Mixed-spin pairing in heavy nuclei

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Collaborators:
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Motivation: Basics

- Known (N>Z) nuclei exhibit *nn* and *pp* pairing.
- However, *np* interaction in spin-triplet channel is stronger.

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Possible answer I:

- Isospin polarization discourages isospin-singlet pairing: look at *N*=*Z* nuclei

A. L. Goodman, Phys. Rev. C **58**, R3051 (1998)

A. O. Macchiavelli *et al.*, Phys. Rev. C **61**, 041303(R) (2000)

Motivation: Basics

RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 58, NUMBER 6 DECEMBER 1998

$T=0$ and $T=1$ pair correlations in $N=Z$ medium-mass nuclei

Alan L. Goodman
Physics Department, Tulane University, New Orleans, Louisiana 70118
(Received 21 July 1998)

The isospin generalized BCS equations and the Hartree-Fock-Bogoliubov equation are solved for the ground states of even $N=Z$ nuclei with mass number $A=76-96$. The calculations include isospin $T=1$ (pp, nn, and np) pair correlations as well as isospin $T=0$ (np) pair correlations. There is a transition from $T=1$ pairing at the beginning of this isotope sequence to $T=0$ pairing at the end of the sequence, with the possibility of a mixed phase containing both $T=0$ and $T=1$ pairing near the middle of the sequence.
[S0556-2813(98)50212-9]

RAPID COMMUNICATIONS

PHYSICAL REVIEW C, VOLUME 61, 041303(R)

Is there np pairing in $N=Z$ nuclei?

A. O. Macchiavelli, P. Fallon, R. M. Clark, M. Cromaz, M. A. Deleplanque, R. M. Diamond, G. J. Lane, I. Y. Lee, F. S. Stephens, C. E. Svensson, K. Vetter, and D. Ward
Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720
(Received 15 April 1999; published 10 March 2000)

The binding energies of even-even and odd-odd $N=Z$ nuclei are compared. After correcting for the symmetry energy we find that the lowest $T=1$ state in odd-odd $N=Z$ nuclei is as bound as the ground state in the neighboring even-even nucleus, thus providing evidence for isovector np pairing. However, $T=0$ states in odd-odd $N=Z$ nuclei are several MeV less bound than the even-even ground states. We associate this difference with the $T=1$ pair gap and conclude from the analysis of binding energy differences and blocking arguments that there is no evidence for an isoscalar (deuteronlike) pair condensate in $N=Z$ nuclei.

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A. L. Goodman, Phys. Rev. C **58**, R3051 (1998)

A. O. Macchiavelli *et al.*, Phys. Rev. C **61**, 041303(R) (2000)

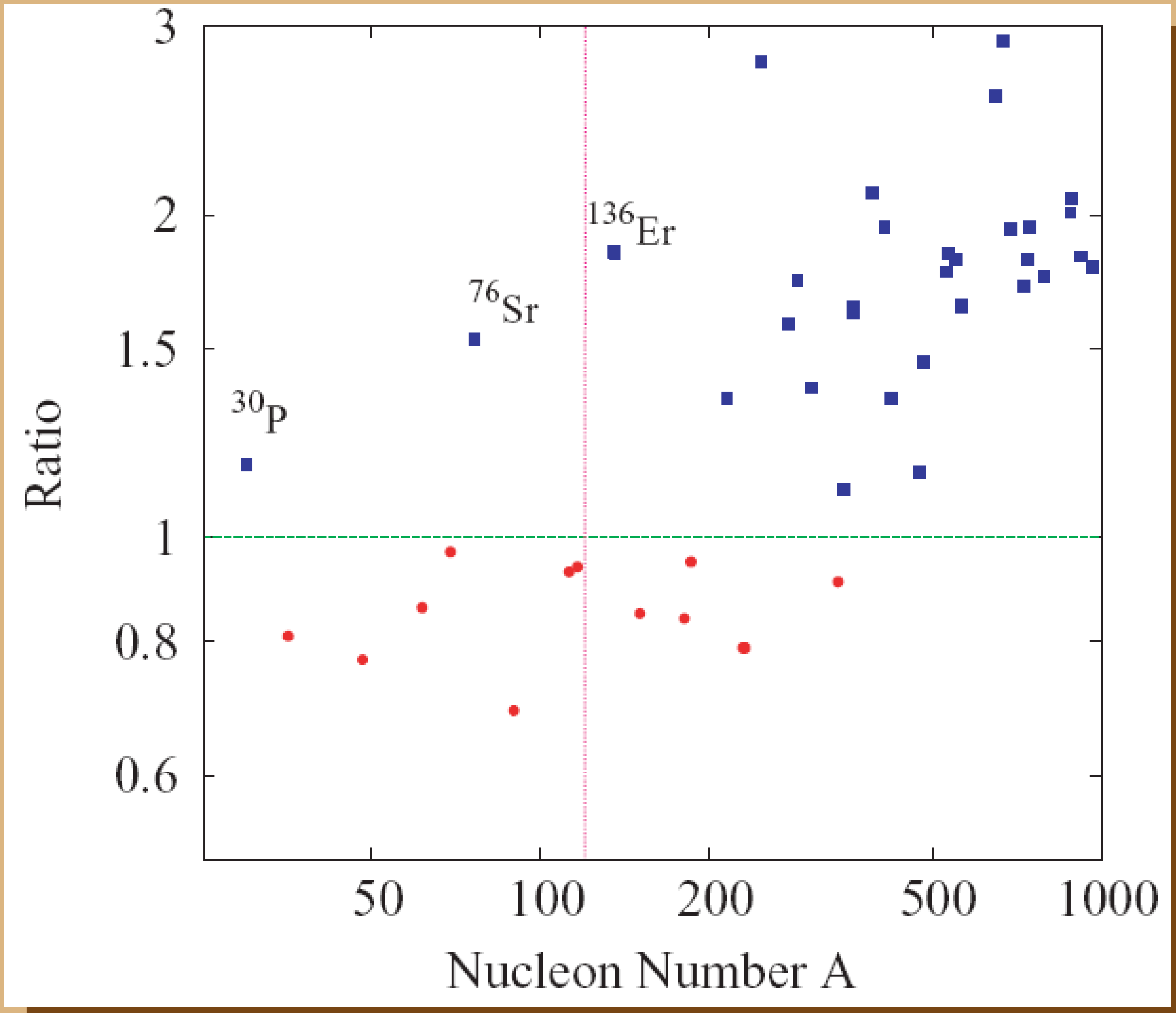
Possible answer II:

- Spin-orbit field interferes with spin-triplet pairing: look at heavy nuclei

A. Poves and G. Martinez-Pinedo, Phys. Lett. B **430**, 203 (1998)

G. F. Bertsch and Y. L. Luo, Phys. Rev. C **81**, 064320 (2010)

Motivation: Recent model for *N*=*Z*



Correlation energies

- Larger than one: spin-triplet
- Less than one: spin-singlet
- Vertical line: proton drip
- Spin-orbit influence mitigated for nuclei that are unrealistically large

G. F. Bertsch and Y. L. Luo, Phys. Rev. C **81**, 064320 (2010)

Hamiltonian

$$\hat{H} = \sum_i \langle i|H_{sp}|j\rangle a_i^\dagger a_j + \sum_{i>j,k>l} \langle ij|v|kl\rangle a_i^\dagger a_j^\dagger a_l a_k$$

- H_{sp} : kinetic + potential well + spin-orbit
- $\langle ij|v|kl\rangle$: contact pairing interaction in 6 channels

$$\langle ij|v|kl\rangle = \sum_\alpha^6 v_\alpha \langle ij|\delta^{(3)}(\mathbf{r}-\mathbf{r}')P_{L=0}P_\alpha|kl\rangle$$

where v_s and v_t are fit to USDB and GX1A and

α	1	2	3	4	5	6
(S, S_z) (T, T_z)	(0,0) (1,1)	(0,0) (1,0)	(0,0) (1,-1)	(1,1) (0,0)	(1,0) (0,0)	(1,-1) (0,0)

Traditional HFB

- Applying the Bogoliubov U and V we go to the quasiparticle representation

- The ordinary and anomalous densities are:

  $\rho = V^* V^t$ and $\kappa = V^* U^t$

- Hartree-Fock-Bogoliubov equations:

$$\begin{bmatrix} h & \Delta \\ -\Delta^* & -h^* \end{bmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = \begin{pmatrix} U_k \\ V_k \end{pmatrix} E_k$$

where $h = \varepsilon + \Gamma - \lambda$ and the interaction is buried inside Γ and Δ

N>Z: HFB + gradient method

- We want to apply numerous constraining fields:

$$H' = H - \sum_i \lambda_i Q_i$$

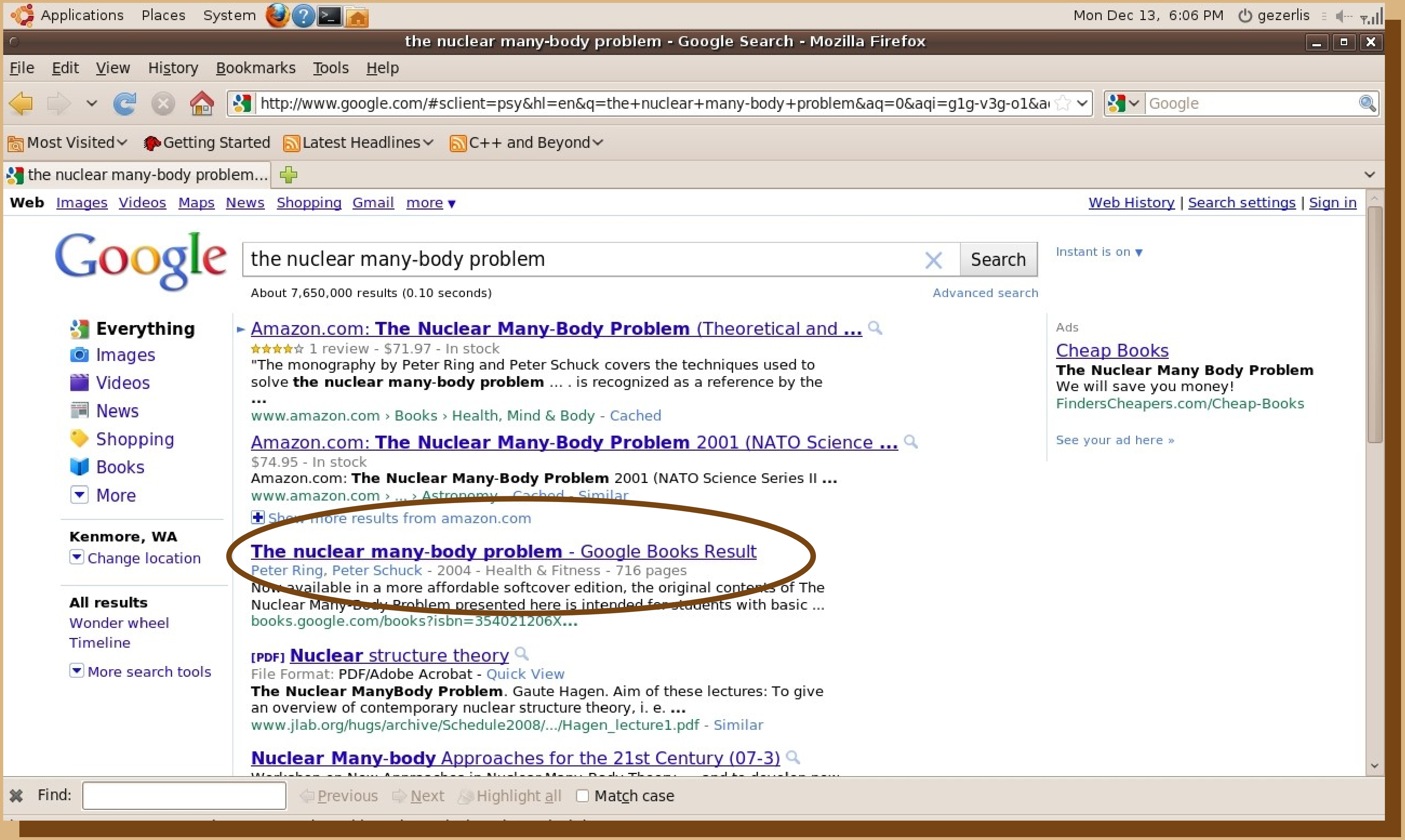
The Q_i are the neutron and proton numbers (and possibly 6 more quantities, 1 per channel).

- Using the Thouless matrix Z the energy can be expanded:

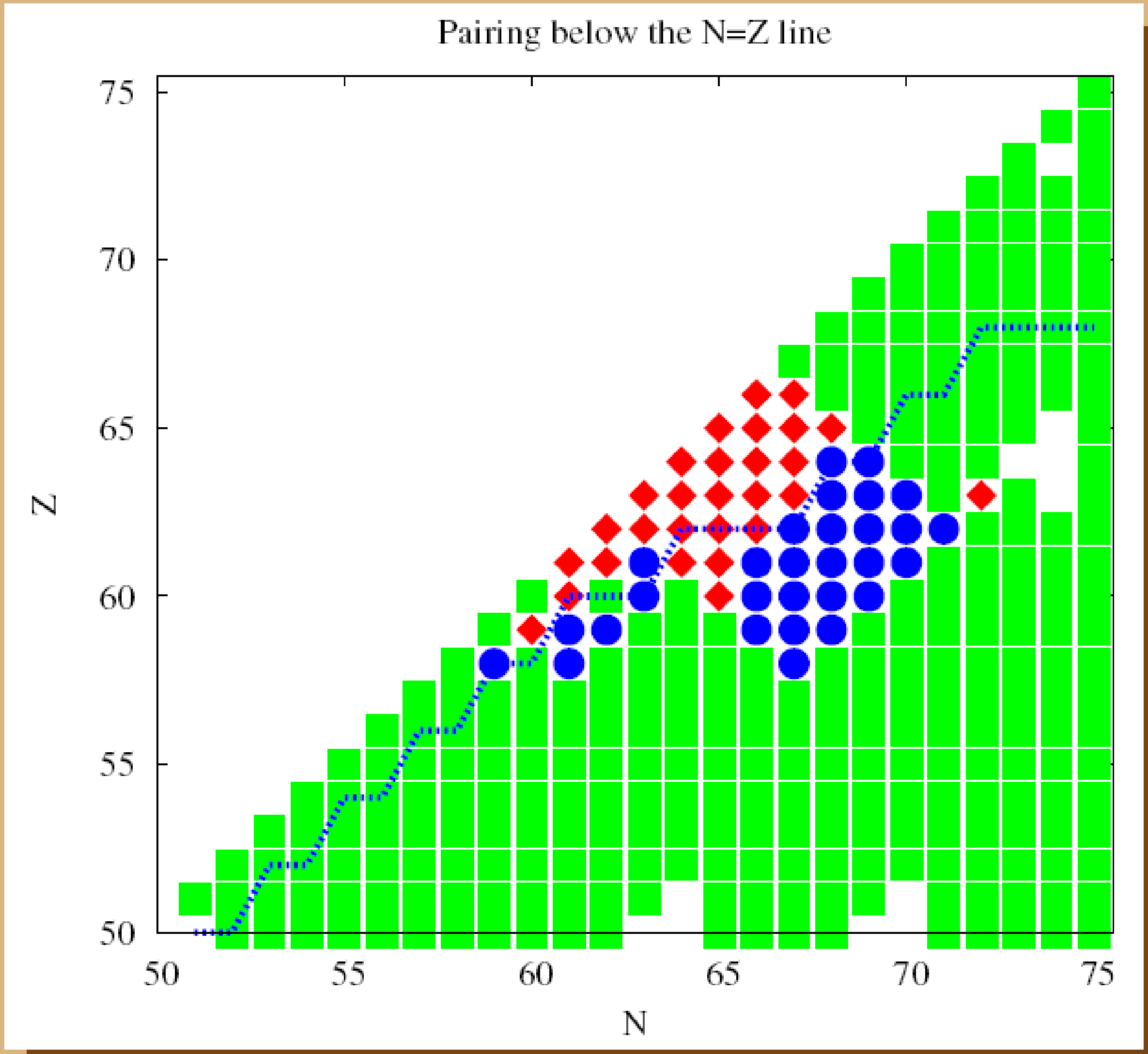
$$(H')^{00}_{new} \approx (H')^{00} - \mathrm{Tr}((H')^{20} Z) - \mathrm{Tr}((H')^{11} Z^2)$$

- More information:
  → L. M. Robledo and G. F. Bertsch, Phys. Rev. C **84**, 014312 (2011)
  → P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (Springer)

the nuclear many body problem



N > *Z* results near A=130

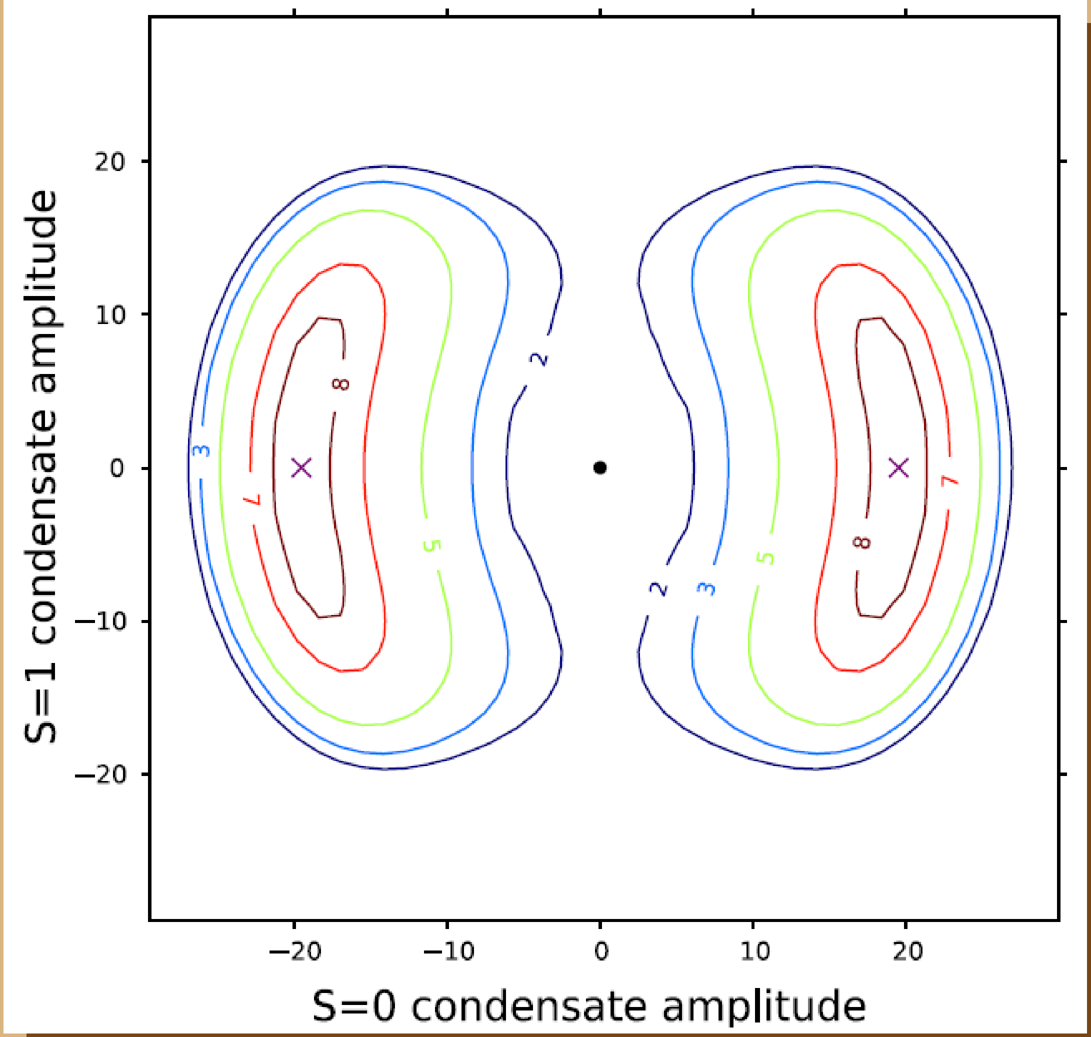


Correlation energies

- Blue line: proton drip
- Green: spin-singlet
- Red: spin-triplet
- Blue: mixed-spin
- Spin-triplet pairing persists off N=Z line
- Mixed-spin pairing appears to be energetically stable

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

Energy contour for spin-singlet

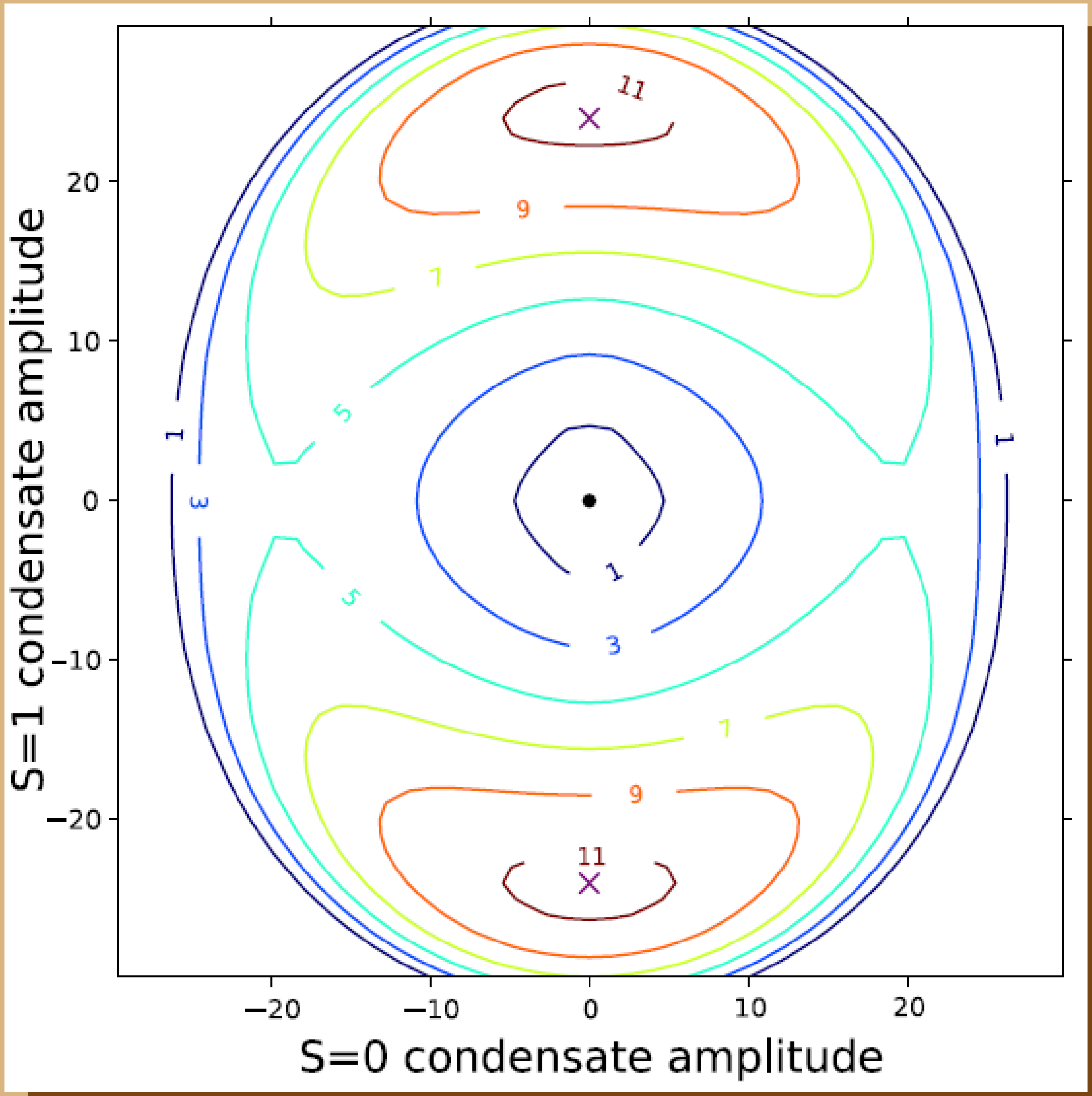


$^{132}_{60}\mathrm{Nd}$

- Dot: uncorrelated
- X: unconstrained
- Energy surface elongated in vertical direction, so is soft with respect to forming a spin-triplet condensate

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

Energy contour for spin-triplet

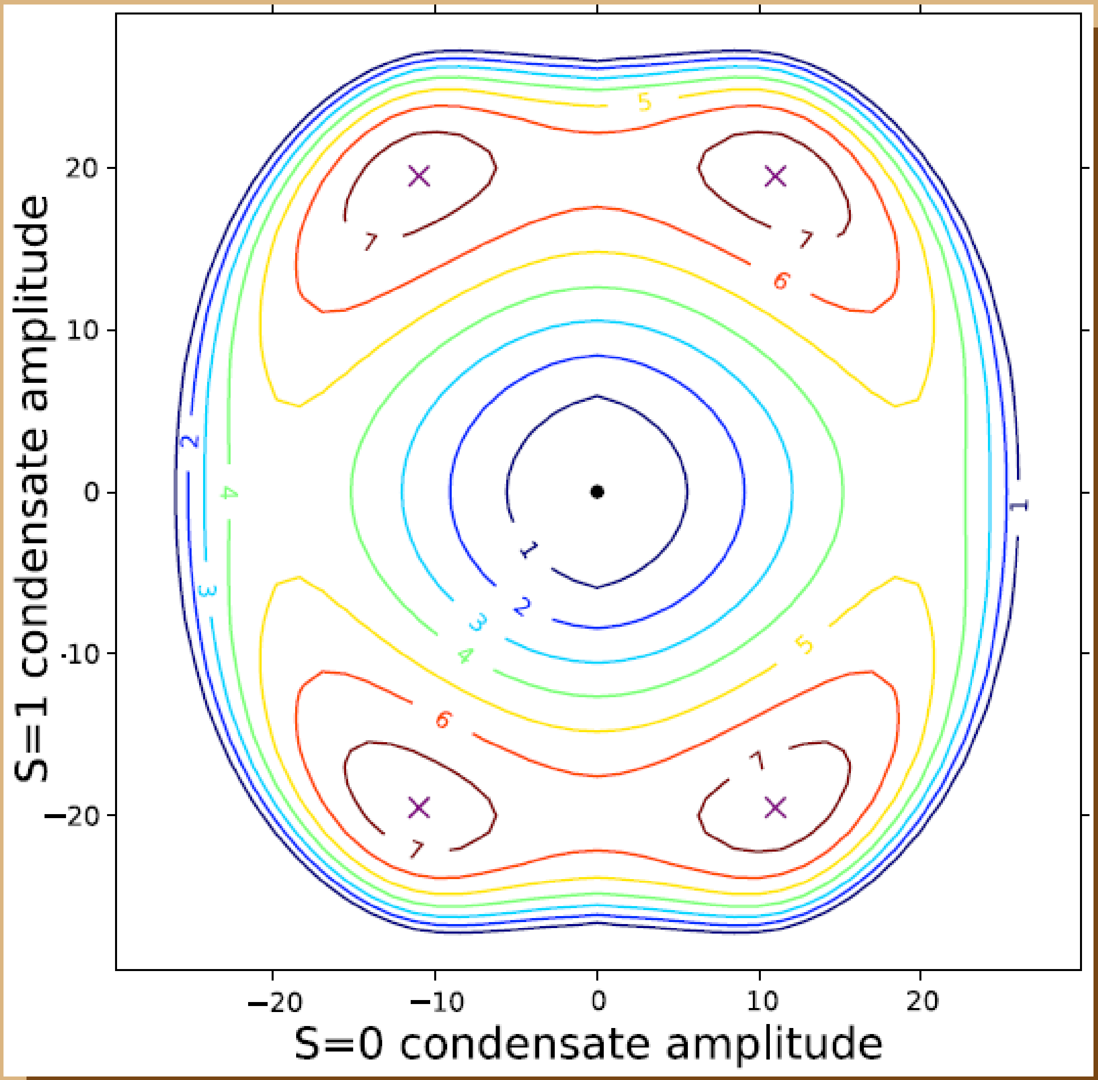


$^{132}_{66}\mathrm{Dy}$

- Dot: uncorrelated
- X: unconstrained
- Maximum along x-axis is only a saddle point in x-y plane. Will this point become a peak?

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

Energy contour for mixed-spin

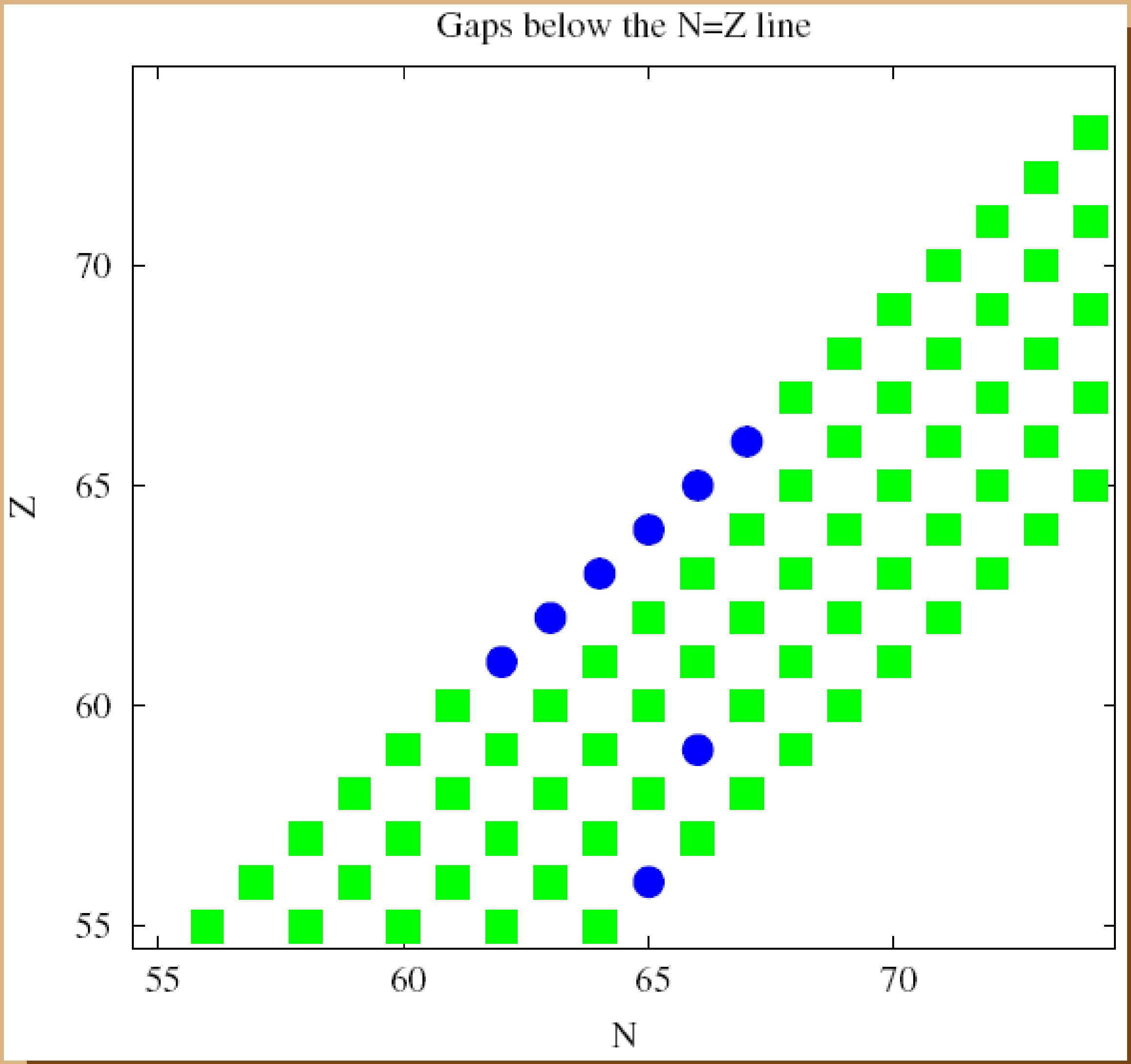


$^{132}_{64}\mathrm{Gd}$

- Dot: uncorrelated
- X: unconstrained
- Smooth transition. Dependent on the presence of spin-orbit splitting. Prediction.

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

Experimental signatures



- Pairing gaps:

$$\Delta_o^{(3)}(n) = E(n) - \frac{1}{2}\left[E(n-1) + E(n+1)\right]$$

blue(=small) one unit off N=Z and a little below

- Spectral: low-lying excitations
- Two-particle transfer direct reaction cross sections

A. Gezerlis, G. F. Bertsch, and Y. L. Luo, Phys. Rev. Lett. **106**, 252502 (2011)

Conclusions / Future Work

Conclusions

- Spin-triplet condensates possibly stable
- Mixed-spin condensates apparently stable
- Experimental signatures

Future Work

- Generalize to include deformation
- Does the mixing persist in asymmetric nuclear matter?
- Experimental signatures?