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(Pathways to) **Exotic pairing in heavy nuclei**

arxiv : 2402.13313

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TRIUMF

PAINT2024

March 1, 2024

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Outline

Ab initio calculations of superfluid neutron matter

- Pushing to higher densities

(Pathways to) exotic pairing in heavy nuclei

- Guidance for future *ab initio*

Summary and next steps

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Collaborators

- **Alex Gezerlis** (UOG)
- **Michael Stuck** (UOG)
- **Stefano Gandolfi** (LANL)
- **Joe Carlson** (LANL)
- **Kevin Schmidt** (ASU)

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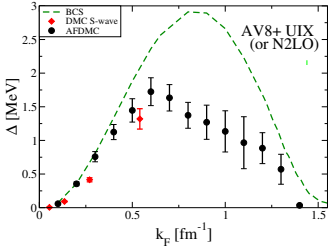
Ab initio for neutrons

Diffusion Monte Carlo (DMC), . . .

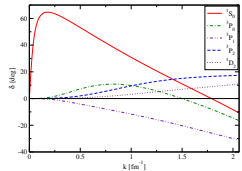
$$\psi(\tau) = e^{-(H-E_0)\tau}\psi_T \to c_0\psi_0 \ , \tau \to \infty$$

starting from a “physics aware”
(i.e., $c_0 \neq 0$) trial state ψ_T



Made possible by better trial state:

$$\Psi = \mathrm{Pf}\left[\phi(1,2), \phi(3,4), \ldots, \phi(N-1,N)\right]$$



Neutron matter’s ground state has singlet pairs
(*Also all experimentally accessible nuclei*)

Guided by phenomenology → Moderate suppression when exact

GP, F. K. Diakonos, and A. Gezerlis, Phys. Rev. C 102, 064324 (2020)
GP, A. Gezerlis, Universe 2021, 7(2)
S. Gandolfi, GP, J. Carlson, A. Gezerlis, and K. E. Schmidt , Cond. Mat. **7**(1) (2022)

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What do we know / Why do we care

Nuclei

- Pairing in all experimentally accessible nuclei is spin-singlet
- Proposed spin-triplet in large nuclei $A \sim 130$ at $N = Z$

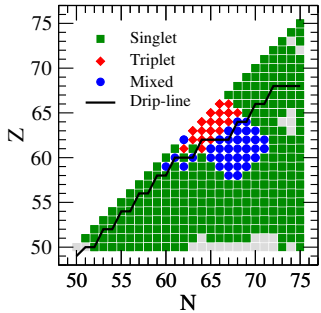
  G. F. Bertsch and Y. Luo, Phys. Rev. C **81** (2010)
- Proposed mixed-spin pairing in $A \sim 130$ at $N \approx Z$

  A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106** (2011)

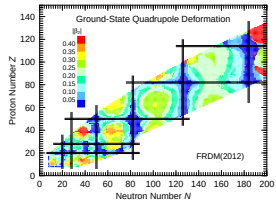
  E. Rrapaj, A. O. Macchiavelli, and A. Gezerlis, Phys. Rev. C **99** (2019)
- Experiment: we expect to see it as:
  - enhanced np transfer reaction cross-sections
  - similarities between the spectra of odd-odd and even-even nuclei

    S. Frauendorf, Rev. Mod. Phys. **73** (2001)
  - triplet gaps must be suppressed*

What do we know / Why do we care



A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. ***106*** *(2011)*



P. Moller, et al., At. Data Nucl. Data Tables ***59*** *185 (1995)*

Deformation neglected: a) damps pairing, b) unknown effect on singlet-triplet competition

S. Frauendorf and A. O. Macchiavelli, Prog. Part. Nucl. Phys. **78**, 24 (2014)
G. Hupin and D. Lacroix, Phys. Rev. C **86** (2012)

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Phenomenological Hamiltonian

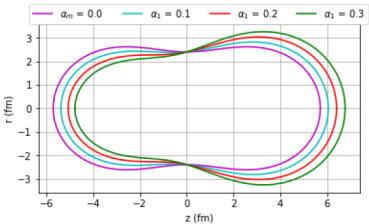
Axially-symmetric deformation in the single-particle states:

$$H_{\rm sp} = \frac{\mathbf{p}^2}{2m} + V_{\rm WS}^{\rm def}(\rho, z; \vec{\alpha}) + C\boldsymbol{\nabla} V_{\rm WS}^{\rm def}(\rho, z; \vec{\alpha}) \cdot (\mathbf{s} \times \mathbf{p})$$

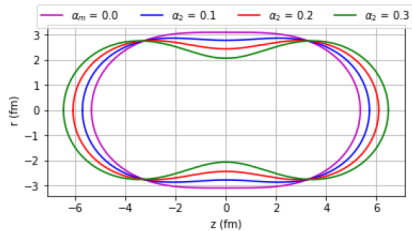
with

$$V_{\rm WS}^{\rm def}(\rho, z) = \frac{V_0}{1 + \exp\left[l(\rho, z; \vec{\alpha})/a\right]}\ , \quad \vec{\alpha} = (\epsilon, \alpha_1, \alpha_2, \dots)$$

(see Cassini ovals: V. V. Pashkevich, Nucl. Phys. A**169** (1971), etc)



(a) Dipole deformations



(b) Quadrupole deformations

Phenomenological Hamiltonian

And a zero-range **pairing interaction(s)**

$$V(\mathbf{r}, \mathbf{r}') = \sum_{\alpha} v_{\alpha} \delta(\mathbf{r} - \mathbf{r}') P_{J_z=0} P_{\alpha}$$

tuned to shell-model Hamiltonians

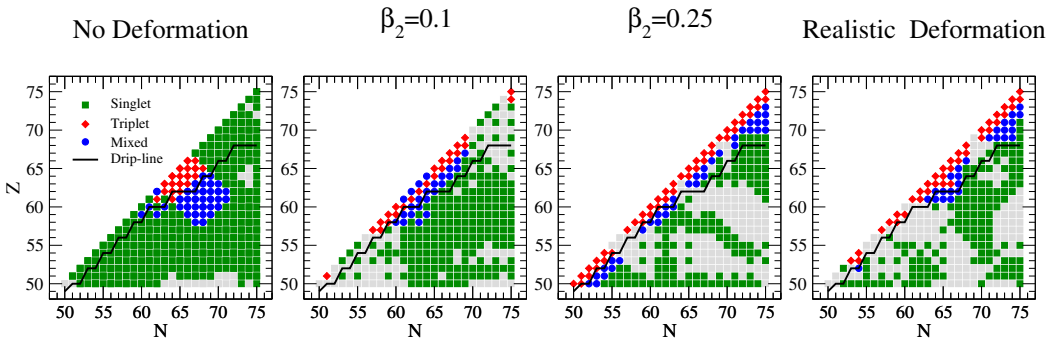
G. F. Bertsch and Y. Luo, Phys. Rev. C **81** (2010); A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106** (2011); E. Rrapaj, A. O. Macchiavelli, and A. Gezerlis, Phys. Rev. C **99** (2019)

Given the HFB treatment:

$$H = H_{\mathrm{sp}} + V = \sum_{ij} \epsilon_{ij} c_i^{\dagger} c_j + \frac{1}{4} \sum_{ijkl} v_{ijkl} c_i^{\dagger} c_j^{\dagger} c_k c_l$$

$$= H^{00} + \beta^{\dagger} H^{11} \beta + \frac{1}{2} \beta^{\dagger} H^{20} \beta^{\dagger} + \dots$$

The nuclear chart



GP, M. Stuck, and A. Gezerlis, arxiv:2402.13313

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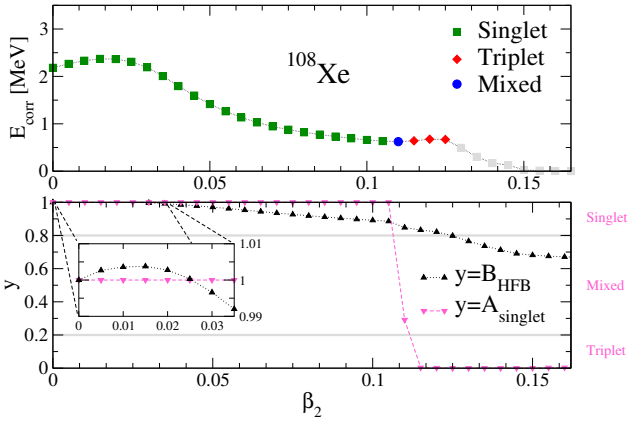
At N=Z: $^{108}_{54}\mathrm{Xe}$

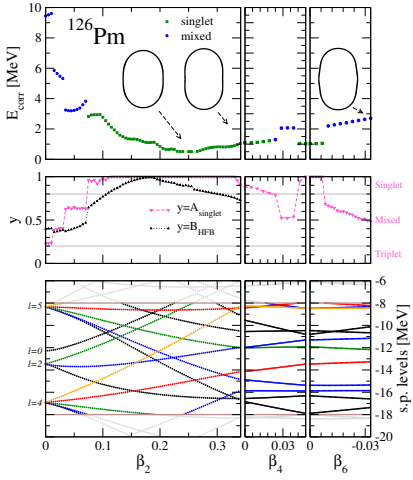


$$E_{\mathrm{corr}} = E - E_{\mathrm{HF}}$$

- ✓ deformation damps pairing
- ★ β_2 suppresses the g.s. spin-orbit field

GP, M. Stuck, and A. Gezerlis, arxiv:2402.13313

In the physical region: $^{126}_{61}\mathrm{Pm}$



Correlation energy quantifies pairing correlations:

$$E_{\mathrm{corr}} = E - E_{\mathrm{HF}}$$

- ✓ deformation damps pairing
- ★ deformation re-arranges higher-j single-particle states $\rightarrow$ creation of triplet pairs

GP, M. Stuck, and A. Gezerlis, arxiv:2402.13313

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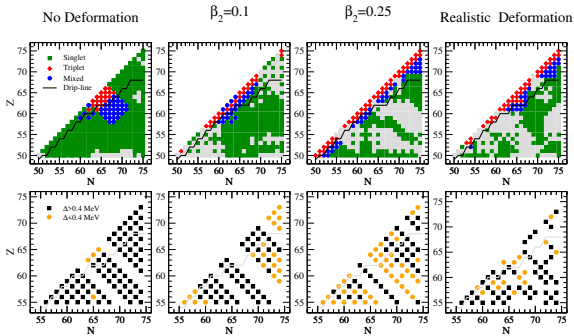
Pairing gaps



$$\Delta(N) = E(N) - \frac{E(N+1) + E(N-1)}{2}$$

- ✓ deformation damps pairing
- ★ triplet-pairing induced suppression in gaps *partially* lifted

GP, M. Stuck, and A. Gezerlis, arxiv:2402.13313
GP and A. Gezerlis, *in preparation (2024)*

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Summary

In two sentences:

- Complete ab initio description of s-wave neutron superfluids for neutron stars
- Novel superfluidity set in the appropriate conditions: guidance for future *ab initio* and experimental studies

Next steps:

- Explore more signatures of spin-triplet pairing in heavy nuclei (e.g., spin-spin neutron-proton correlations*, etc.)

Next-next-steps:

... Investigate dynamics, fission etc.

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Thank you

People:

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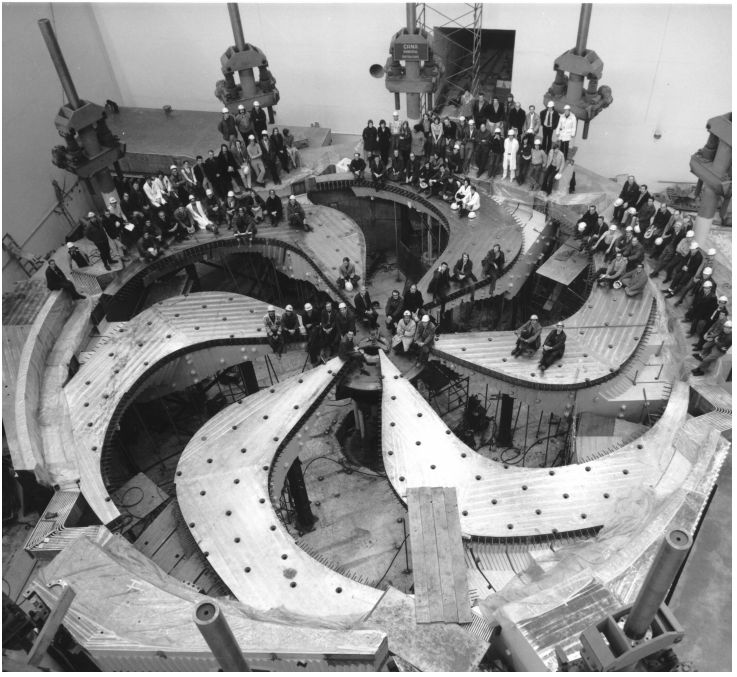
Thank you
Merci



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