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Applications of the NCSM

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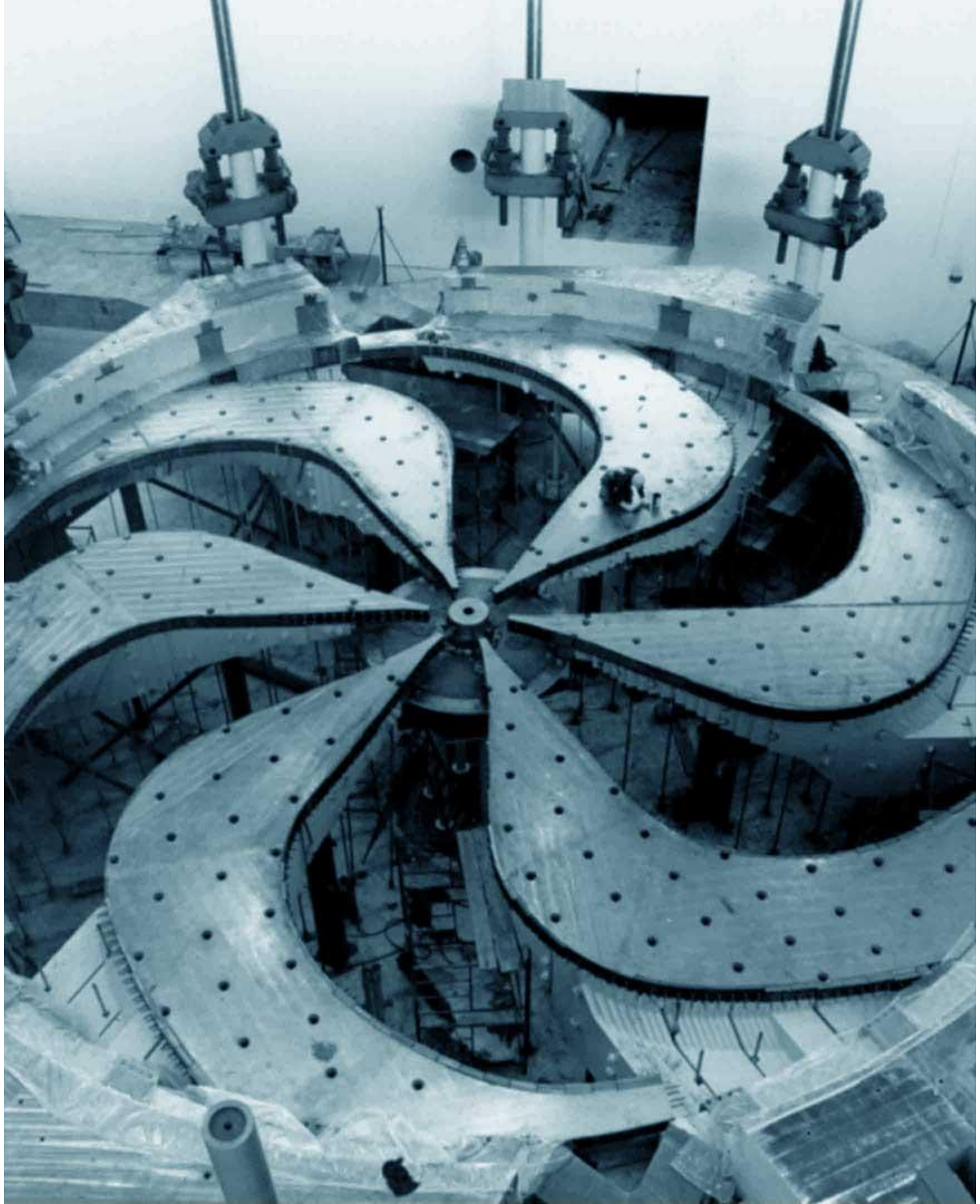
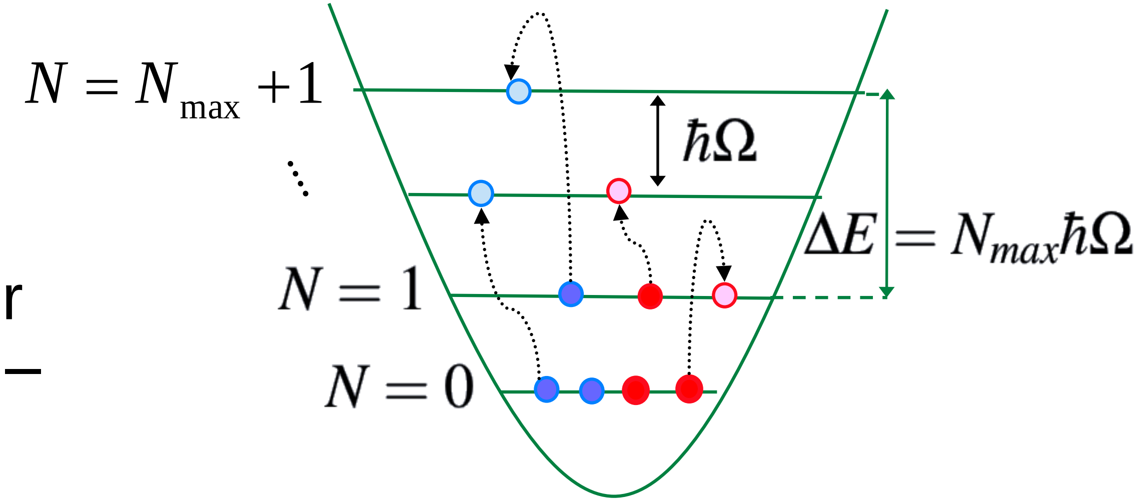
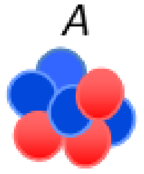


Discovery, accelerated

No-core shell model (NCSM)

- NCSM is an *ab initio* approach to solve the many-body Schrödinger equation for bound states – and narrow resonances – starting from *high-precision NN+NNN interactions* [1]
- Uses large and finite expansions in HO many-body basis states
- Translational invariance of internal wave function is preserved when single particle Slater Determinant (SD) basis is used with N_{max} truncation





$$\Psi^A = \sum_{N=0}^{N_{max}} \sum_i c_{Ni} \Phi_{Ni}^A$$

$$\langle \vec{r}_1 \cdots \vec{r}_A \vec{\sigma}_1 \cdots \vec{\sigma}_A \vec{\tau}_1 \cdots \vec{\tau}_A | A\lambda JM \rangle_{SD} = \langle \vec{\xi}_1 \cdots \vec{\xi}_{A-1} \vec{\sigma}_1 \cdots \vec{\sigma}_A \vec{\tau}_1 \cdots \vec{\tau}_A | A\lambda JM \rangle \varphi_{000}(\vec{\xi}_0)$$

Natural orbitals

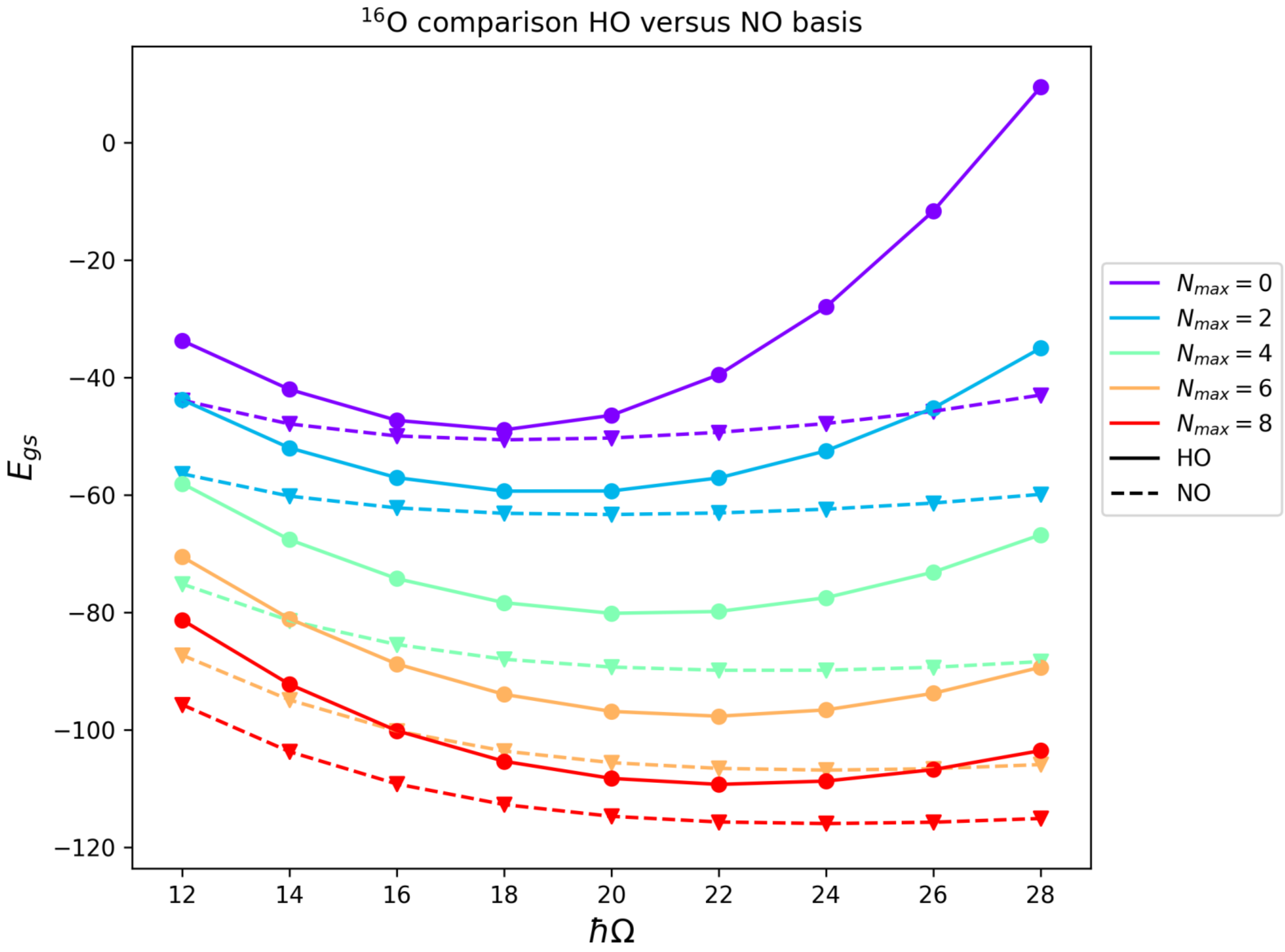
- Largest obstacle in *ab initio* nuclear theory is accurate description of many-body systems while maintaining reasonable computation times
- Want to choose basis which emphasizes physical structure of nuclei
- Diagonalization of one-body density matrix can better adapt single-particle basis of nucleons to many-body wavefunction [2]

$$\rho_{ab} = {}_{SD}\langle A\lambda_f J_f || (a_b^\dagger \widetilde{a}_a)^{(0)} || A\lambda_i J_i \rangle_{SD}$$

- Similarity transformation from harmonic oscillator (HO) to natural orbitals (NO) basis implemented with eigenvectors of density matrix

Natural orbitals

- N_{max} convergence of HO and NO basis calculations of ground state energy of ^{16}O
- N^2LO_{opt} interaction
- Importance truncation used at $N_{max} = 8$ for both bases
- NO basis increases convergence by about one step in N_{max}



Antiproton scattering

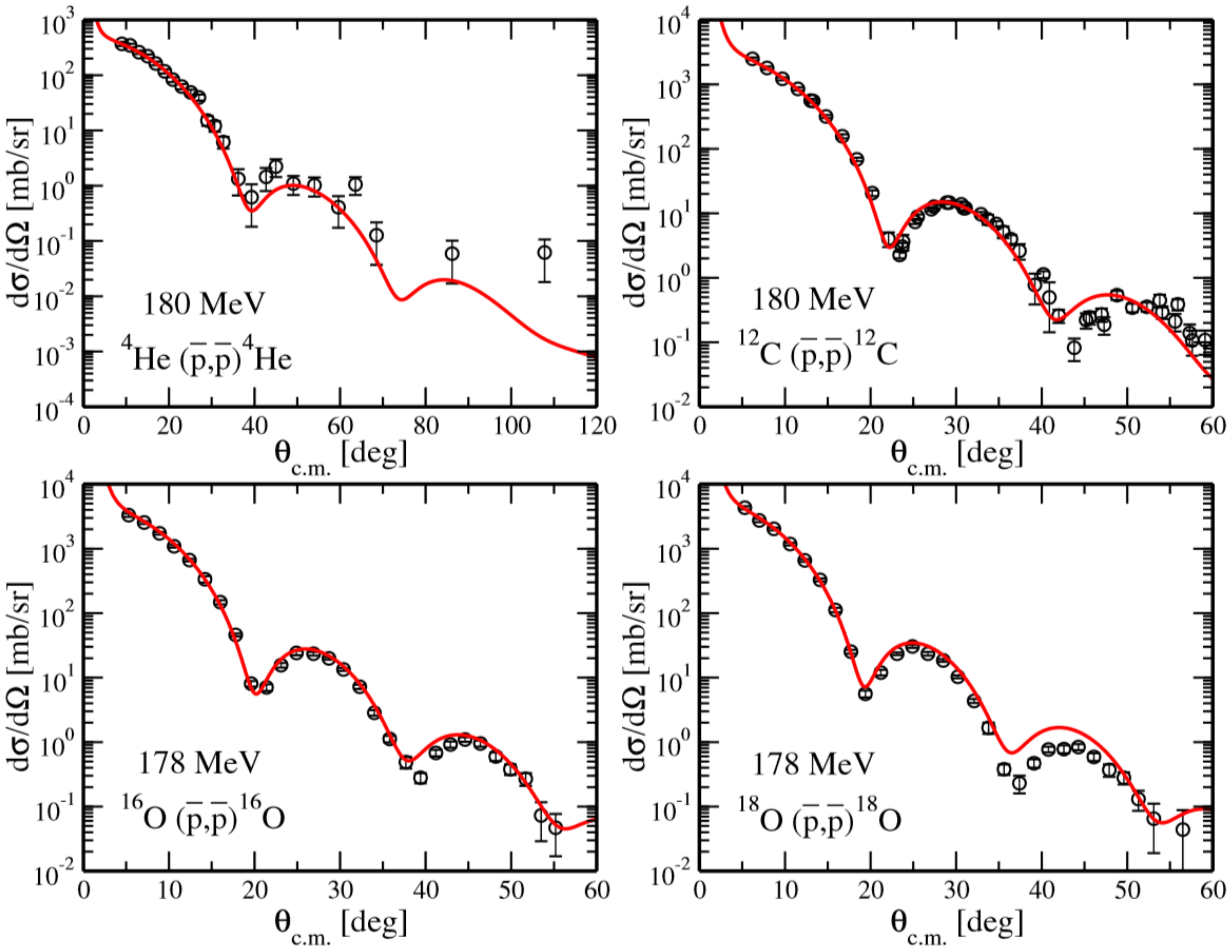
- Fully microscopic description of antiproton elastic scattering off nuclei possible from chiral effective field theory (EFT)
- $\bar{p}N$ t-matrix computed from antiproton-nucleon interaction in chiral EFT [3] and nonlocal target densities computed in NCSM with SRG evolved $NN - N^4LO(500) + 3N_{lnl}$ interaction
- Optical potentials calculated in full from folding integral of nonlocal target densities and $\bar{p}N$ t-matrix

$$U(\vec{q},\vec{K}) = \sum_{N=n,p} \int d\vec{P} \;\; \eta(\vec{q},\vec{K},\vec{P})\, t_{\bar{p}N}(\vec{q},\vec{K},\vec{P})\, \rho_N(\vec{q},\vec{P})$$

- *Ab initio* scattering cross sections for antiproton scattering are extracted from the optical potentials [4]

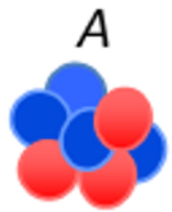
Antiproton scattering

- Differential cross sections of elastic antiproton scattering as function of center-of-mass scattering angle
- $NN - N^4LO(500) + 3N_{lnl}$ interaction with $\lambda_{SRG} = 2.0\ fm^{-1}$, $\hbar\Omega =$ 20.0 MeV for ^{4}He and $\hbar\Omega = 16.0$ MeV for ^{12}C, ^{16,18}O
- $\overline{p}N$ t-matrix and nonlocal densities reproduce data and minima well



No-core shell model with continuum (NCSMC)

- Many observables in quantum theory are accessible through NCSM, but ultimately NCSM is a theory of bound states – must incorporate continuum basis states
- Explicitly include NCSM eigenstates $|A\lambda J^\pi T\rangle$ in a generalized expansion of many-body wave function



$$|\Psi^{J^\pi T}\rangle = \sum_\lambda c_\lambda^{J^\pi T} |A\,\lambda\,J^\pi T\rangle + \sum_\nu \int dr\, r^2\, \frac{g_\nu^{J^\pi T}(r)}{r}\, \hat{A}_\nu |\Phi_{\nu r}^{J^\pi T}\rangle$$

- Resulting wave function provides accurate description of bound and unbound states, a wave function suitable for describing clustering, scattering and breakup processes [5]

Precision beta decay

- Cabibbo-Kobayashi-Maskawa (CKM) matrix unitarity is established as sensitive probe of physics beyond the Standard Model

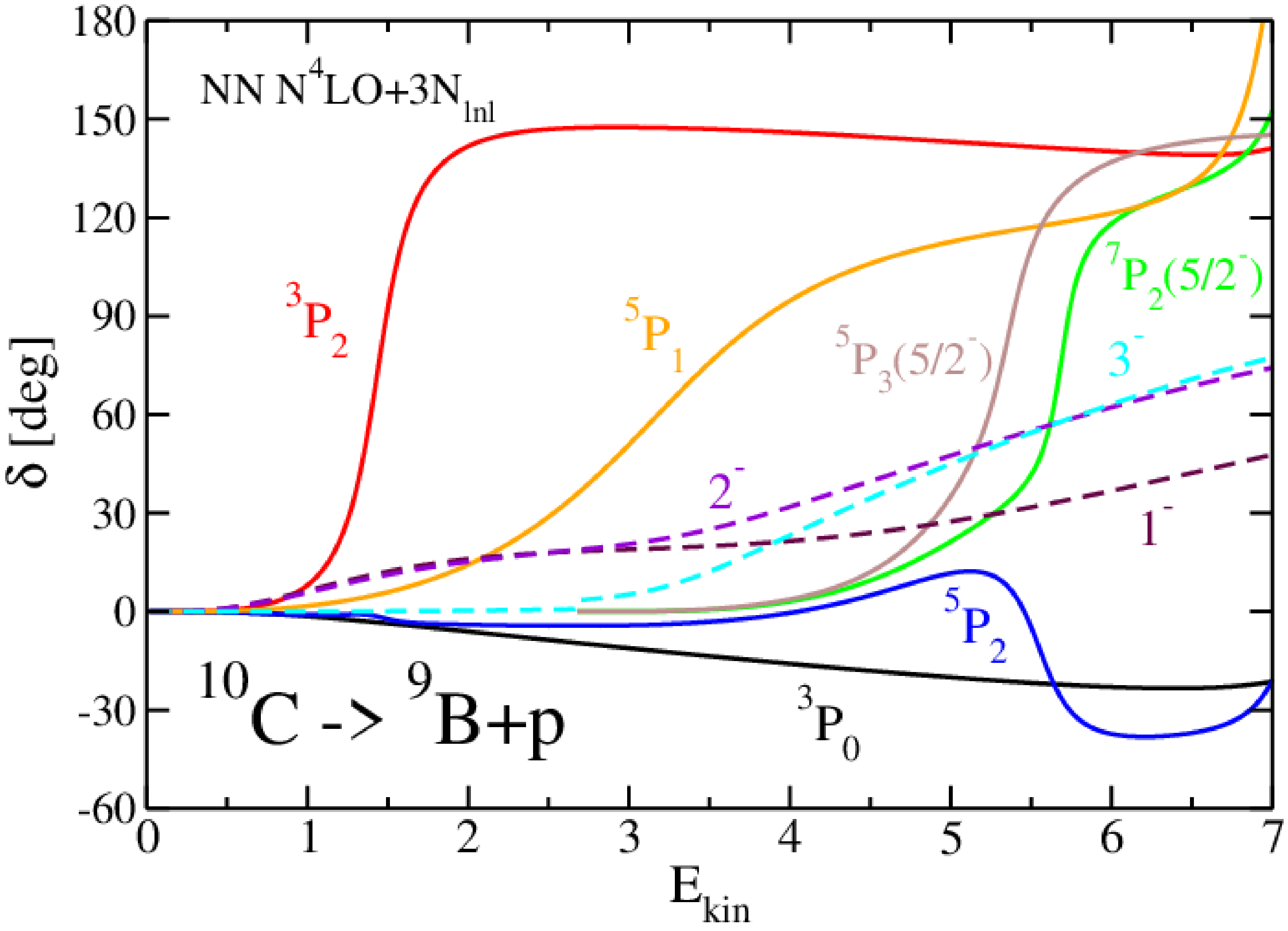
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- Largest contribution to sum comes from V_{ud} matrix element
- Extraction of V_{ud} from super-allowed $0^+ \rightarrow 0^+$ Fermi beta decay transitions requires theoretical calculation of isospin symmetry breaking correction δ_c [6]
- We study the beta decay $^{10}\mathrm{C} \rightarrow {}^{10}\mathrm{B}$ where this correction can be computed with high precision in the NCSMC

Intermediate result

Structure of ^{10}C as ^{9}B + p

- Phase shifts (solid lines) and eigenphase-shifts (dashed lines) for ^{9}B + p scattering
- NCSMC calculations include $^{3}/_{2}^{-}$ and $^{5}/_{2}^{-}$ states from ^{9}B
- $NN - N^4LO(500) + 3N_{lnl}$ interaction with $\hbar\Omega =$ 18.0 MeV $\lambda_{SRG} = 1.8\ fm^{-1}$



Conclusions and outlook

- **Conclusions**
  - Exploration of physically motivated similarity transformations can help improve convergence rates in traditional HO basis calculations
  - Elastic antiproton scattering off nuclei from *ab initio* theory now possible with development of antiproton-nucleon chiral EFT interactions and nonlocal nuclear densities
  - Constraints on Standard Model CKM matrix unitarity possible through *ab initio* nuclear structure calculations

- **Outlook**
  - Pursuing extensions to natural orbitals framework in the NCSM
  - Improvements to connection between NCSM and scattering theory
  - Completing calculation of isospin symmetry breaking correction δ_c

References

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Thank you
Merci

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