 2013

The concept of isospin

- Formalism first applied to nuclei by Heisenberg
  - W. Heisenberg, Z. Phys. 77 (1932) 1
- The name `isotopic spin’ first given by Wigner
  - E. Wigner, Phys. Rev. 51 (1937) 106

- Isospin of a nucleon: $t = 1/2$

  Projection of isospin: neutron $t_z = +1/2$

  proton $t_z = -1/2$

- Total isospin projection: $T_z = \sum_{i=1}^{A} t_z(i) = (N - Z)/2$

  Total isospin: $T_z = -T, -T+1, \cdots, T-1, T$

Isospin symmetry

- Historically, isospin symmetry led directly to the discovery and understanding of quarks.

- Charge independence: $v_{np} = (v_{nn} + v_{pp}) / 2$
- Invariance of any rotation in isospin space

- Charge symmetry: $v_{nn} = v_{pp}$
- Invariance under a rotation by 180^{o} about an axis in isospin space perpendicular to z-direction

- Scattering data show that both symmetries are broken
- R. Machleidt & H. Muether, Phys. Rev. C 63 (2001) 034005

Isospin-symmetry breaking in nuclei

- Charge-symmetry breaking
  - Difference between pp and nn interactions (~1%)
  - Experimental signal: Coulomb displacement energy (CDE)

    -- binding-energy difference between mirror nuclei

$$\mathrm{CDE}\,(A,T) = \mathrm{BE}(T,T_{z<}) - \mathrm{BE}(T,T_{z>})$$

- Charge-independence breaking
  - In T=1 states, pp (T_z=-1), np (T_z=0), nn (T_z=+1) interactions are slightly different
  - Experimental signal: triplet displacement energy (TDE)

$$\mathrm{TDE}\,(A,T) = \mathrm{BE}(T,T_{z<}) + \mathrm{BE}(T,T_{z>}) - 2\mathrm{BE}(T,T_z=0)$$

Isospin-symmetry breaking

- Reason for volation of isospin symmetry:
  - Coulomb interaction between protons
  - Isospin-nonconserving (INC) nuclear interactions

- Wigner et al. (1957):
- Assuming the two-body nature for any charge-dependent effects and the Coulomb force between the nucleons as perturbation, they noted that masses of the $2T+1$ members of an isobaric multiplet are related by the isobaric multiplet mass equation (IMME).

Isospin-symmetry breaking

- This can be easily derived:

Let H_{CI} be charge-independent Hamiltonian, $|\alpha T T_z\rangle$ is its eigenstate. H'_{CV} is charge-violating interaction

$$\mathrm{BE}(\alpha T T_z) = \langle \alpha T T_z | H_{\mathrm{CI}} + H'_{\mathrm{CV}} | \alpha T T_z \rangle$$

Assuming two-body interactions:

$$H'_{\mathrm{CV}} = \sum_{k=0}^{2} H_{\mathrm{CV}}^{(k)}$$

$$H_{\mathrm{CV}}^{(0)} = \frac{v_{\mathrm{pp}} + v_{\mathrm{nn}} + v_{\mathrm{np}}}{3}$$

$$H_{\mathrm{CV}}^{(1)} = v_{\mathrm{pp}} - v_{\mathrm{nn}}$$

$$H_{\mathrm{CV}}^{(2)} = v_{\mathrm{pp}} + v_{\mathrm{nn}} - 2v_{\mathrm{np}}$$

Isospin-symmetry breaking

Taking H'_{CV} as a perturbation

$$\Delta\mathrm{BE}(\alpha T T_z) = \left\langle \alpha T T_z \left| \sum_{k=0}^{2} H_{\mathrm{CV}}^{(k)} \right| \alpha T T_z \right\rangle$$

$$= \sum_{k=0}^{2} (-)^{T-T_z} \begin{pmatrix} T & k & T \\ -T_z & 0 & T_z \end{pmatrix} \langle \alpha T \| H_{\mathrm{CV}}^{(k)} \| \alpha T \rangle$$

One obtains the famous Isobaric Multiplet Mass Equation (IMME):

$$\Delta\mathrm{BE}(\alpha T T_z) = a + bT_z + cT_z^2$$

which depends on T_z up to the quadratic term.

Isospin-symmetry breaking

$$\Delta \mathrm{BE}(\alpha T T_z) = a + bT_z + cT_z^2$$

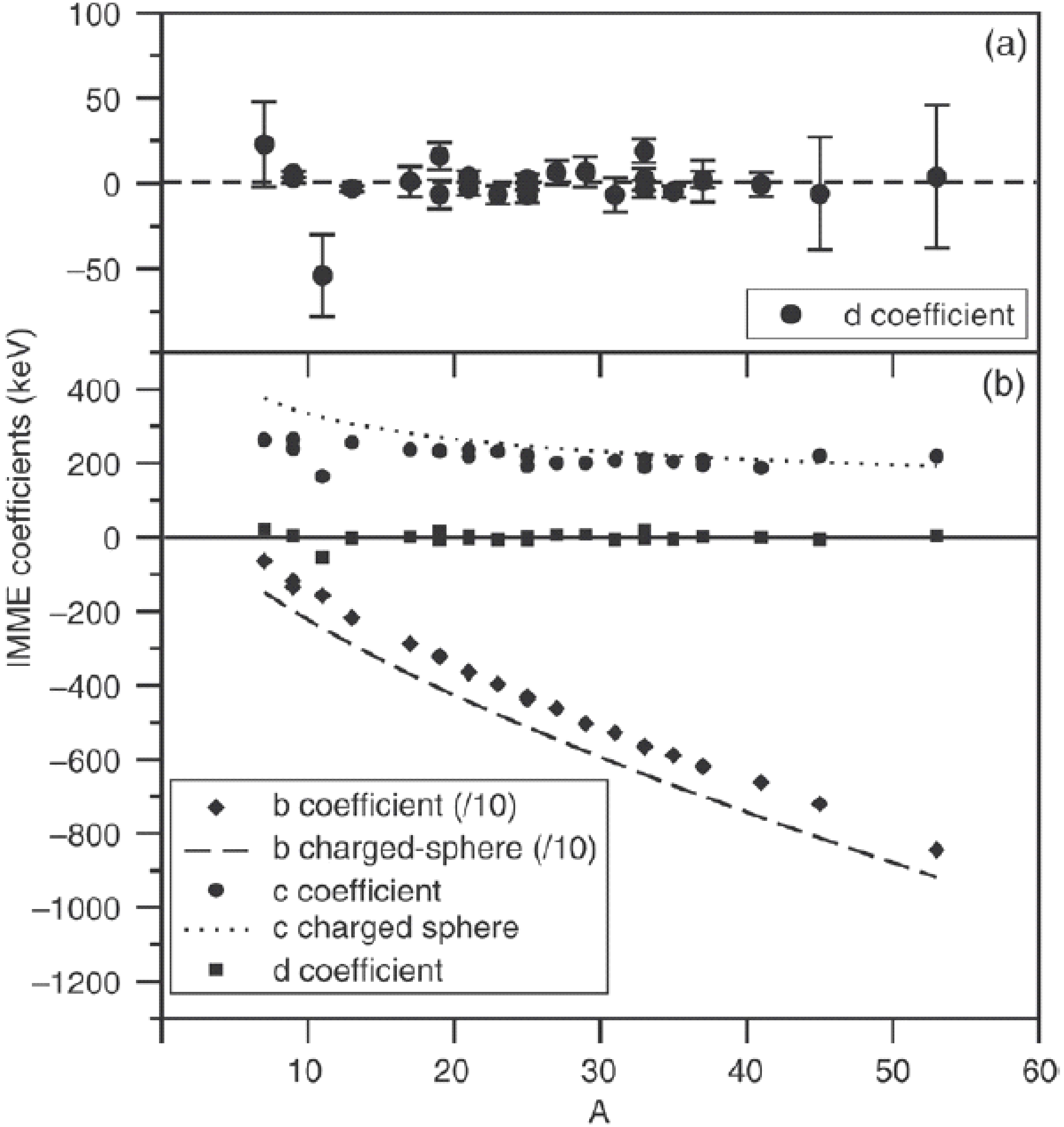
- Higher orders of T_z (dT_z^3, eT_z^4,…) in IMME are possible, due to
  - Higher order perturbations
  - Effective three-body forces
  - Any other complicated structure effects

    such as: shape coexistence

    shape phase transition

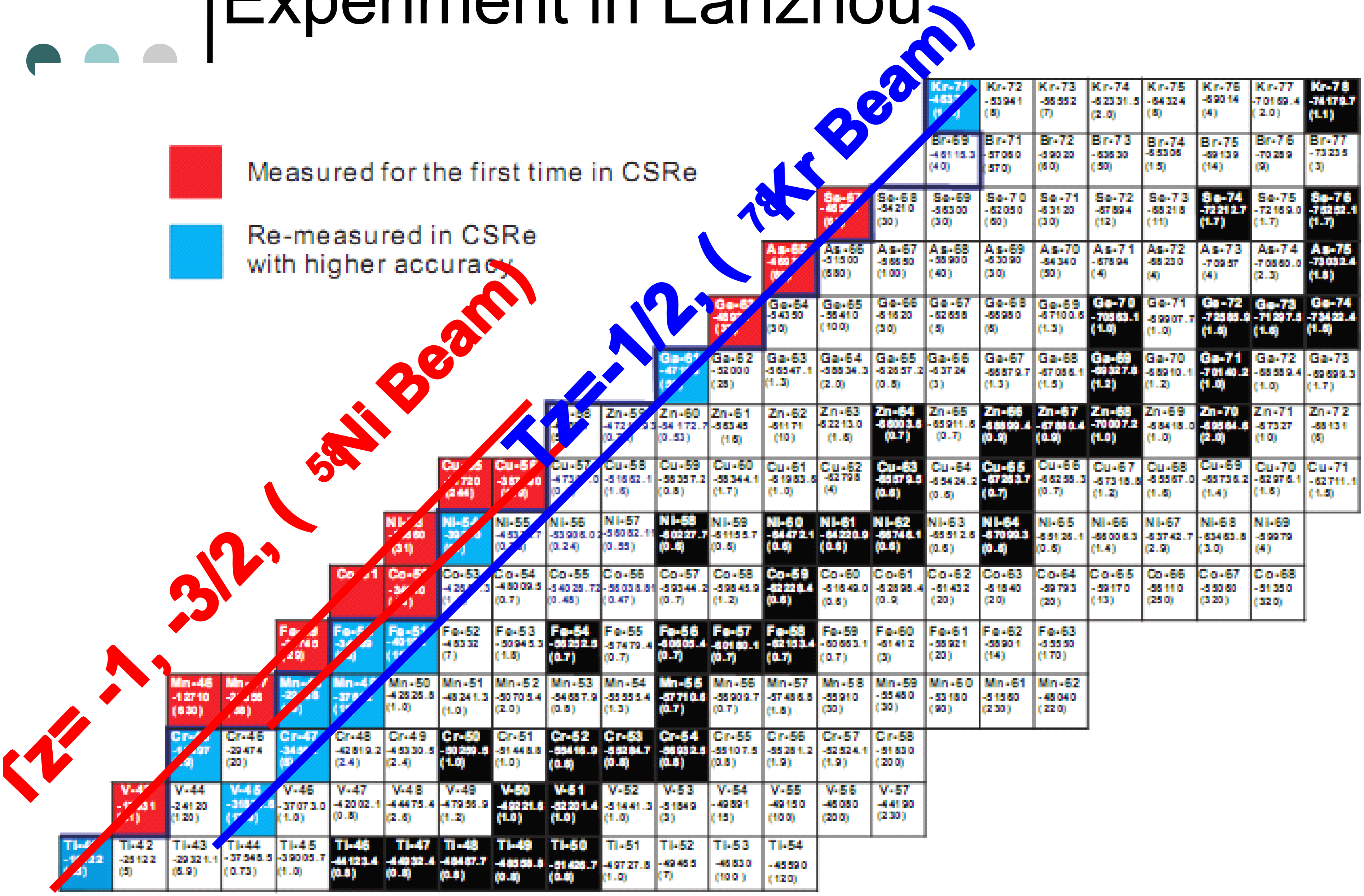
    ……

I



IMME has been tested to be very accurate up to A~40

Experiment in Lanzhou

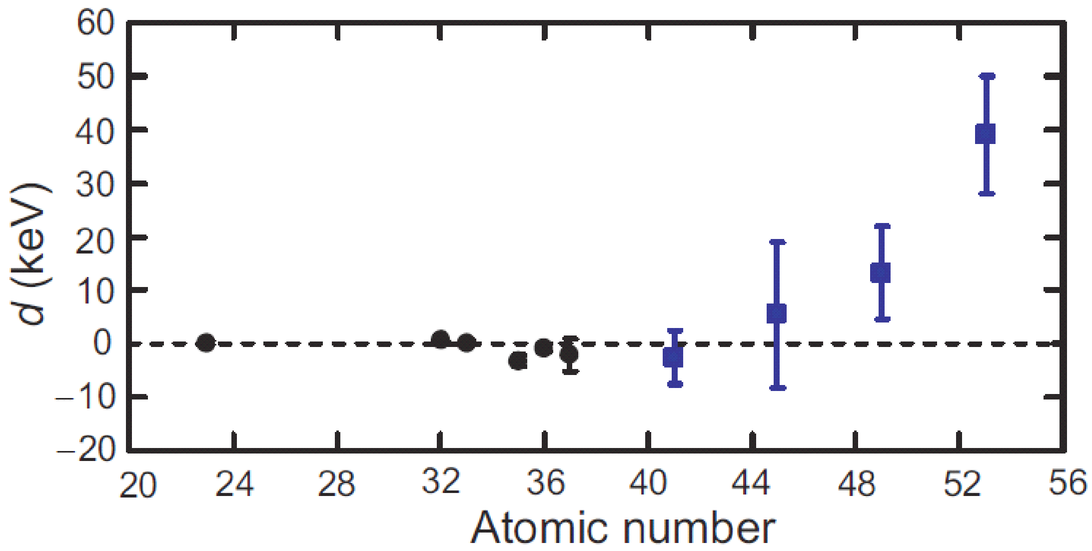


Large deviation of IMME at A~53

- Clear deviations are found for IMME:

$$ME(A,T,T_z) = a(A,T) + b(A,T)T_z + c(A,T)T_z^2 + d(A,T)T_z^3$$

Y.-H. Zhang et al, Phys. Rev. Lett. 109 (2012) 102501



ME=mass excess

Large deviation for A=53, T=3/2 quartet.

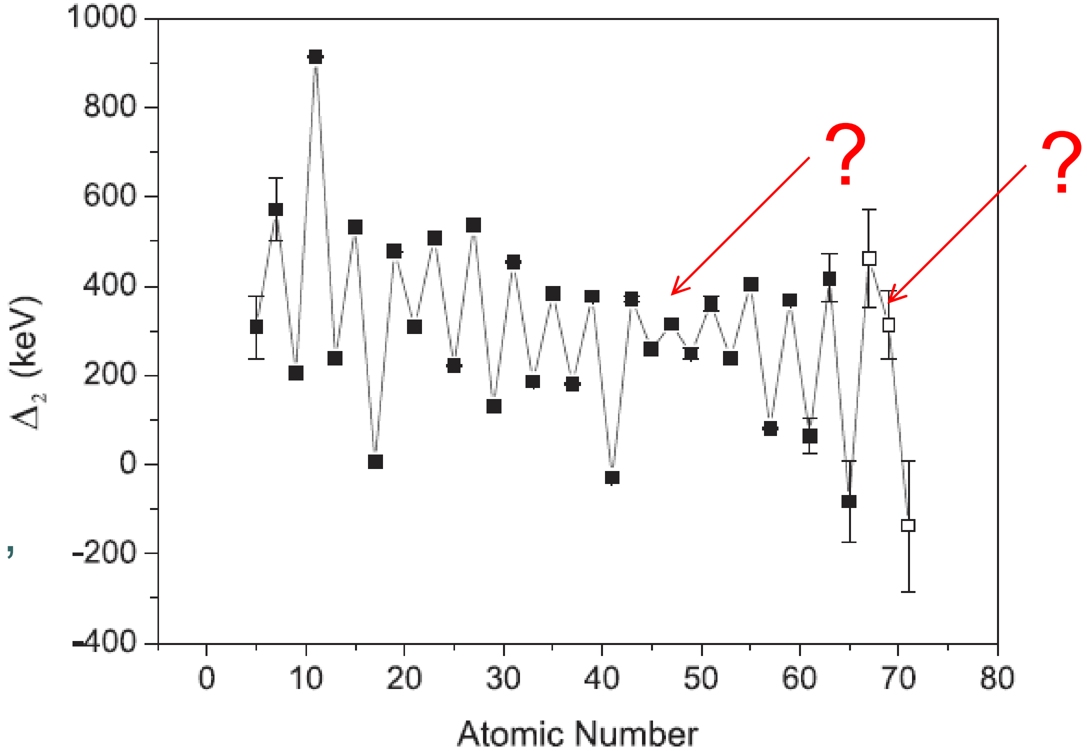
A non-zero *d* term is needed.

Anomalies in CDE at A~70

- A more sensitive plot: the difference in CDE

$$D_2(A) = D(A) - D(A-2)$$

- Results show the well-known odd-even staggering, but find anomaly near A~70: the staggering changes phase!



Odd-even staggering explained by E. Feenberg and G. Goertzel, Phys. Rev. 70 (1946) 597

X.-L. Tu et al., submitted

fp and *fpg* shell model calculations

- The charge-dependent and isospin nonconserving forces are considered:

$$V'_{CV} = H'_{sp} + V_C + \sum_{k=1}^{2} V_{INC}^{(k)}$$

V_C: Coulomb interaction

H'_{sp}: Coulomb single-particle interaction including shifts due to electromagnetic spin-orbit interaction

The last term: $V_{INC}^{(1)} = V_{pp} - V_{nn}, \quad V_{INC}^{(2)} = V_{pp} + V_{nn} - 2V_{pn}$

- Comparison of data with calculated difference in CDE by GXPF1A and JUN45 forces, and by A. Brown calculation.

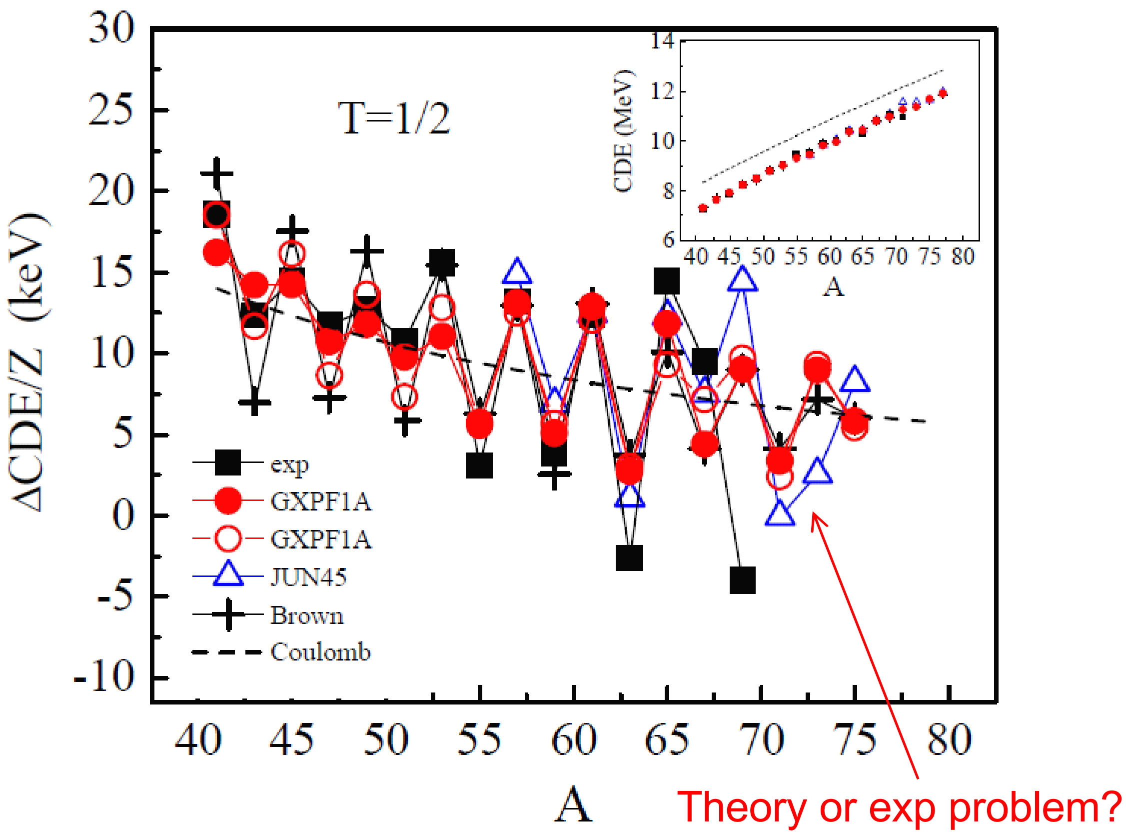


FIG. 3: (Color online) Calculated $\Delta\mathrm{CDE}(A,T)/Z$ with GXPF1A and JUN45 interactions are compared with experimental data. Solid (open) symbols indicate results with (without) the INC nuclear interactions in the $f_{7/2}$ shell. For comparison, results from Brown *et al.* [19] and from the Coulomb prediction [6] are also shown. The insert is the calculated CDE compared with experimental data and the Coulomb prediction. Experimental data are taken from Ref. [15, 25].

Kaneko, Sun, Mizusaki, Tazaki, Phys. Rev. Lett. 110 (2013) 172505

Isospin-symmetry breaking seen in excited nuclear states

- Nuclei are strongly correlated many-systems, having two very important properties:
  - Strong spin-orbit interaction
  - Shape effects and collective motion

- The effects can be enhanced in heavier nuclei.

- Difference in excitation energy of the same spin between isobaric analogue states (IAS) of the same isospin T.

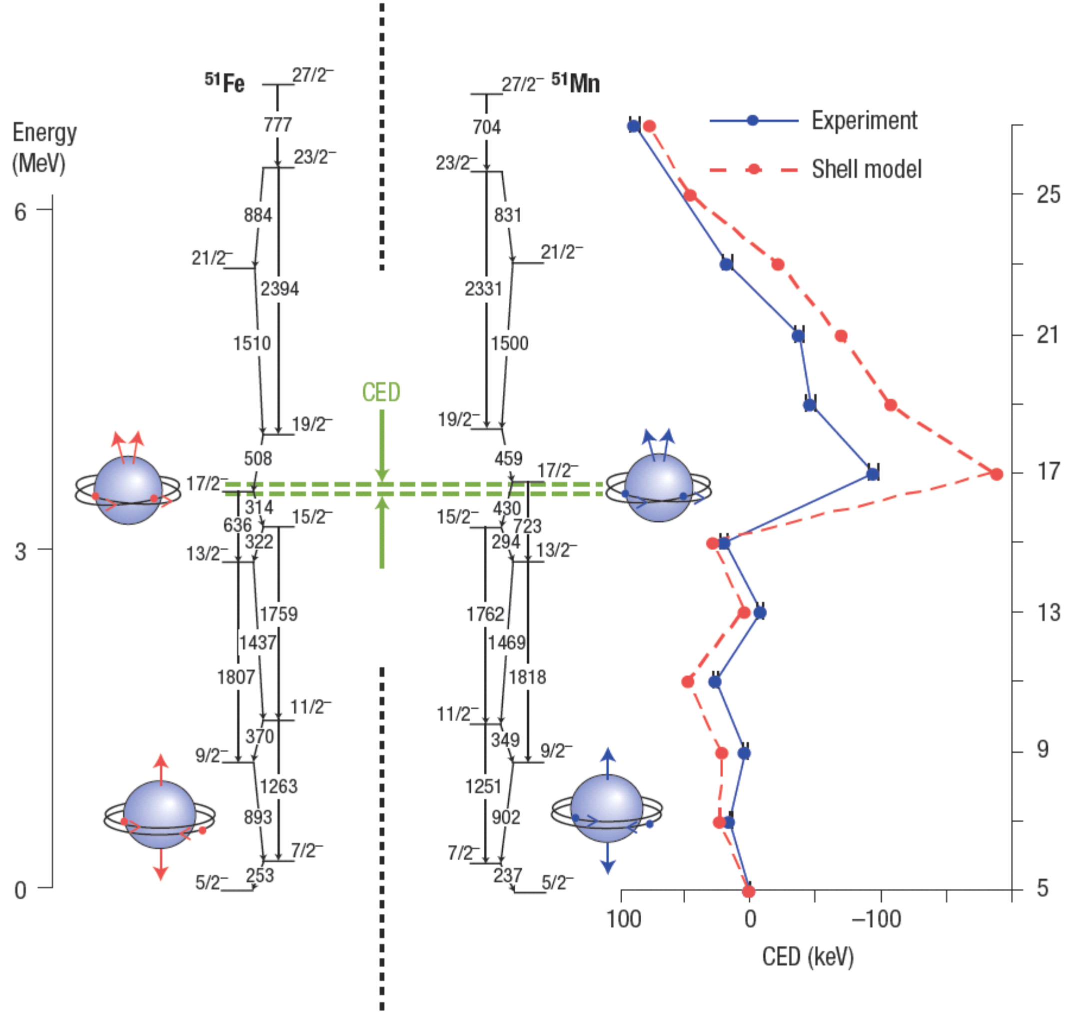
Isospin-symmetry breaking seen in excited nuclear states

- Isospin is to classify different nuclear states having same quantum numbers.

^{51}Fe: N=25, Z=26, T_z=-1/2

^{51}Mn: N=26, Z=25, T_z=1/2

- States of same T are clearly different.



Warner et al., Nature Phys. 2 (2006) 311

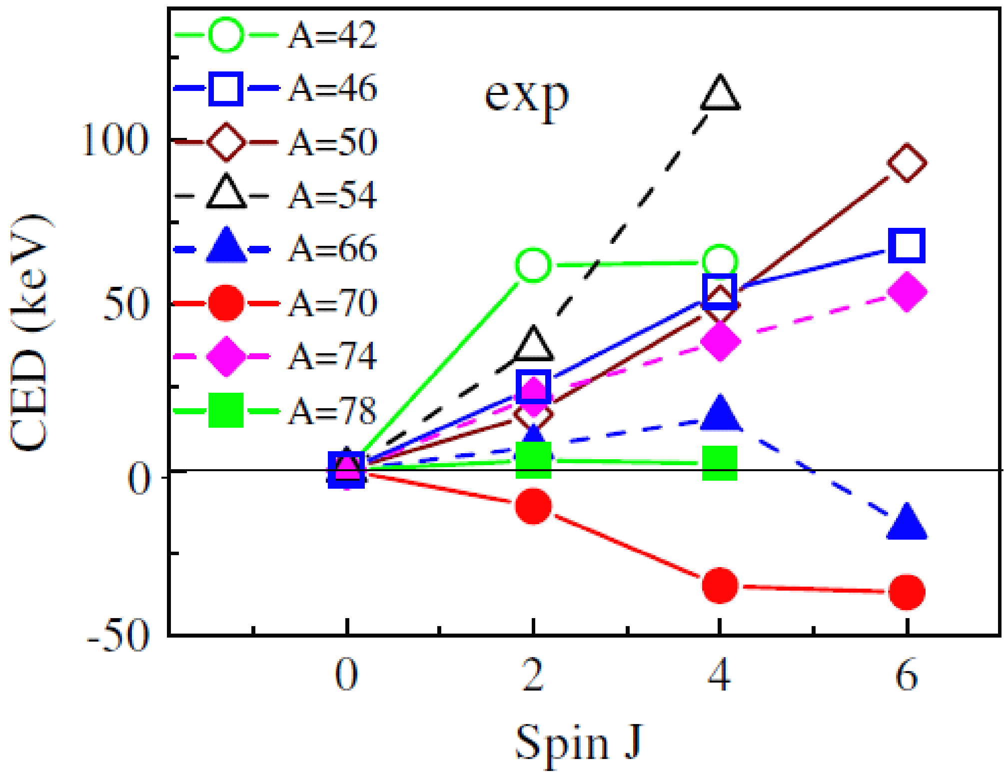


FIG. 1 (color online). Experimental CED between the isospin $T = 1$ states in odd-odd $N = Z$ nuclei and the IAS in even-even nuclei for mass numbers $A = 42 - 78$. Data were taken from Refs. [4–6,11].

$$\mathrm{CED}(J) = E_x(J, T = 1, T_z = 0) - E_x(J, T = 1, T_z = 1)$$

Effect of enhanced electromagnetic spin-orbit interaction

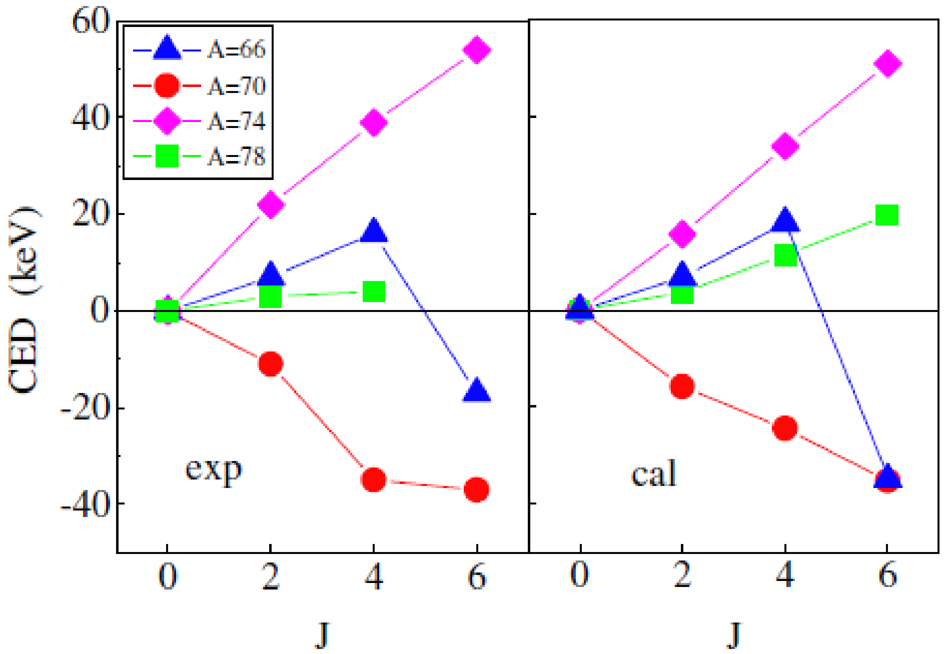


FIG. 2 (color online). Comparison of calculated CED with experimental data for mass number $A = 66$, 70, 74, and 78. Note that for $A = 66$, the calculated CED correspond to the second 6^+ states.

Kaneko, Mizusaki, Sun, Tazaki, de Angelis, *Phys. Rev. Lett.* 109 (2012) 092504

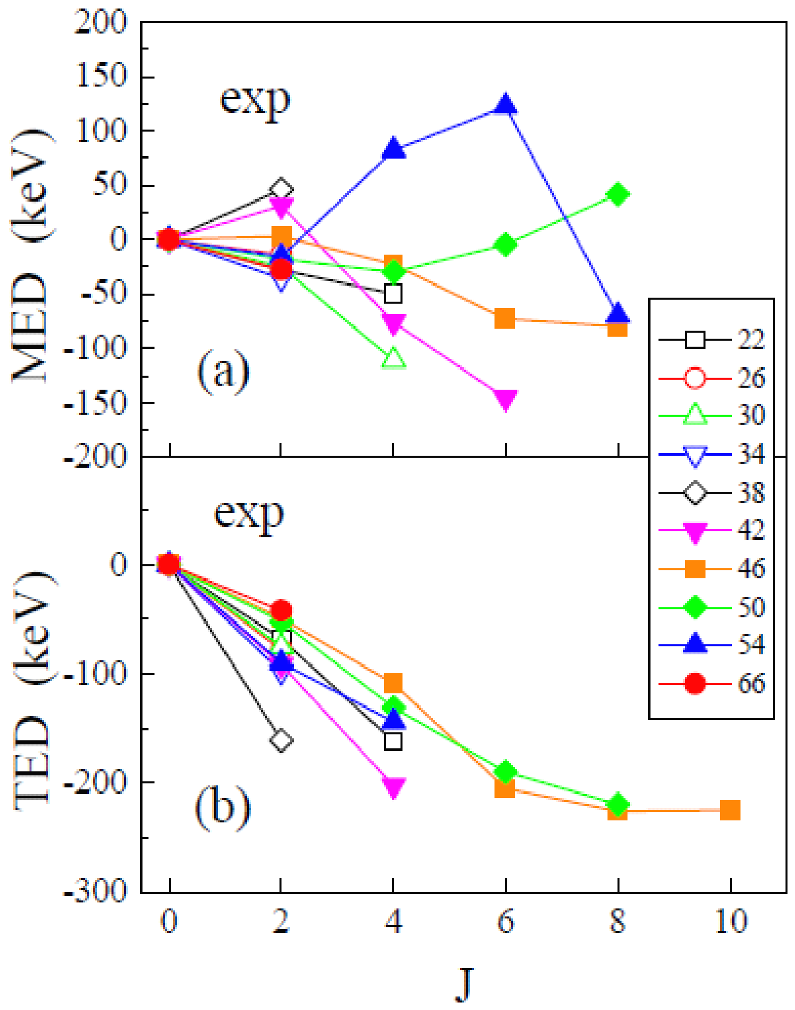


FIG. 1: (Color online) Experimentally-known MED and TED for masses of $A = 22 - 66$. Data are taken from Refs. [16–24].

$$\mathrm{MED}(J) = E_x(J, T = 1, T_z = -1) - E_x(J, T = 1, T_z = 1)$$

$$\mathrm{TED}(J) = E_x(J, T = 1, T_z = -1) + E_x(J, T = 1, T_z = 1) - 2E_x(J, T = 1, T_z = 0),$$

Prediction of unknown masses using CDE

Difference in binding energy of mirror nuclei

$$D(A,T) = BE(A,T_z^<) - BE(A,T_z^>)$$

Binding energy of the proton-rich nucleus $BE(A,T_z^<)$

Binding energy of the neutron-rich nucleus $BE(A,T_z^>)$

$$T = |T_z^<| = |T_z^>|$$

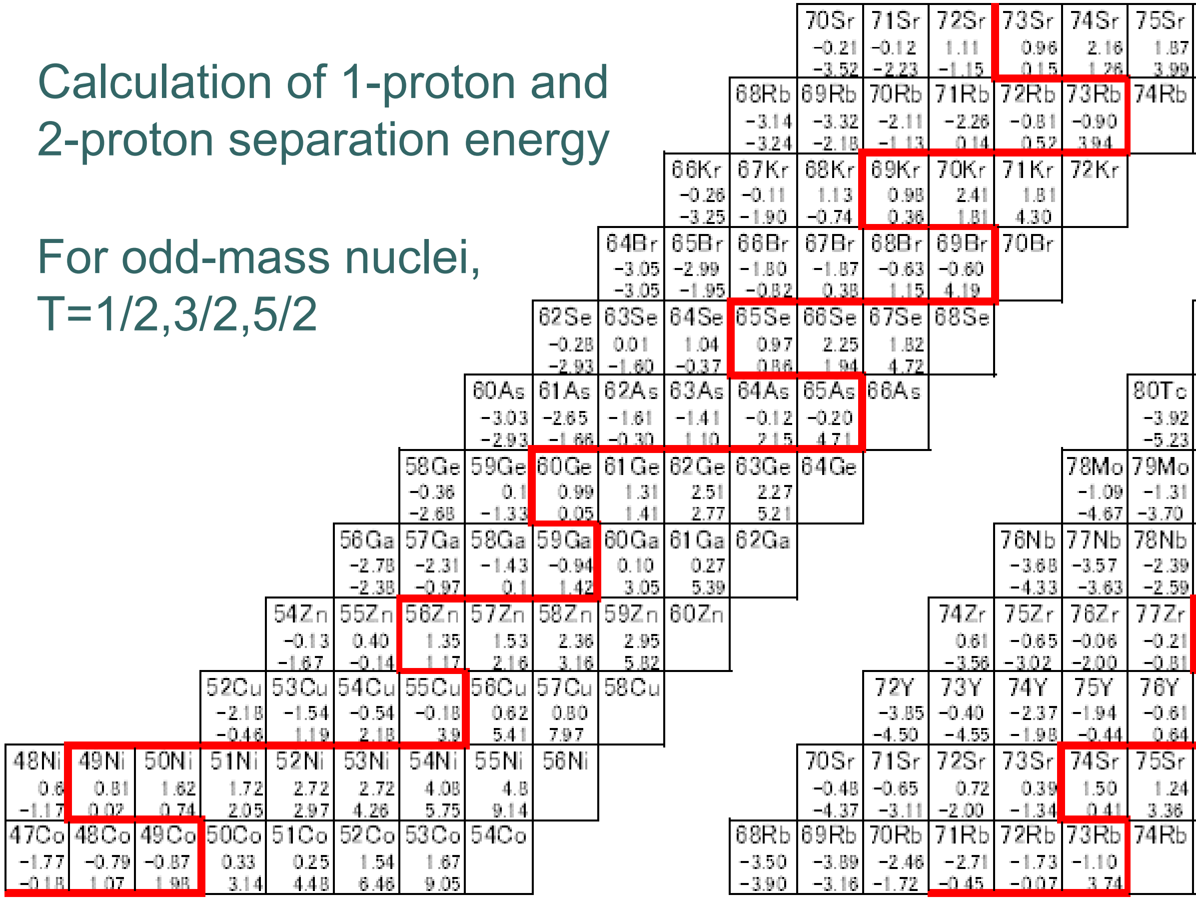
If D(A,T) can be accurately calculated, then

$$BE(A,T_z^<) = D(A,T)_{HF} + BE(A,T_z^>)_{\exp}$$

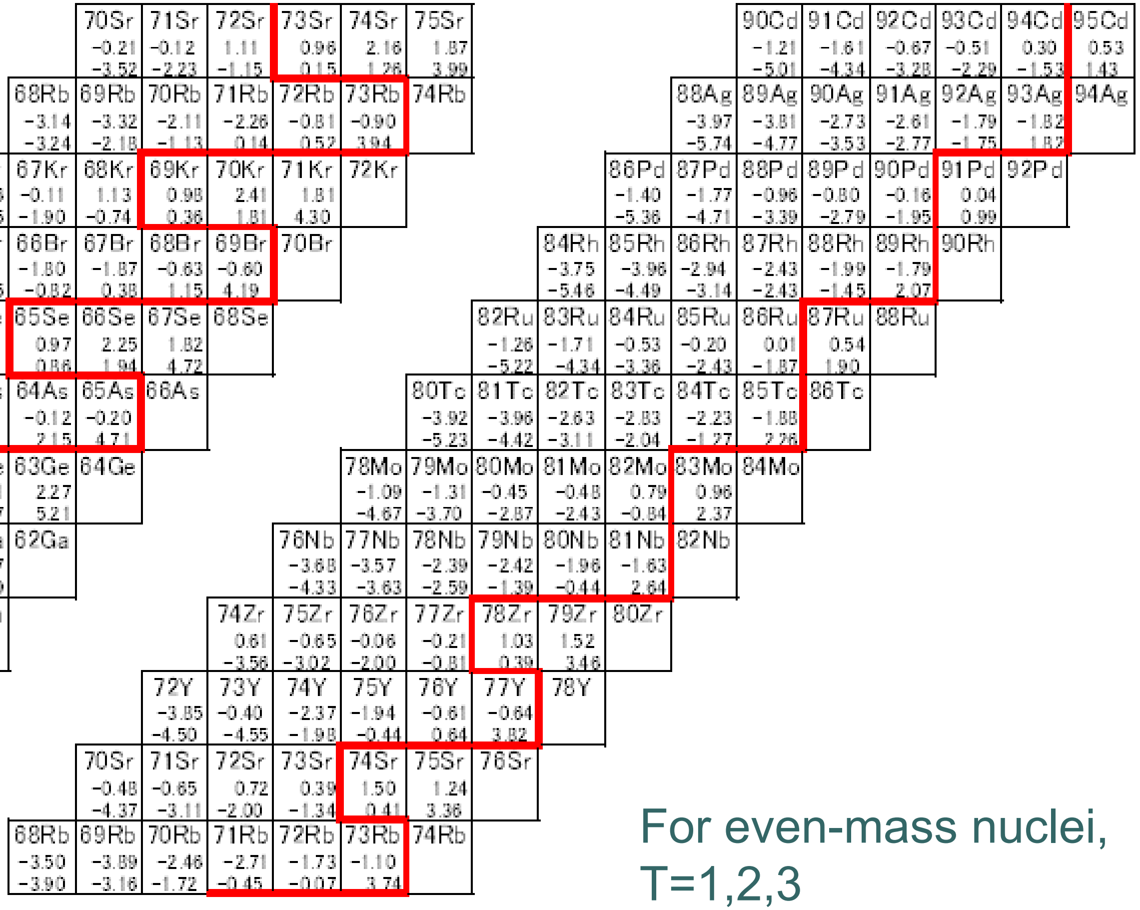
Mapping the proton drip-line

Calculation of 1-proton and 2-proton separation energy

For odd-mass nuclei, T=1/2,3/2,5/2



GXPF1A



JUN45

For even-mass nuclei, T=1,2,3

Kaneko, Sun, Mizusaki, Tazaki, Phys. Rev. Lett. 110 (2013) 172505

Summary

- Measurement of exotic masses can test nuclear models and arise questions in fundamental physics.
- The new mass measurements allow us to think of the fundamental questions in isospin-symmetry breaking in effective interactions in heavier nuclei for the first time.
- The mass measurement and the CDE study allow to map the proton drip-line, and have impact on the study of nucleosynthesis in the rp-processs.
- Excited spectra for proton-rich nuclei are very desired.