Xavier Vinas Meeting

- Xavier Vinas Meeting
  19-20 September 2017
  Milano

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- Nguyen Van Giai
- Institut de Physique Nucléaire, Orsay

- I have been knowing Xavier practically since he started in physics (I am a bit older ...)
- We have always shared an interest in all topics related to the properties of atomic nuclei, and often used the same theoretical tools.
- I highly appreciate Xavier as a scientist, and as a person.
- Here, I'll present – as a modest contribution to this event organized for Xavier - some results recently

Magicity of s-d shell neutron-rich nuclei: Relativistic Hartree-Fock-Bogoliubov predictions

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Outline of talk

- 1. Experimental facts in the Ca chain
- 2. Why do we use Relativistic Hartree-Fock Bogoliubov (RHFB) and not Relativistic Hartree Bogoliubov (RHB, usually called RMF)
- 3. Single-particle spectra and subshell closures
- Ref: Phys. Lett. B 753, 97 (2016)

LETTER

doi:10.1038/nature12522

Evidence for a new nuclear 'magic number' from the level structure of ^{54}Ca

D. Steppenbeck[1], S. Takeuchi[2], N. Aoi[3], P. Doornenbal[2], M. Matsushita[1], H. Wang[2], H. Baba[2], N. Fukuda[2], S. Go[1], M. Honma[4], J. Lee[2], K. Matsui[5], S. Michimasa[1], T. Motobayashi[2], D. Nishimura[6], T. Otsuka[1,5], H. Sakurai[2,5], Y. Shiga[7], P.-A. Söderström[2], T. Sumikama[8], H. Suzuki[2], R. Taniuchi[5], Y. Utsuno[9], J. J. Valiente-Dobón[10] & K. Yoneda[2]

Nature 502, 207 (2013)

- Data from proton knock out reactions
- First 2+ state in 54Ca found at about 2 MeV: indication that 2p1/2 (neutron) is partly occupied while 1f5/2 (neutron) is partly empty.

How much « partly »?

We show the importance of the effective tensor interaction in answering this question

Recent theoretical studies

- M. Grasso, Phys. Rev. C 89, 034316 (2014)
- found magicity for 52,54Ca if described by Skyrme Hartree-Fock, using SLy5+Tensor

- E. Yüksel, NVG, E. Khan, K. Bozkurt, Phys. Rev. C 89, 064322 (2014)
- have performed Skyrme Hartree-Fock-Bogoliubov plus QRPA, using SLy5, SLY5+T, and T44 effective interactions

General guidelines

- The s.p. level scheme of atomic nuclei determines, to a large extent, the shell and subshell closures, i.e., the magic and semi-magic numbers.
- Theoretical predictions of s.p. levels rely firstly on self-consistent (s.c.) methods: HF, HFB.
- We are familiar with NR s.c. mean fields, like Gogny, Skyrme, etc… where the rank-2 irreducible tensor interaction (we refer to it as the « tensor interaction ») plays a decisive role.
- How to identify this « tensor interaction » in relativistic approaches like the RMF (Relativistic Hartree), the RHF, the RHFB ? The answer is: through a Foldy-Wouthuysen transformation (L.L. Foldy & S.A. Wouthuysen, Phys. Rev. 78, 29 (1950)).
- With the FW transformation, we can determine and discuss the « tensor interaction » of any RMF(B)/RHF(B) model

Pseudo-Vector (PV) and Lorentz Tensor (T) couplings

$$\Gamma_{\pi}^{PV}(1,2) \equiv -\frac{1}{m_{\pi}^{2}}\left(f_{\pi}\vec{\tau}\gamma_{5}\gamma_{\mu}\partial^{\mu}\right)_{1}\cdot\left(f_{\pi}\vec{\tau}\gamma_{5}\gamma_{\nu}\partial^{\nu}\right)_{2},$$

$$\Gamma_{\rho}^{T}(1,2) \equiv +\frac{1}{4M^{2}}\left(f_{\rho}\vec{\tau}\sigma_{\lambda\mu}\partial^{\mu}\right)_{1}\cdot\left(f_{\rho}\vec{\tau}\sigma^{\lambda\nu}\partial_{\nu}\right)_{2},$$

These are the 2 possible terms in the Interaction Lagrangian which could give rise to a non-relativistic Tensor Interaction

BUT: they contribute only by their exchange term ☾ no contribution in RMF !

Connection with NR interaction: L.L. Foldy & S.A. Wouthuysen, Phys. Rev. 78, 29 (1950)

- For example, the pi-N part leads to:

$$V_\pi^T(\boldsymbol{r}) = \frac{1}{3} f_\pi^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, S_{12} \left(1 + \frac{3}{m_\pi r} + \frac{3}{(m_\pi r)^2}\right) \frac{e^{-m_\pi r}}{r},$$

$$V_\pi^C(\boldsymbol{r}) = \frac{1}{3} f_\pi^2\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2 \frac{e^{-m_\pi r}}{r},$$

where S_{12} is a standard rank-2 tensor operator,

$$S_{12}(\boldsymbol{r}) \equiv 3(\boldsymbol{\sigma}_1 \cdot \boldsymbol{e}_r)(\boldsymbol{\sigma}_2 \cdot \boldsymbol{e}_r) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2.$$

and similarly for the rho-N interaction.

In covariant theory with exchange interactions, the central and rank-2 tensor forces cannot be independent

The relativistic models discussed in this talk:

- Relativistic Hartree (known as RMF)
- DD-ME2 and DD-ME(delta): no pi, no rho

- Relativistic Hartree-Fock
- PKO3: has pi-PV
- PKA1: has pi-PV and rho-Tensor

- Pairing is treated

The RHFB Model

Lagrangian Density

- Lagrangian density: Nucleon (ψ), Mesons (σ, ω, ρ, π), Photon (A)

$$\mathscr{L} = \mathscr{L}_M + \mathscr{L}_\sigma + \mathscr{L}_\omega + \mathscr{L}_\rho + \mathscr{L}_\pi + \mathscr{L}_A + \mathscr{L}_I,$$

- Nucleon-Meson (Photon) interactions $\mathscr{L}_I$:

$$\mathscr{L}_I = \bar{\psi}\left(-g_\sigma\sigma - g_\omega\gamma^\mu\omega_\mu - g_\rho\gamma^\mu\vec{\tau}\cdot\vec{\rho}_\mu - e\gamma^\mu\frac{1-\tau_3}{2}A_\mu + \frac{f_\rho}{2M}\sigma_{\mu\nu}\partial^\nu\vec{\rho}^\mu\cdot\vec{\tau} - \frac{f_\pi}{m_\pi}\gamma_5\gamma^\mu\partial_\mu\vec{\pi}\cdot\vec{\tau}\right)\psi \quad (5)$$

- **Covariant** scalar (σ), vector (ω, ρ, A), **tensor (ρ) and pseudo-vector (π)**

RHFB equation

W. H. Long (2010)

- Bogoliubov transformation: $\{c_\alpha, c_\alpha^\dagger\}$ to $\{\beta_\alpha, \beta_\alpha^\dagger\}$ $(\alpha = 1, \cdots, M)$

$$\begin{pmatrix} c_\alpha \\ c_\alpha^\dagger \end{pmatrix} = \mathcal{W} \begin{pmatrix} \beta_\alpha \\ \beta_\alpha^\dagger \end{pmatrix} = \begin{pmatrix} \psi_U & \psi_V^* \\ \psi_V & \psi_U^* \end{pmatrix} \begin{pmatrix} \beta_\alpha \\ \beta_\alpha^\dagger \end{pmatrix}, \qquad \mathcal{W}^\dagger \mathcal{W} = 1. \tag{28}$$

- RHFB equation: Chemical potential λ

H. Kucharek(1991)

$$\int d\boldsymbol{r}' \begin{pmatrix} h(\boldsymbol{r},\boldsymbol{r}') - \lambda & \Delta(\boldsymbol{r},\boldsymbol{r}') \\ \Delta(\boldsymbol{r},\boldsymbol{r}') & \lambda - h(\boldsymbol{r},\boldsymbol{r}') \end{pmatrix} \begin{pmatrix} \psi_U(\boldsymbol{r}') \\ \psi_V(\boldsymbol{r}') \end{pmatrix} = E \begin{pmatrix} \psi_U(\boldsymbol{r}) \\ \psi_V(\boldsymbol{r}) \end{pmatrix} \tag{29}$$

- Pairing potential, pairing tensor κ and Pairing forces:

$$\Delta_\alpha(\boldsymbol{r},\boldsymbol{r}') = -\frac{1}{2}\sum_\beta V_{\alpha\beta}^{pp}(\boldsymbol{r},\boldsymbol{r}')\,\kappa_\beta(\boldsymbol{r},\boldsymbol{r}'), \kappa_\alpha(\boldsymbol{r},\boldsymbol{r}') = \psi_{V_\alpha}^*(\boldsymbol{r})\psi_{U_\alpha}(\boldsymbol{r}') \tag{30}$$

$$V(\boldsymbol{r},\boldsymbol{r}') = V_0\delta(\boldsymbol{r}-\boldsymbol{r}')\frac{1}{4}(1-\boldsymbol{\sigma}\cdot\boldsymbol{\sigma}')\left(1-\frac{\rho(r)}{\rho_0}\right) \tag{31}$$

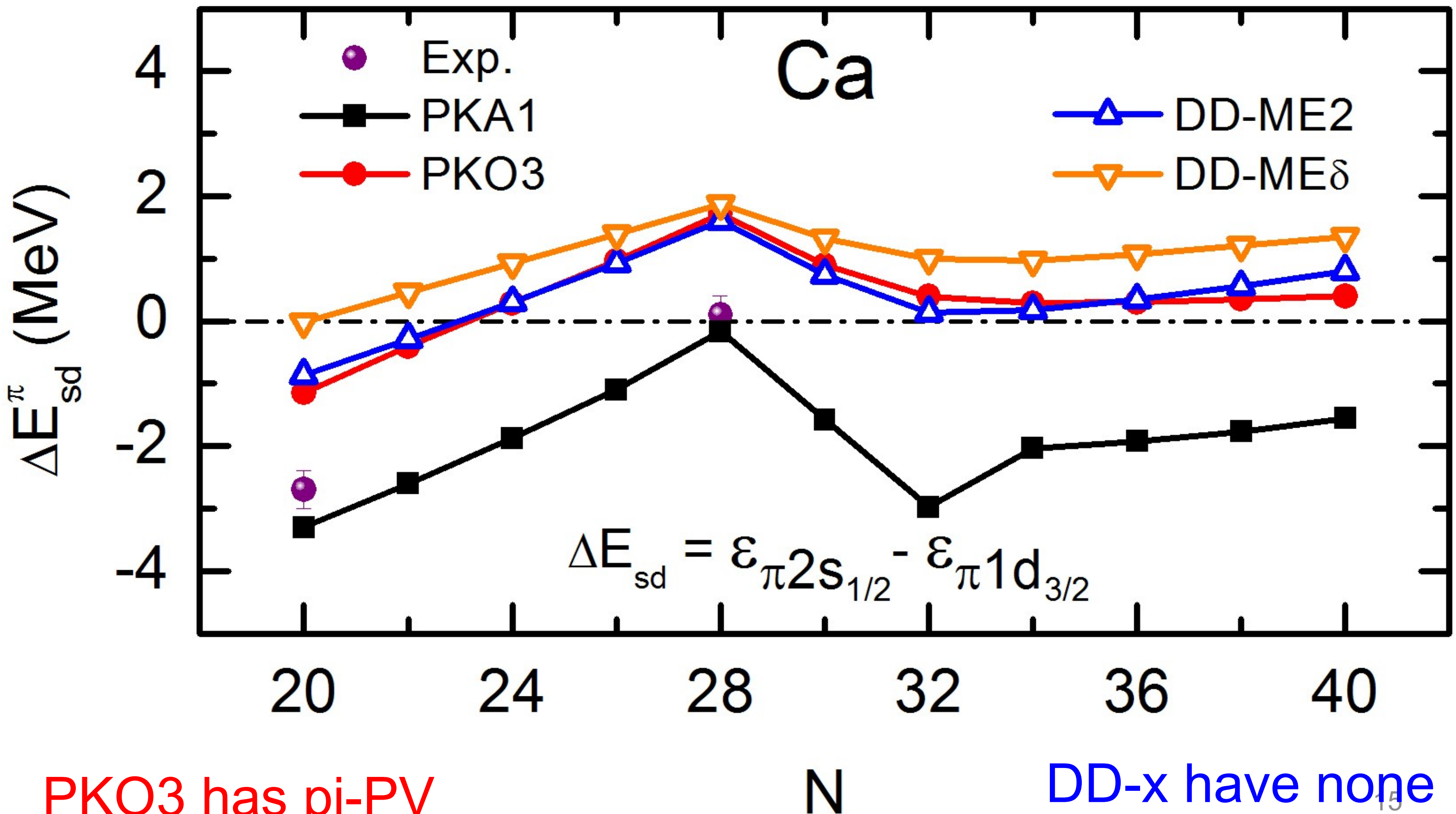
$$\boxed{V(\boldsymbol{r},\boldsymbol{r}') = \sum_{i=1,2} e^{((r-r')/\mu_i)^2}(W_i + B_i P^\sigma - H_i P^\tau - M_i P^\sigma P^\tau)} \tag{32}$$

Numerical methods

- - here, it is necessary to describe correctly the long distance behaviour of wave functions when solving RHFB equations: harmonic oscillator basis would not do.

- - we adopt the Dirac-Woods-Saxon basis (S.G. Zhou, J. Meng, P. Ring, Phys. Rev. C 68, 034323 (2003))

Strong effects of rho-T coupling on 2s-1d proton energies



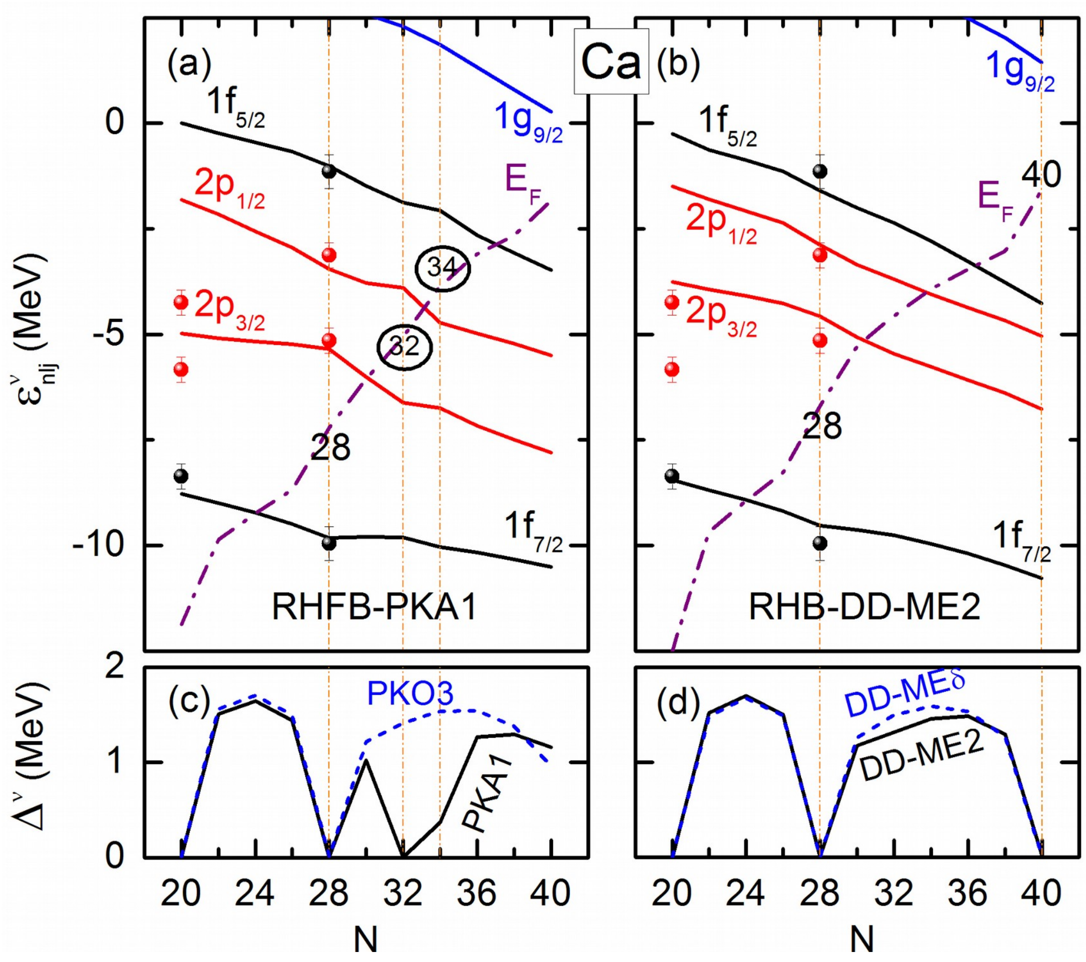
PKO3 has pi-PV

DD-x have none

PKA1 has pi-PV and rho-T (2 MeV effect!)

Pairing: D1S

New shell closure in Ca isotopes: vanishing pairing gap at N=32?



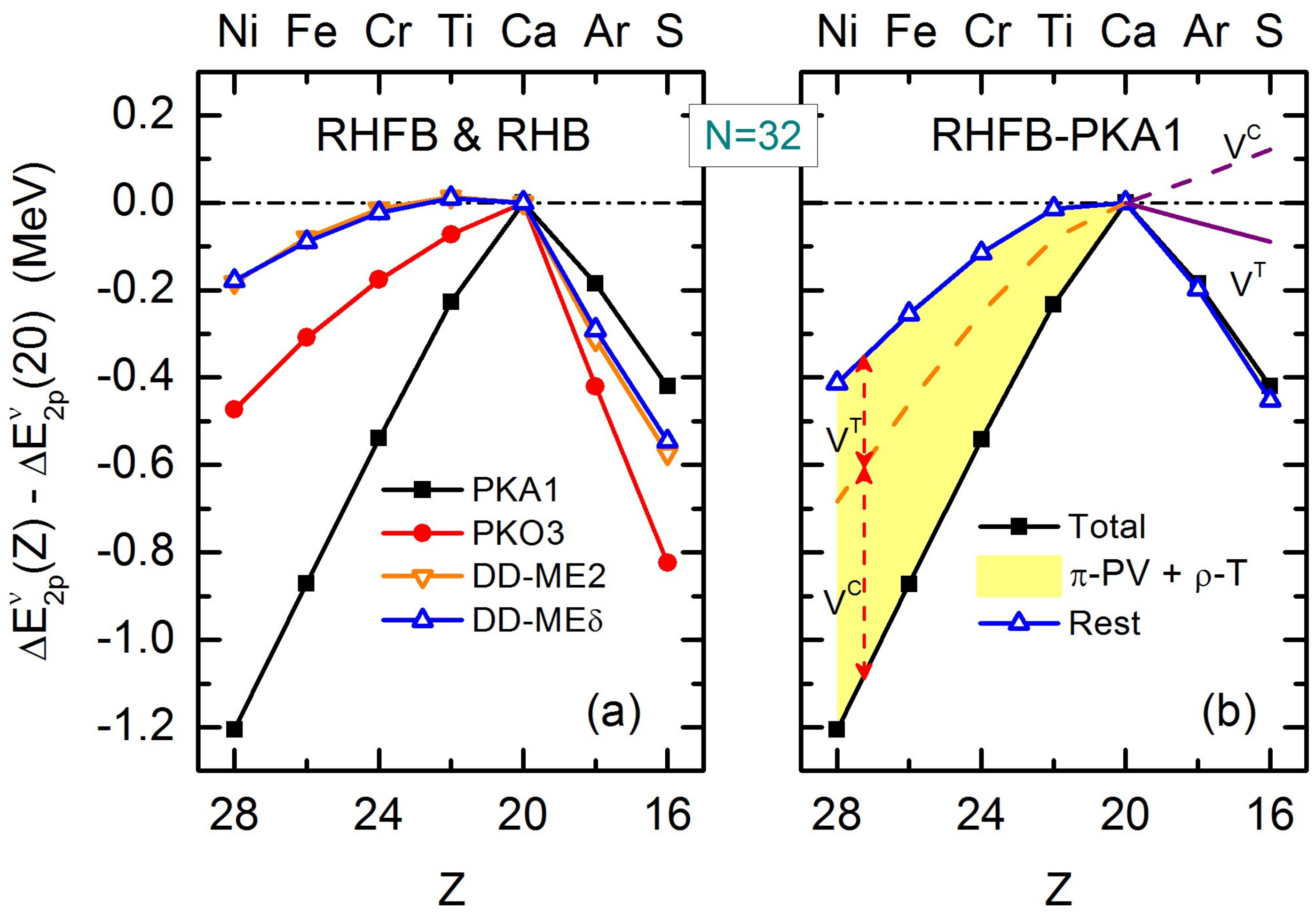
RMFB: no
RHFB: yes
(panels c-d)

TABLE I. Energy difference $\Delta E(i,i') \equiv \varepsilon_i - \varepsilon_{i'}$ (in MeV) in Ni, Ca and Si at $N = 32$ and 34. The results correspond to RHFB-PKA1, PKO3 and RHB-DD-ME2 Lagrangians. See the text for details.

Force	$\Delta E(i,i')$	N	Ni	Ca	Si
PKA1	$(\nu 2p_{1/2}, \nu 2p_{3/2})$	32	1.51	**2.72**	0.81
	$(\nu 1f_{5/2}, \nu 2p_{1/2})$	34	1.04	**2.45**	**4.05**
PKO3	$(\nu 2p_{1/2}, \nu 2p_{3/2})$	32	1.22	1.69	0.68
	$(\nu 1f_{5/2}, \nu 2p_{1/2})$	34	−1.72	0.77	2.72
DD-ME2	$(\nu 2p_{1/2}, \nu 2p_{3/2})$	32	1.58	1.76	0.92
	$(\nu 1f_{5/2}, \nu 2p_{1/2})$	34	−1.23	1.21	3.18

A strong effect of the Lorentz tensor interaction (PKA1) on single-particle energies

Evolution of 2p s.o. splitting along N=32 chain: importance of pi-PV and rho-T



Summary

- The RHFB model confirms the N=34 subshell in Z=20 isotopes
- For this, one must have the contribution of
- The Lorentz tensor rho-N coupling

THANK YOU, Xavier
for your contributions to our field.

And for your stimulating and active presence in our nuclear theory community.