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Exotic nuclear superfluidity in heavy nuclei

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Discovery, accelerated

Outline

Introduction and theory tools

- What do we know/Why do we care
- The mean-field treatment of pairing and deformation

Main results

- Interplay of pairing and deformation
- Implications for the nuclear chart

Superfluidity in nuclei

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

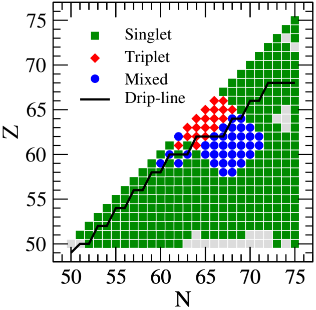
  G. F. Bertsch and Y. Luo, Phys. Rev. C **81** (2010)
- Proposed mixed-spin pairing in $A \sim 130$ at $N \approx Z$

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

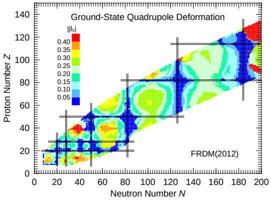
  E. Rrapaj, A. O. Macchiavelli, and A. Gezerlis, Phys. Rev. C **99** (2019)
- Experiment: we expect to see it as:
  - enhanced np transfer reaction cross-sections
  - similarities between the spectra of odd-odd and even-even nuclei

    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

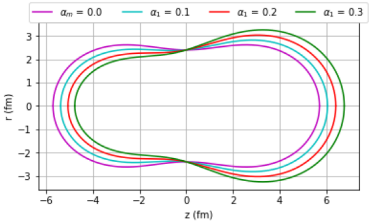
Axially-symmetric deformation in the single-particle states:

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

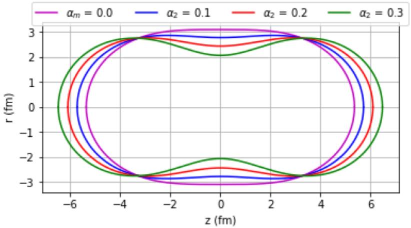
with

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

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



(a) Dipole deformations



(b) Quadrupole deformations

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Phenomenological Hamiltonian

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

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

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); B. Bulthuis and A. Gezerlis, Phys. Rev. C **93** (2016); E. Rrapaj, A. O. Macchiavelli, and A. Gezerlis, Phys. Rev. C **99** (2019)

Given the HFB treatment:

$$H = H_{\mathrm{sp}} + V = \sum_{ij} \epsilon_{ij} c_i^{\dagger} c_j + \frac{1}{4}\sum_{ijkl} v_{ijkl} c_i^{\dagger} c_j^{\dagger} c_k c_l$$
$$= H^{00} + \beta^{\dagger} H^{11} \beta + \frac{1}{2}\beta^{\dagger} H^{20} \beta^{\dagger} + \dots$$

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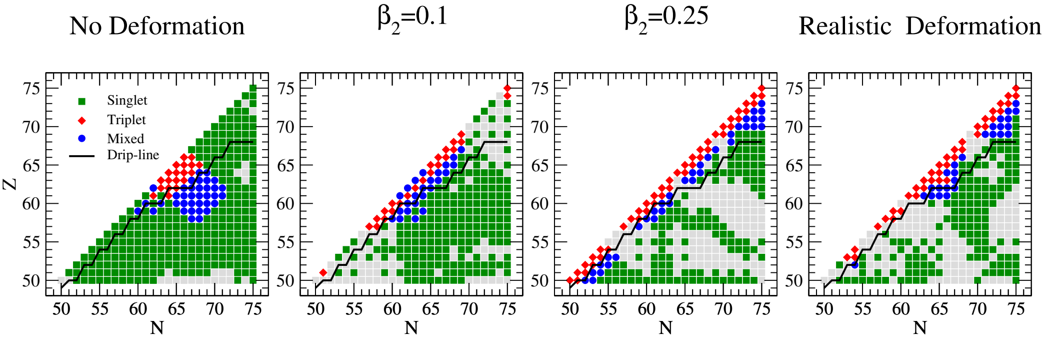
The nuclear chart



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

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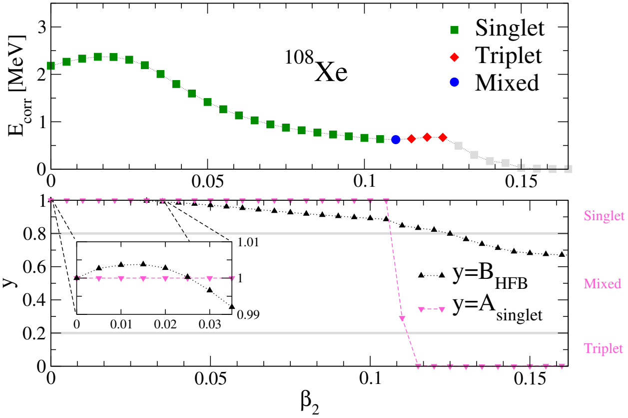
At N=Z: $^{108}_{54}\mathrm{Xe}$



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

✓ deformation damps pairing

★ β_2 suppresses the g.s. spin-orbit field

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

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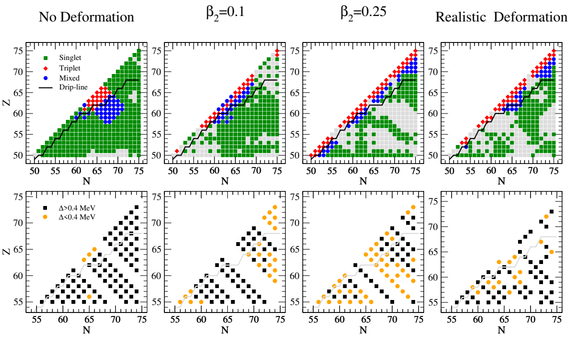
Pairing gaps



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

- ✓ deformation damps pairing
- ★ triplet-pairing induced suppression in gaps *partially* lifted (but more is needed)

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

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Summary

In two sentences:

- We've identified the role of deformation in novel pairing phenomena
- Novel nuclear superfluidity set in the appropriate conditions: guidance for future *ab initio* and experimental studies

Next steps:

- Explore signatures of spin-triplet pairing in heavy nuclei
- Guide upcoming experiments

Next-next-steps:

... Investigate dynamics, fission etc.

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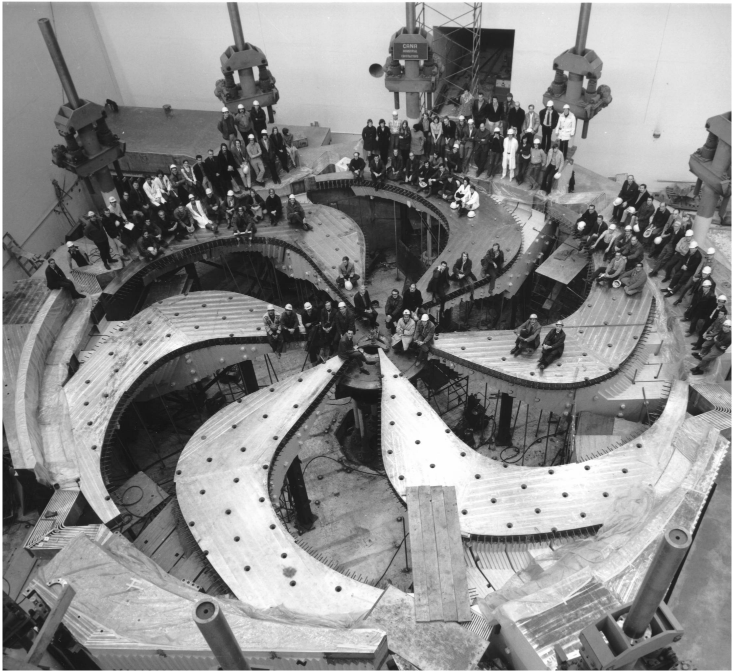
Thank you
Merci



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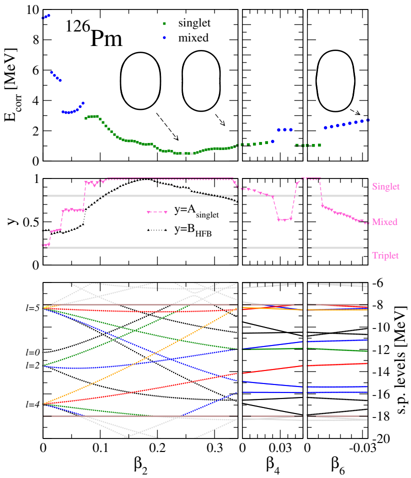
In the physical region: $^{126}_{61}\mathrm{Pm}$



Correlation energy quantifies pairing correlations:

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

✓ deformation damps pairing

★ deformation re-arranges higher-j single-particle states → creation of triplet pairs

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

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The TRIUMF experiment

(Revival from 2019 of) **Precision mass measurements in the light Lanthanides region approaching N=Z** with TITAN. (Spokespeople: A. Kwiatkowski and E. Leistenschneider)

Aims (and what we can do):

- **Explore exotic pairing phenomena (triplet pairing, mixed-spin pairing)**: the odd-even staggering of the masses gives pairing gaps $(\Delta(N) = E(N) - [E(N+1) + E(N-1)]/2)$
  - Theory input: Disentangle the suppression due to deformation and triplet pairing
- **Map the proton drip-line**

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The LNL experiment

Fusion evaporation experiment creating Gd ($Z = 64$), Eu ($Z = 63$), Sm ($Z = 62$), Pm ($Z = 61$), Nd ($Z = 60$), Pr($Z = 59$), with AGATA. (Spokespeople: Marlène Assié and Jèrèmie Dudouet.)

Example reaction

$$^{76}\mathrm{Kr} +^{58}\mathrm{Ni} \rightarrow^{134}\mathrm{Gd}^*$$

The cross-sections in the region are expected to be *very* small ($\sim 10\,\mathrm{nb}$) and so the statistics will be limited: only the first few excited states will be feasible.

Aims (and what we can do):

- **Probe the spectrum of exotic pairing phenomena (triplet and mixed-spin pairing)**
  - Theory input: Identify consequences of the pairing phases to the low-lying excited states (some we already know)
  - Theory input: Evolution of low-lying states in the isotopic chain
- **Maybe measure deformation**
  - Theory input: Identify expectations from the increased binding from triplet pairing

Experimental probes

Main theme: No smoking-gun (at least where it matters)

- **Transfer reactions**: straightforward signature of the superfluid phase. It has shown isovector pairing where possible and currently not available for $A \gtrsim 40$ (maybe up to $A \sim 90$ in next generation of facilities).
- **Wigner (symmetry) energy**: the phenomenological T-dependent term added to reproduce experimental results. Full explanation seems to involve $T = 0$ pairing.
- **Binding energies and spectra of adjacent nuclei**: Similar binding energies between even-even and odd-odd nuclei point to (isovector) neutron-proton pairing for $A \leq 80$. Comparison of spectra excludes isoscalar pairing (which would make them similar).
- **Response to rotation** the two phases respond differently to rotations (i.e., the Coriolis force). Certain effects like delayed alignment of pairs when increasing rotational frequency point to isoscalar pairing.