NUCLEAR STRUCTURE NEAR THE DRIPLINES

Kai Schweda

Outline

Chiral effective field theory

Neutron drip line

Charge radii

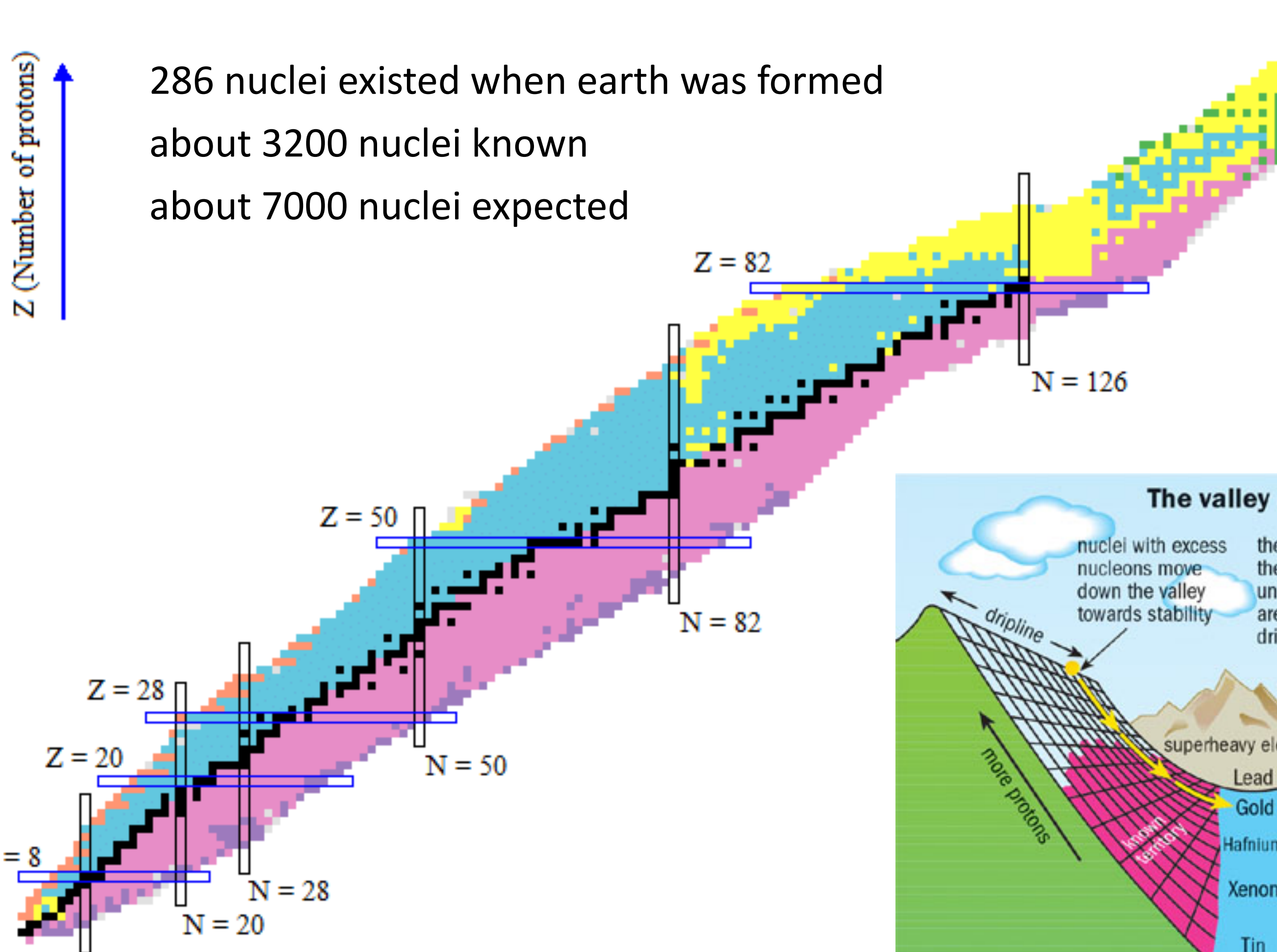
Future facilities

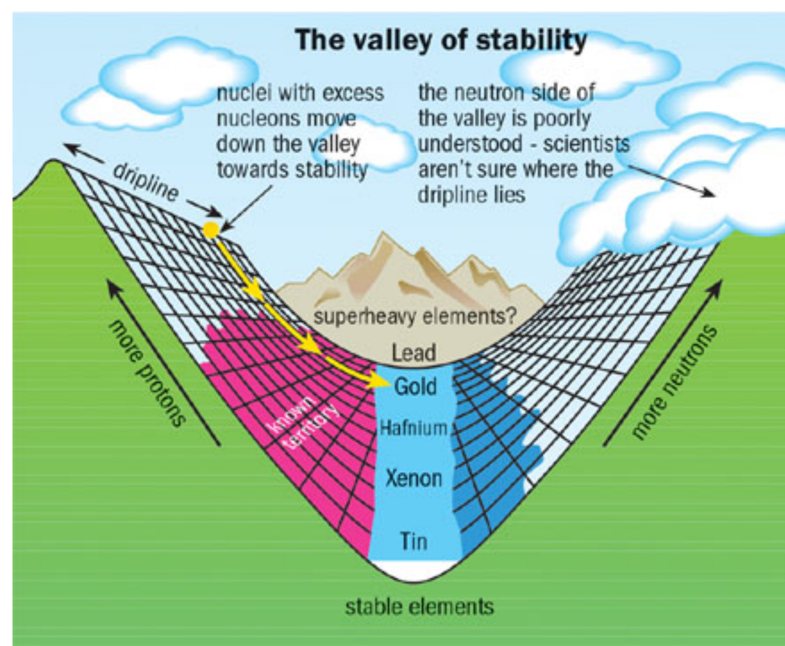
NUCLEAR CHART

286 nuclei existed when earth was formed

about 3200 nuclei known

about 7000 nuclei expected





BRIEF HISTORY

1930’s
Chadwick (1932) neutron
Heisenberg (1932) isospin
Yukawa (1935) meson hypothesis

1940’s
Discovery of the pion in cosmic rays (1947) and in the Berkeley Cyclotron Lab (1948)

1950’s
One-Pion-Exchange (OPE) models
Multi-pion exchanges

1960’s
many pions = multi-pion resonances
$\sigma(600),\ \rho(770),\ \omega(728)$
one-boson-exchange model

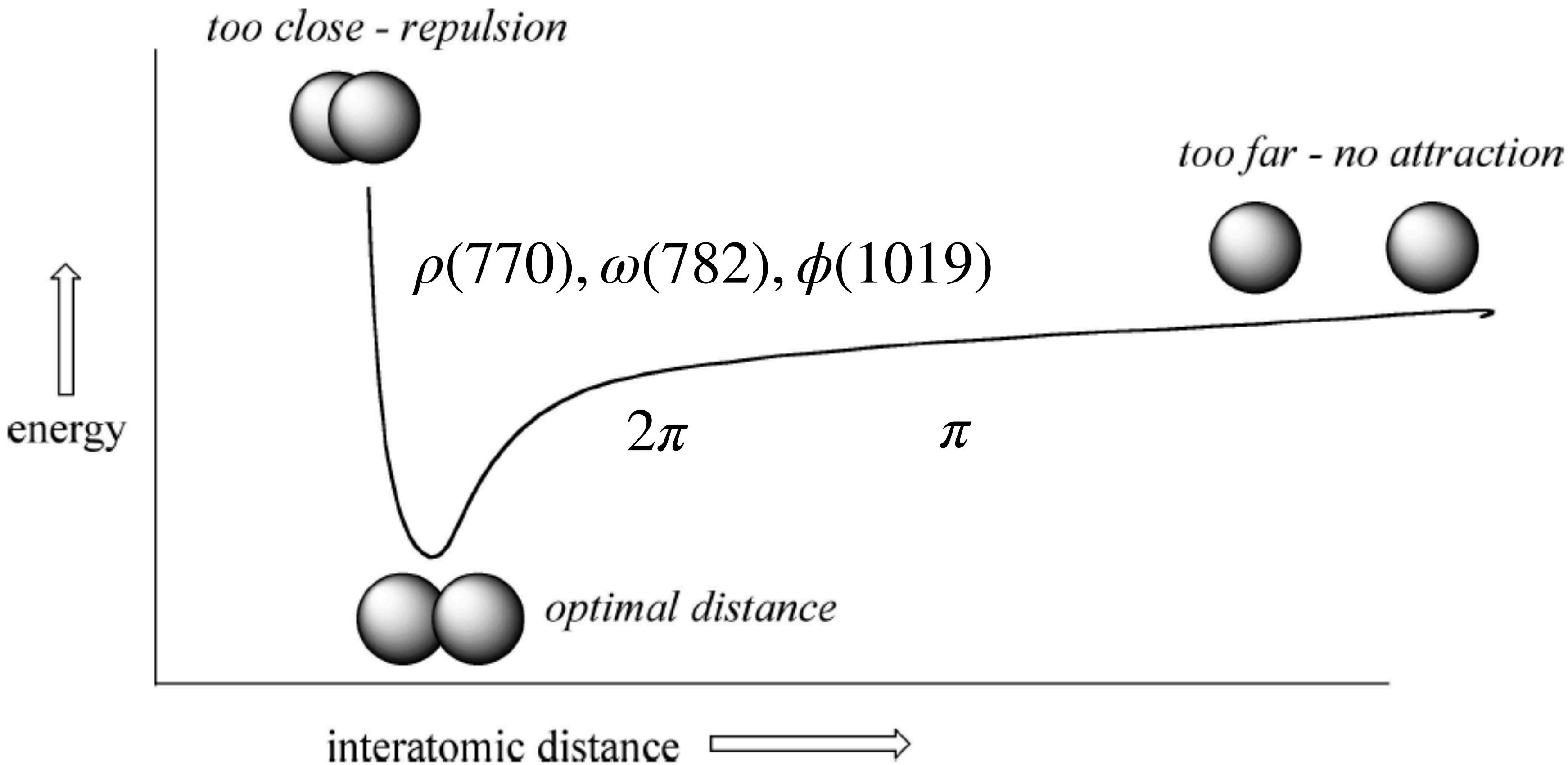
BRIEF HISTORY

1970’s
Refined meson theories
Sophisticated models for two-pion exchange
Paris potential, Bonn potential, Argonne potential

1980’s
nuclear physicists discover QCD
quark cluster models

1990’s
nuclear physicists discover Effective Field Theory (EFT)
Steven Weinberg

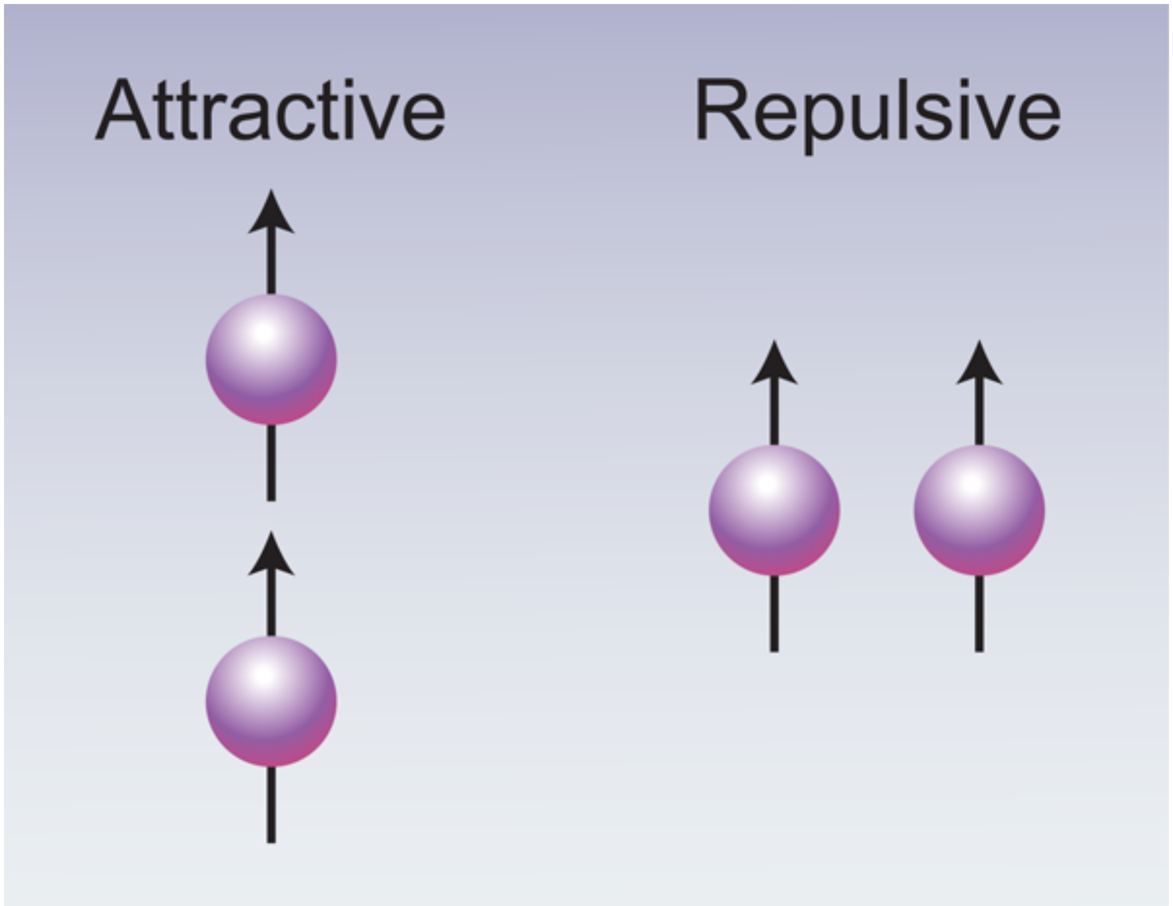
NUCLEON-NUCLEON FORCE



$$1/M(\pi) = 1.5\text{fm}$$
$$1/M(\rho) \approx 0.2\text{fm}$$

TENSOR FORCE

$$(-S_{12}) = -3(\overrightarrow{\sigma}_1 \cdot \hat{r})(\overrightarrow{\sigma}_2 \cdot \hat{r}) + \overrightarrow{\sigma}_1 \cdot \overrightarrow{\sigma}_2$$



source: APS
Otsuka, T et al., Phys. Rev. Lett. 104, 012501 (2010),
Fujita J, Miyazawa H. Prog. Theor. Phys. 17:360 (1957).

GENERAL TWO-BODY POTENTIAL

$$
\begin{aligned}
V_{NN} = {} & V_0(r) + V_\sigma(r)\sigma_1 \cdot \sigma_2 + V_\tau(r)\tau_1 \cdot \tau_2 + V_{\sigma\tau}(r)(\sigma_1 \cdot \sigma_2)(\tau_1 \cdot \tau_2) \\
& + V_{LS}(r)L \cdot S + V_{LS\tau}(r)(L \cdot S)(\tau_1 \cdot \tau_2) \\
& + V_T(r)S_{12} + V_{T\tau}(r)S_{12}\,\tau_1 \cdot \tau_2 \\
& + V_Q(r)Q_{12} + V_{Q\tau}(r)Q_{12}\,\tau_1 \cdot \tau_2 \\
& + V_{PP}(r)(\sigma_1 \cdot p)(\sigma_2 \cdot p) + V_{PP\tau}(r)(\sigma_1 \cdot p)(\sigma_2 \cdot p)(\tau_1 \cdot \tau_2)
\end{aligned}
$$

CENTRAL ^

spin-orbit

tensor

"quadratic sp.-orb."

source:R. Machleidt, CNS summer school 2005
Okubo and Marshak, Ann. Phys. 4, 166 (1958).

YUKAWA POTENTIAL AND CONTACT INTERACTION

Potential: $V(r) = -\frac{g^2}{4\pi}\frac{e^{-mr}}{r}$

Propagator: $P(Q) = \frac{1}{Q^2 + M^2}$

If $M \gg Q$, spatial structure not resolved → contact interaction

CHIRAL EFFECTIVE FIELD THEORY

Chiral momenta $Q \sim 1/\lambda \sim m_\pi$

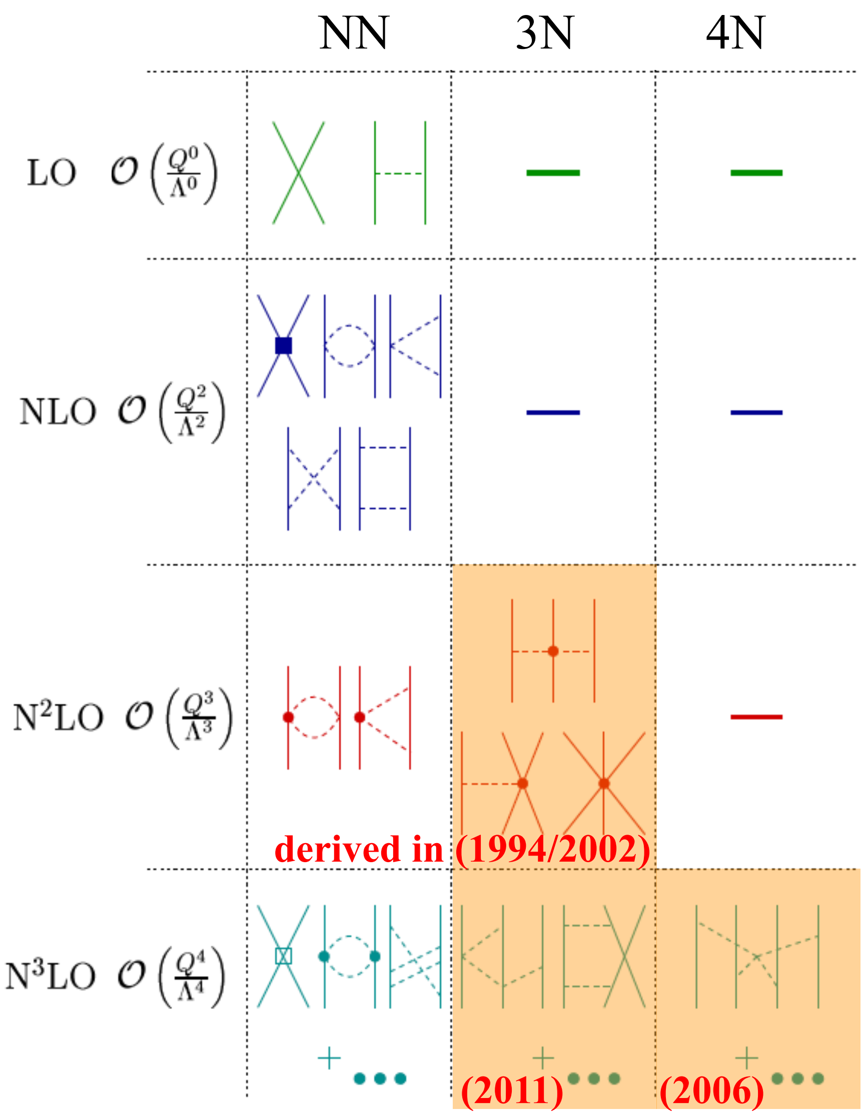
Hard scale: $\Lambda = m_\rho$

Expand in powers of: $Q/\Lambda < 1$

$$H(\Lambda) = T + V_{NN}(\Lambda) + +V_{3N}(\Lambda) + +V_{4N}(\Lambda) + \ldots$$

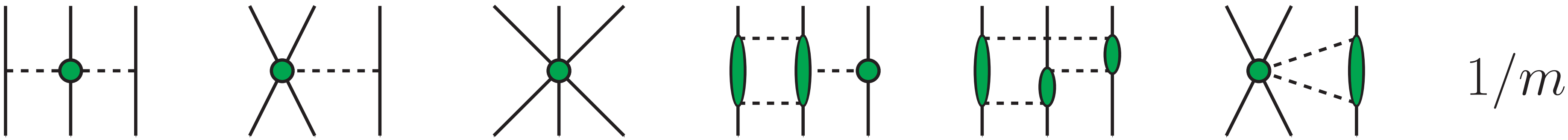
3N forces: fit binding energy and half life of ^{3}H or
binding energy of ^{3}H and charge radius of ^{4}He

CHIRAL EFFECTIVE FIELD THEORY FOR NUCLEAR FORCES



At higher orders, many-body forces occur naturally.

3-NUCLEON FORCES UP TO N³LO



(a) (b) (c) (d) (e) (f) (g)

Shaded vertices denote the amplitudes of the corresponding pion/nucleon interactions.

(a) 2π exchange

(b) 1π-contact

(c) 3N contact

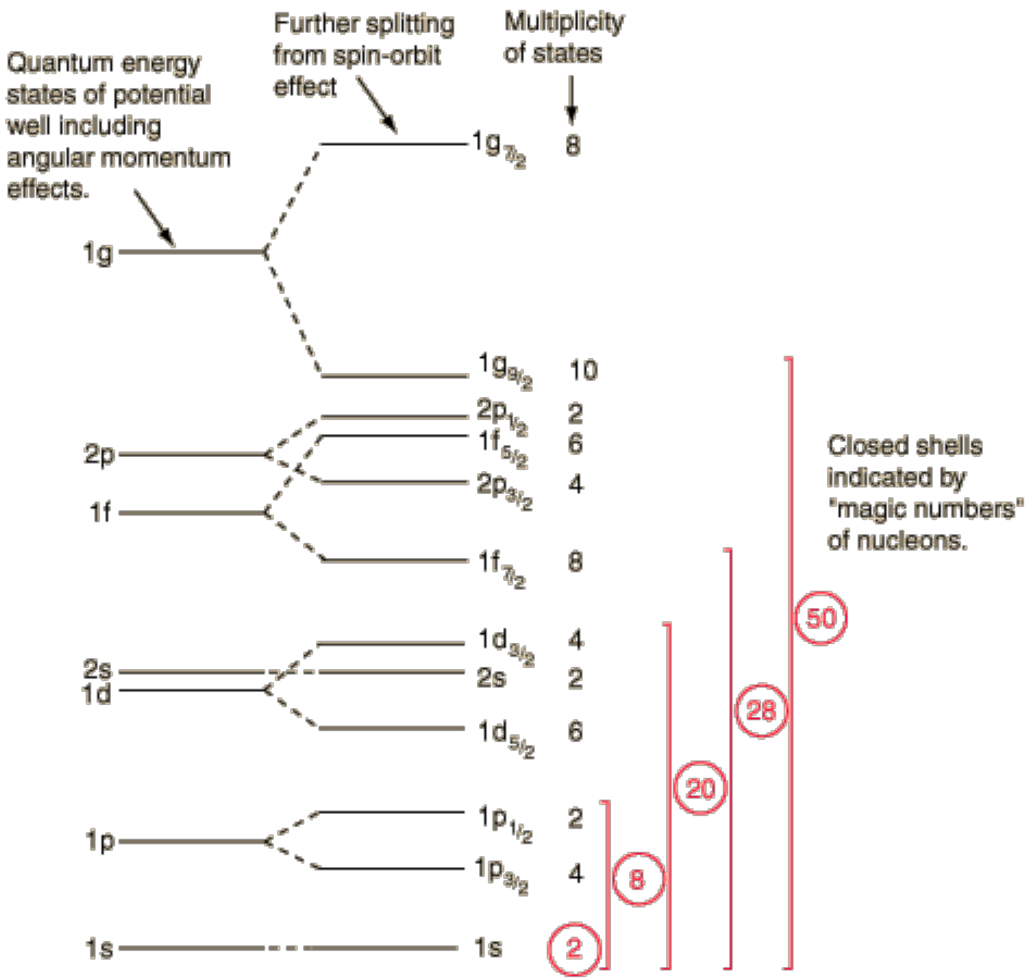
(d) 2π-1π exchange

(e) ring contributions

(f) 2π-contact

(g) relativistic corrections

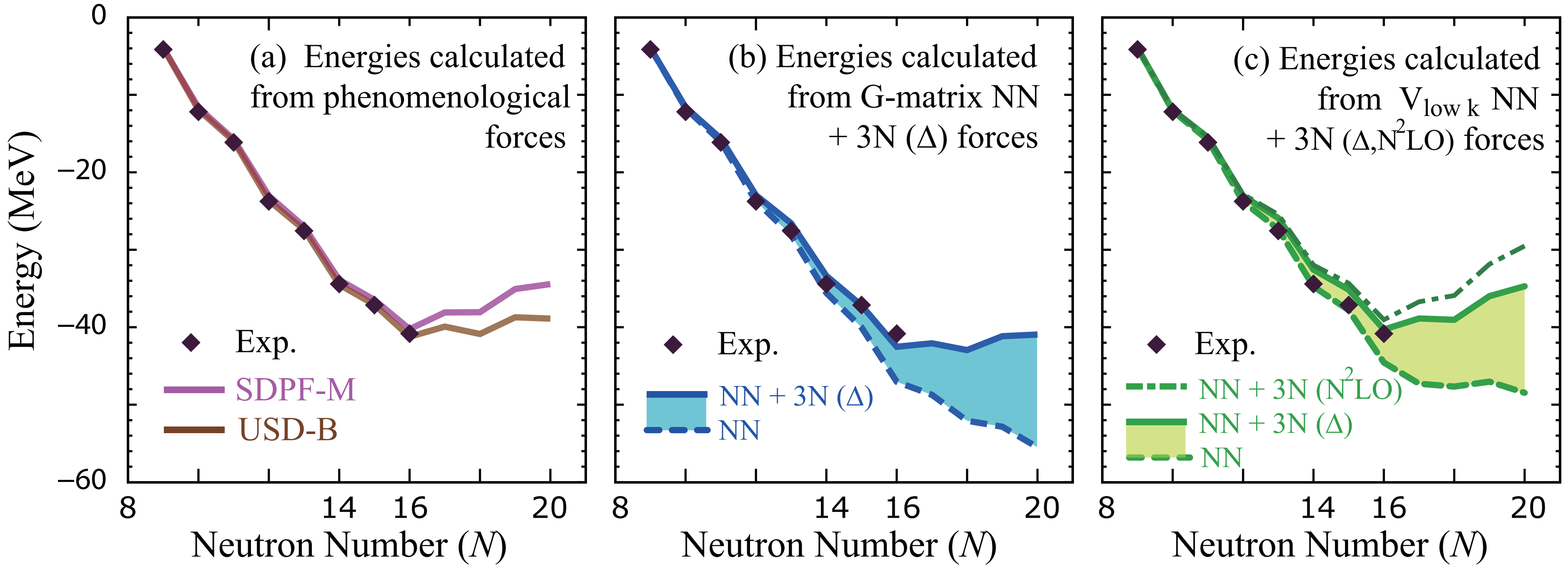
REMINDER: NUCLEAR SHELL MODEL



${}^{40}_{20}\mathrm{Ca}$

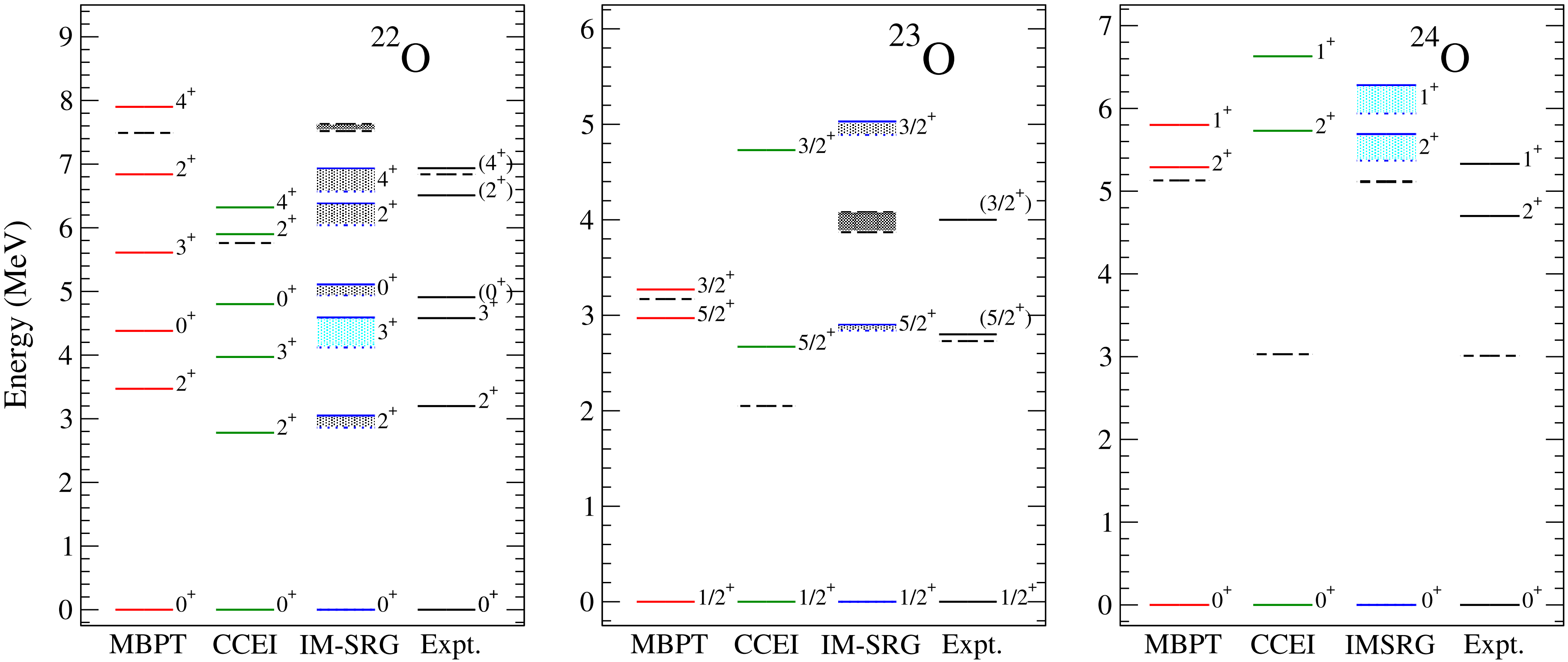
${}^{16}_{8}\mathrm{O}$

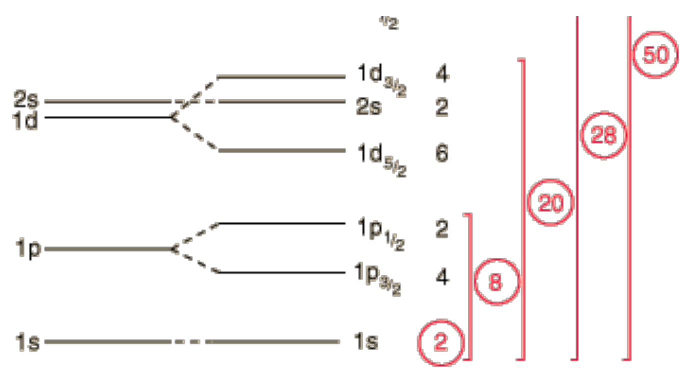
NEUTRON DRIPLINE ON OXYGEN ISOTOPES



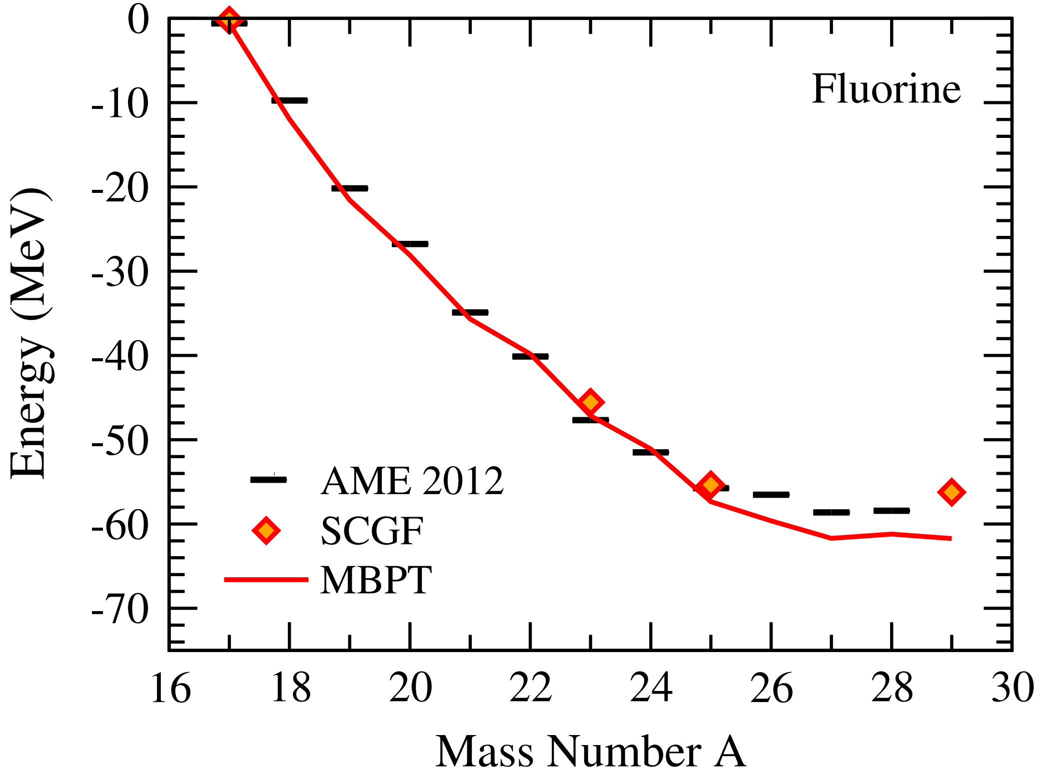
repulsive 3N forces correctly predict neutron dripline at $^{24}_{8}O$

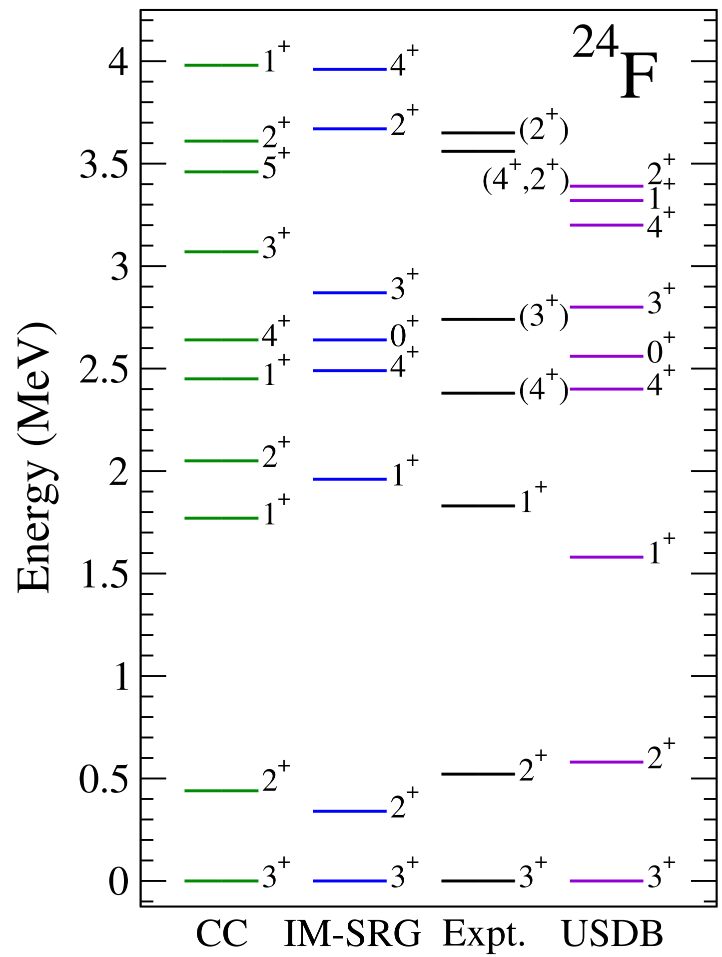
SPECTROSCOPY





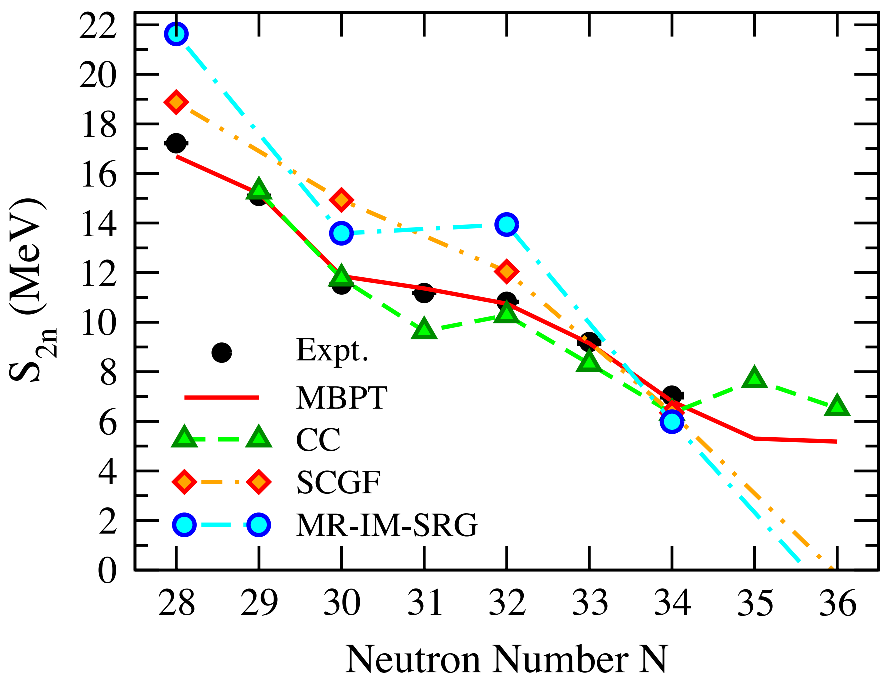
NEIGHBORING OPEN-SHELL NUCLEI

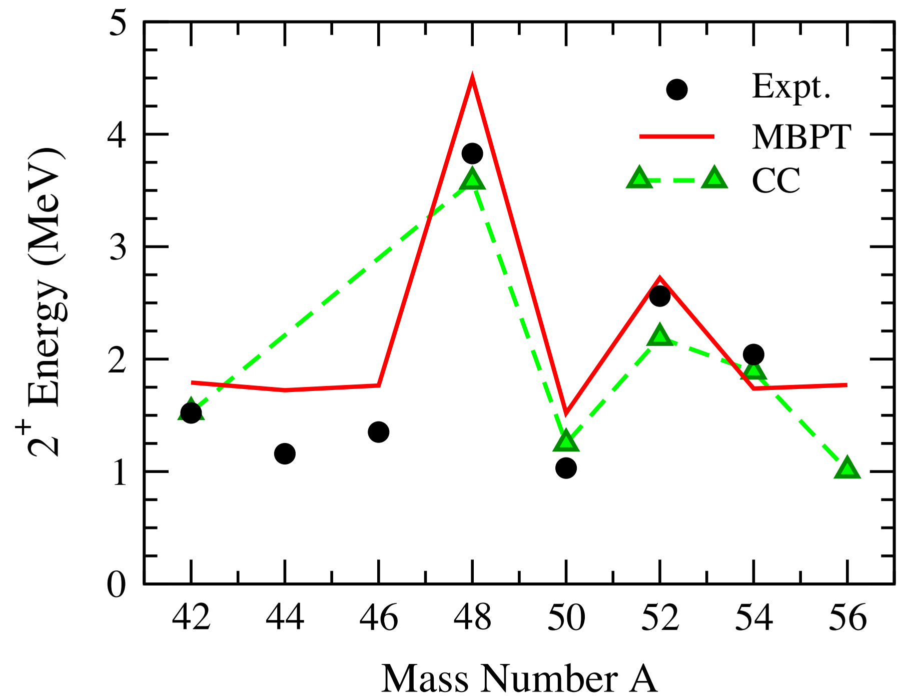




1 additional proton in $_9$F binds 6 more neutrons

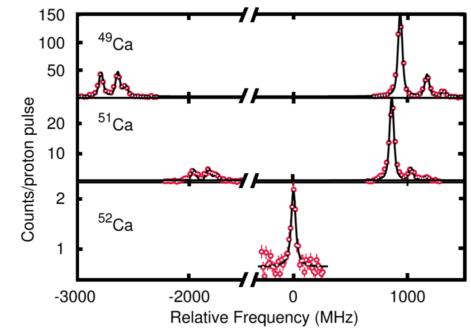
NEUTRON RICH CALCIUM ISOTOPES

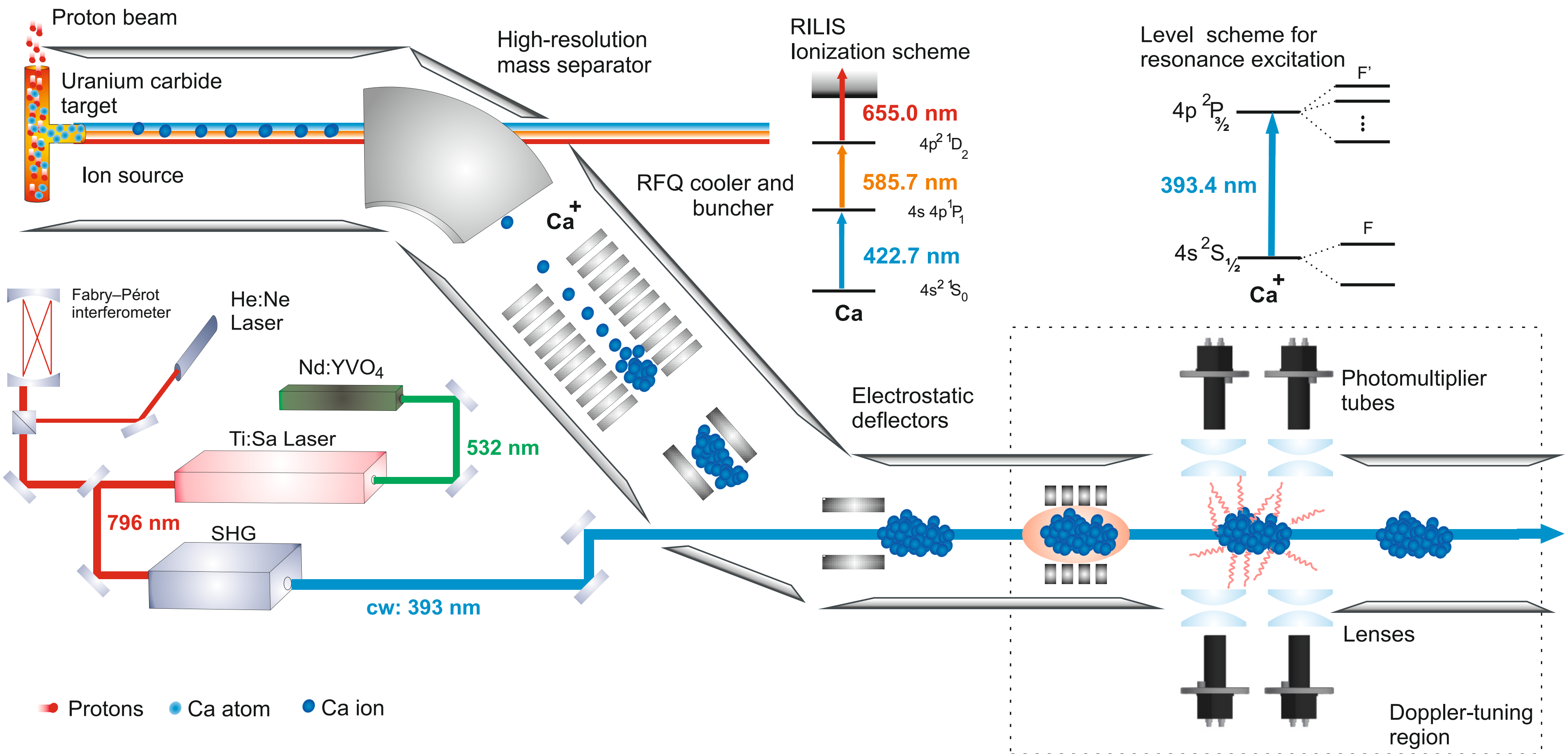




magic numbers at N=28 and N=32 and N=34

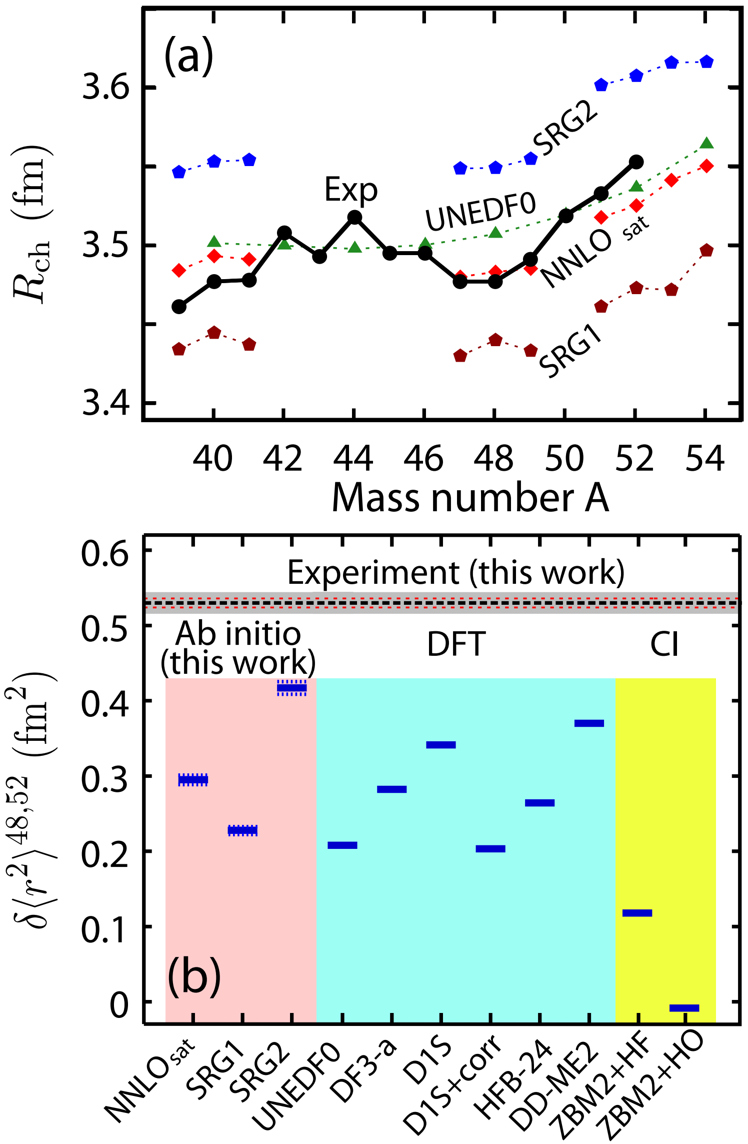
CHARGE RADIUS MEASUREMENT





ISOLDE, CERN, Nature Physics 12, 594-598 (2016).

CHARGE RADII



little change from N=20 to N=28

dramatic change for N>28

due to core-break up of the protons

well described by theory using 3N forces

ISOLDE, CERN, Nature Physics 12, 594-598 (2016), Nature Physics 15, 432–436 (2019).

NICKEL ISOTOPES

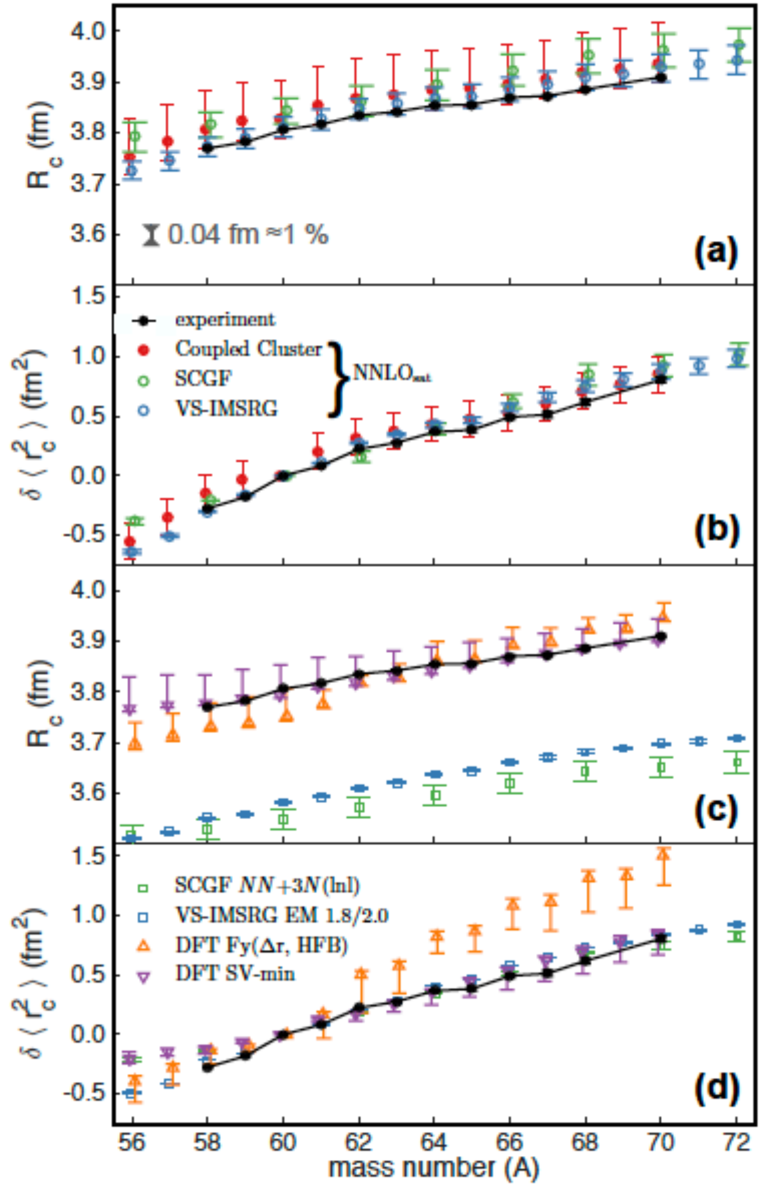
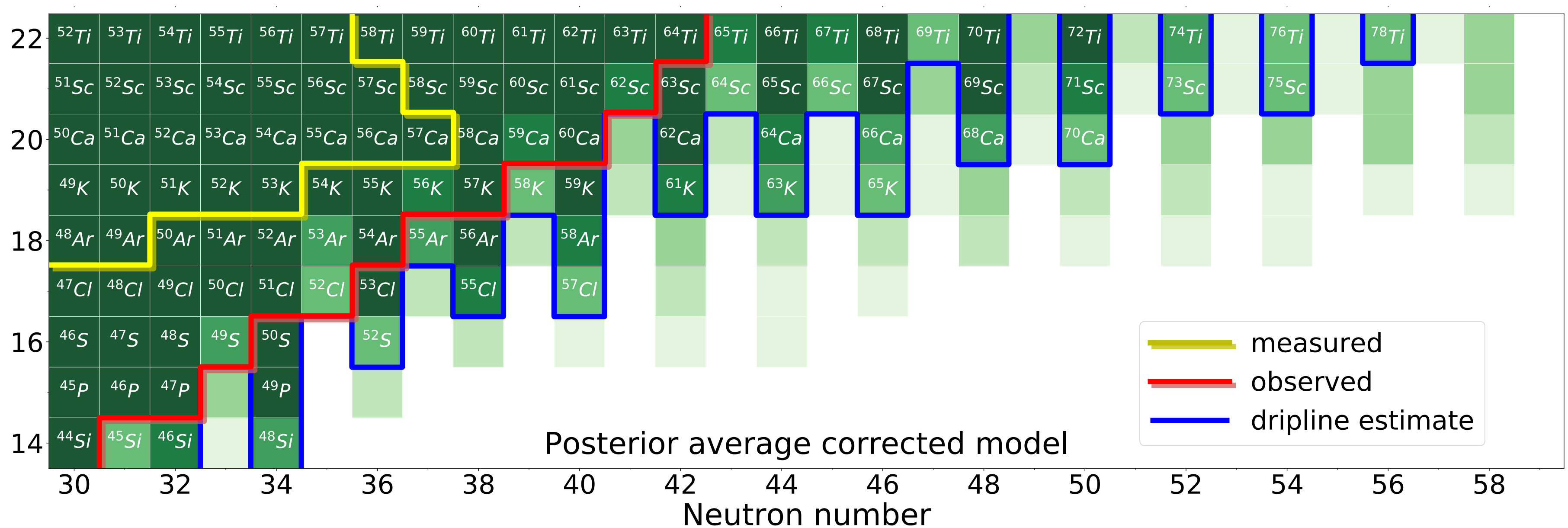


FIG. 2. Nuclear charge radii R_c and differentials $\delta \langle r_c^2 \rangle^{60,A}$ of Ni isotopes with respect to ^{60}Ni as reference. Experimental data are compared to theoretical results. See text for details.

Phys. Rev. Lett. 128, 022502 (2021)
https://arxiv.org/abs/2112.03382

A WALK ALONG THE NEUTRON DRIPLINE

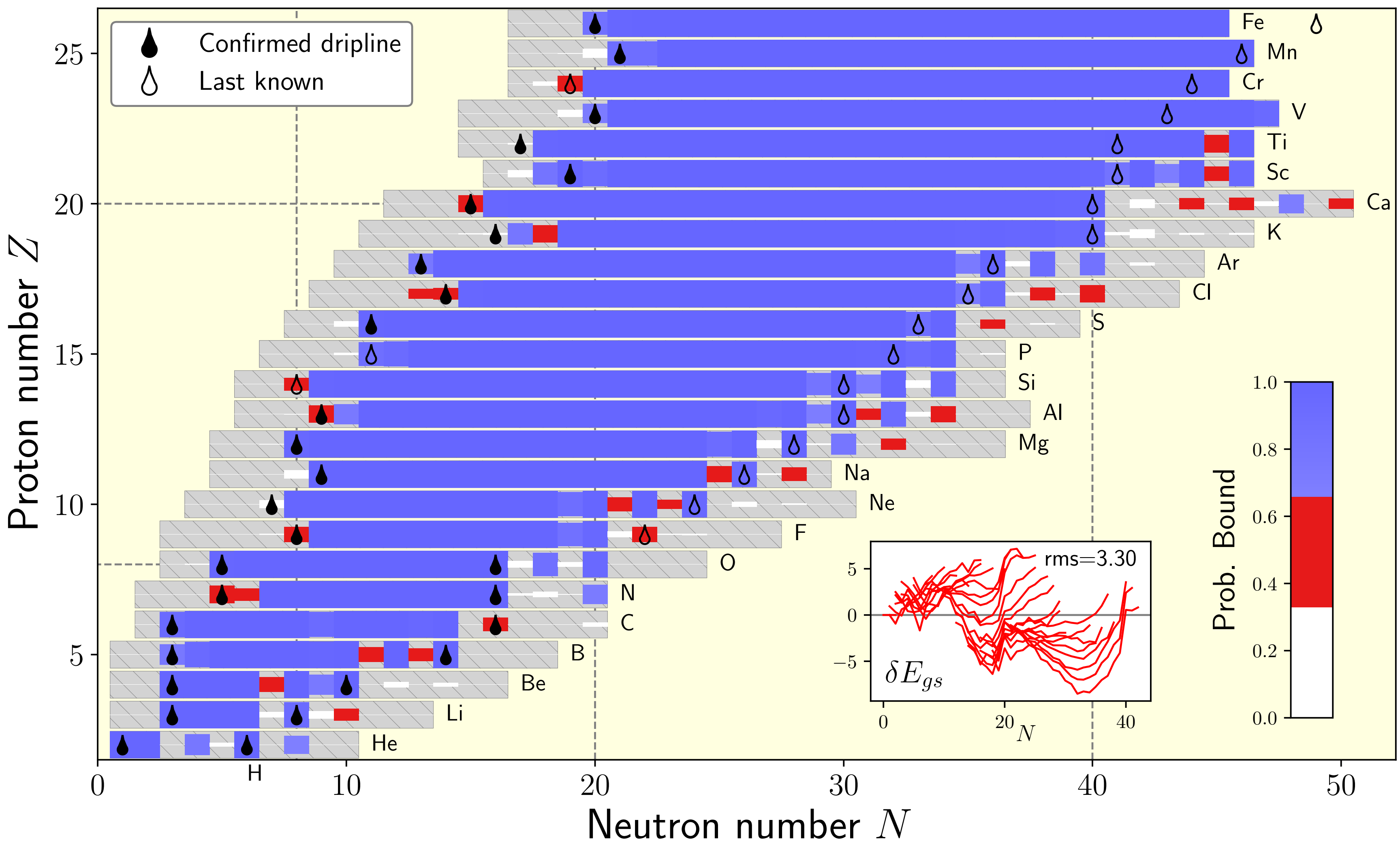


			14F P	15F 1.0 MeV P: 100.00%	16F 40 KeV P: 100.00%	17F 64.49 S ϵ: 100.00%	18F 1.8291 H ϵ: 100.00%	19F STABLE 100%	20F 11.07 S β-: 100.00%	21F 4.158 S β-: 100.00%	22F 4.23 S β-: 100.00% β-n < 11.00%	23F 2.23 S β-: 100.00%	24F 390 MS β-: 100.00% β-n < 5.90%	25F 50 MS β-: 100.00% β-n: 14.00%	26F 9.6 MS β-: 100.00% β-n: 11.00%	27F 5.0 MS β-: 100.00% β-n: 77.00%	28F <40 NS N	29F 2.5 MS β-: 100.00% β-n: 100.00%	30F <260 NS N	31F >250 NS β- β-n
		12O 0.40 MeV P	13O 8.58 MS ϵp≈ 100.00% ϵ: 100.00%	14O 70.606 S ϵ: 100.00%	15O 122.24 S ϵ: 100.00%	16O STABLE 99.762%	17O STABLE 0.038%	18O STABLE 0.200%	19O 26.88 S β-: 100.00%	20O 13.51 S β-: 100.00%	21O 3.42 S β-: 100.00%	22O 2.25 S β-: 100.00% β-n < 22.00%	23O 82 MS β-: 100.00% β-n: 31.00%	24O 65 MS β-: 100.00% β-n: 58.00%	25O <50 NS N	26O <40 NS N	27O <260 NS N	28O <100 NS N		
	10N P: 100.00%	11N 1.58 MeV P: 100.00%	12N 11.000 MS ϵ: 100.00%	13N 9.965 M ϵ: 100.00%	14N STABLE 99.634%	15N STABLE 0.366%	16N 7.13 S β-: 100.00% β-α: 1.2E-3%	17N 4.173 S β-: 100.00% β-n: 95.1%	18N 624 MS β-: 100.00% β-n: 14.30%	19N 271 MS β-: 100.00% β-n: 54.60%	20N 130 MS β-: 100.00% β-n: 57.00%	21N 85 MS β-: 100.00% β-n: 81.00%	22N 24 MS β-: 100.00% β-n: 36.00%	23N 14.5 MS β-: 100.00% β-n	24N <52 NS N	25N <260 NS N				
8C 230 KeV P: 100.00% α	9C 126.5 MS ϵ: 100.00% ϵp: 61.60%	10C 19.290 S ϵ: 100.00%	11C 20.334 M ϵ: 100.00%	12C STABLE 98.89%	13C STABLE 1.11%	14C 5700 Y β-: 100.00%	15C 2.449 S β-: 100.00%	16C 0.747 S β-: 100.00% β-n: 99.00%	17C 193 MS β-: 100.00% β-n: 32.00%	18C 92 MS β-: 100.00% β-n: 31.50%	19C 49 MS β-n: 61.00% β-	20C 14 MS β-: 100.00% β-n: 72.00%	21C <30 NS N	22C 6.1 MS β-: 100.00% β-n: 61.00%						

Source: Wikipedia

W. Nazarewicz et al., Phys. Rev. Lett. 122, 062502 (2019)

PREDICTIONS FROM THEORY



Phys. Rev. Lett. 126, 022501 (2021)

A. Schwenk at al., 1905.10475

→ Facility for Rare Isotope Beams (FRIB), Michigan, USA (2022); FAIR, Darmstadt (2025).

FACILITY FOR ANTIPROTON AND ION RESEARCH (FAIR)

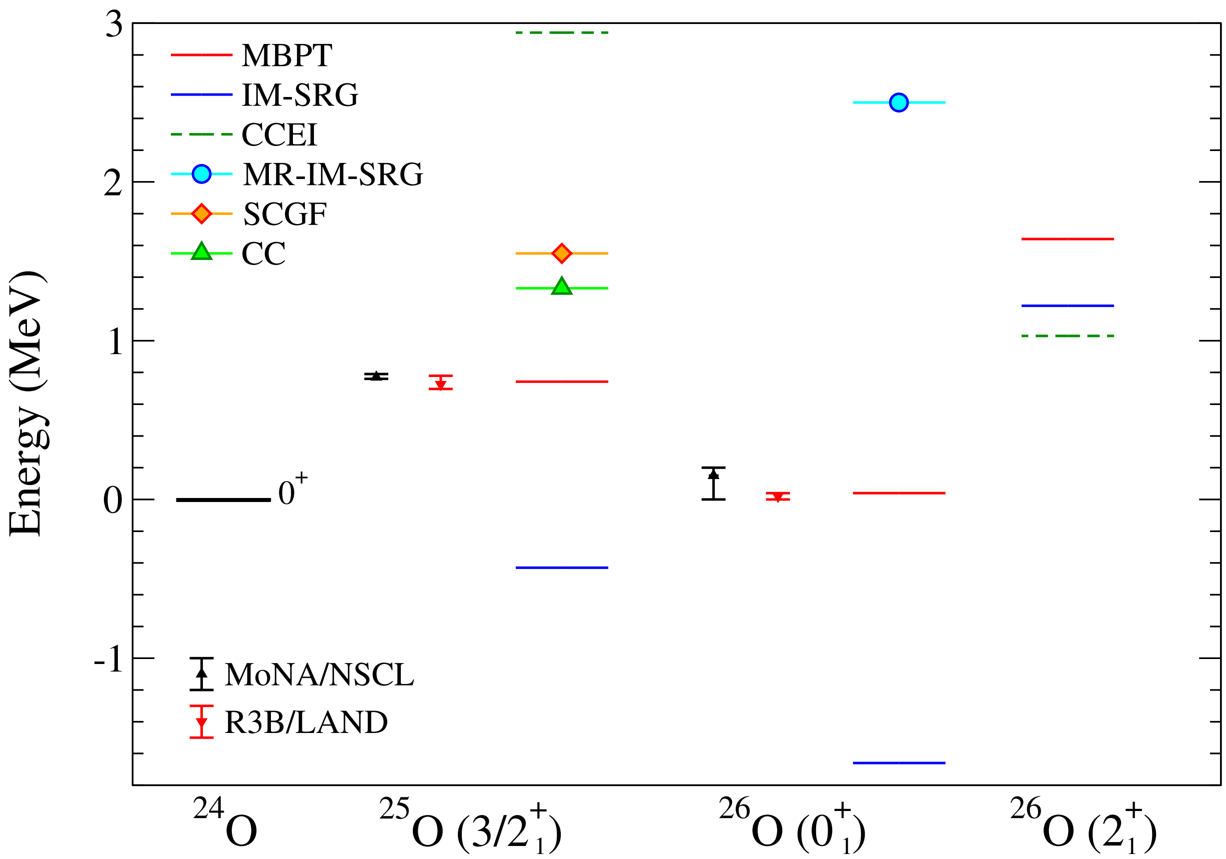
Start: 2025

Nuclear structure astrophysics
Neutron stars
Antimatter research
Atomic plasma physics and applications

Also: Facility for Rare Isotope Beams (FRIB), Michigan, USA (2022).

EXTRA SLIDES

BEYOND THE NEUTRON DRIPLINE



MAGNETIC MOMENT AND ELECTRIC QUADRUPOLE MOMENT