MICROSCOPIC CALCULATIONS OF FISSION BARRIERS IN THE ACTINIDE REGION

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INTRODUCTION

AIM OF RESEARCH

- calculation of fission barrier heights of **odd-mass** nuclei in the actinide region
- dependence of the inner barrier height on the K^π quantum numbers (assuming K is conserved along fission process)
- study of the energy spectra in the ground-state and fission-isomeric wells and transition (discrete) states at the top of the first barrier

Microscopic approach to odd nuclei

Hartree-Fock (HF) plus pairing (BCS)

- breaking of time-reversal symmetry (due to the addition of one unpaired nucleon)
  - proper account of the effect through **self-consistent blocking (SCB)** calculations
  - vs. the Equal Filling Approximation (EFA); see e.g.
    - F. de la Iglesia, V. Martin, S. Perez Martin and L. M. Robledo, AIP Conf. Proc. **1175**, 199 (2009) : ^{239}**Pu**
    - S. Perez Martin and L. M. Robledo, Int. J. Mod. Phys. E **18** 788-797 (2009): ^{235}**U**
    - Koh Meng Hock, L. Bonneau and P. Quentin, EPJ Web of Conferences **62**, 04004 (2013)
- blocking of a single-particle state with specific K^{π} quantum numbers, and taking the lowest-energy solution

Microscopic approach to odd nuclei

Defining a pair state in BCS scheme

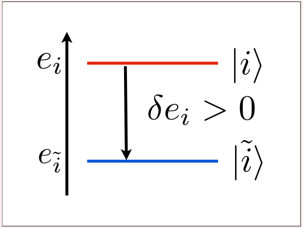
- Definition of a "Kramers quasi-pair" $(|i\rangle, |\tilde{i}\rangle)$:

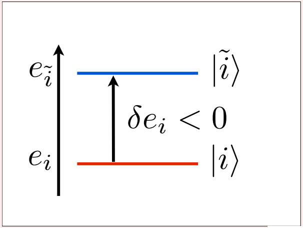
$$\hat{h}_{\rm HF}|i\rangle = e_i|i\rangle \qquad \hat{J}_z|i\rangle = \Omega_i|i\rangle \quad \text{with } \Omega_i > 0$$

$$\hat{h}_{\rm HF}|\tilde{i}\rangle = e_{\tilde{i}}|\tilde{i}\rangle \qquad \hat{J}_z|\tilde{i}\rangle = \Omega_{\tilde{i}}|\tilde{i}\rangle \quad \text{with } \Omega_{\tilde{i}} = -\Omega_i < 0$$

$$\left|\langle\bar{i}|\widetilde{i}\rangle\right| \text{ maximum (close to 1 in practice)}$$

- Energy splitting in a Kramers quasi-pair: $\delta e_i = e_i - e_{\tilde{i}}$





Microscopic approach to odd nuclei

Numerical parameters

- effective nucleon-nucleon interaction : Skyrme SkM* force
- the single-particle states are expanded on a cylindrical harmonic-oscillator basis with a basis size, $N_0 = 14$
- seniority force with pairing strength in the BCS scheme where the pairing strengths were fitted to the odd-even binding energy differences of some actinide nuclei, with retained values of $G_0(\text{neutron}) = \text{G}_0(\text{proton}) = -16.0 \text{ MeV}$
  - pairing window up to $\epsilon_F + 6.0$ MeV with a diffuseness parameter of 0.2 MeV

Microscopic approach to odd nuclei

Unified model picture

- HFBCS solution $|\Psi_K\rangle$ as intrinsic state
- rotational correction to intrinsic energy
- Coriolis coupling for $K = \frac{1}{2}$ states
- energy of the J^π member of the K^π rotational band:

$$E_J = E_{K=J} + \frac{\hbar^2}{2\mathcal{I}}\Big[J(J+1) - K(K+1)\Big]$$

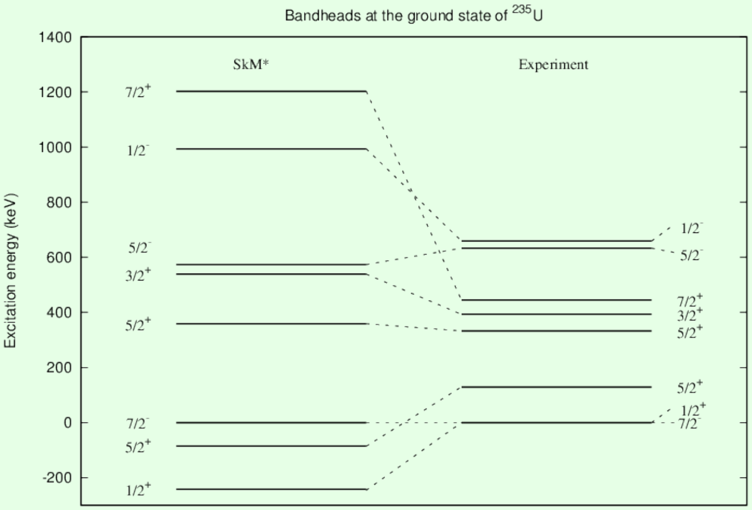
with

$$E_{J=K} = \underbrace{\langle\Psi_K|\hat{H}|\Psi_K\rangle}_{intrinsic\ energy} - \underbrace{\frac{\hbar^2}{2\mathcal{I}}\Big(\langle\Psi_K|\hat{\mathbf{J}}^2|\Psi_K\rangle - K(K+1)\Big)}_{rotational\ correction} - \underbrace{\frac{\hbar^2}{2\mathcal{I}}\delta_{K\frac{1}{2}}(-)^{J+\frac{1}{2}}(J+\frac{1}{2})a}_{Coriolis\ coupling}$$

$\mathcal{I}$ is the moment of inertia calculated for the even-even core (preliminary)

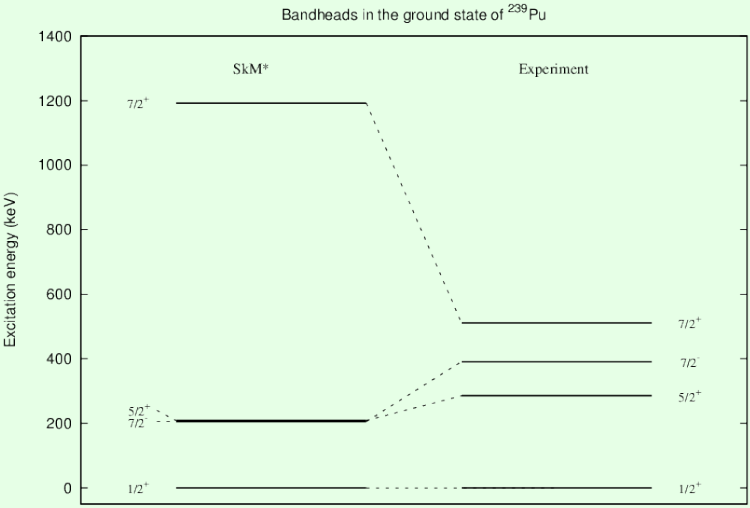
RESULTS

ONE-QUASIPARTICLE BANDHEADS IN ^{235}U (GS WELL)



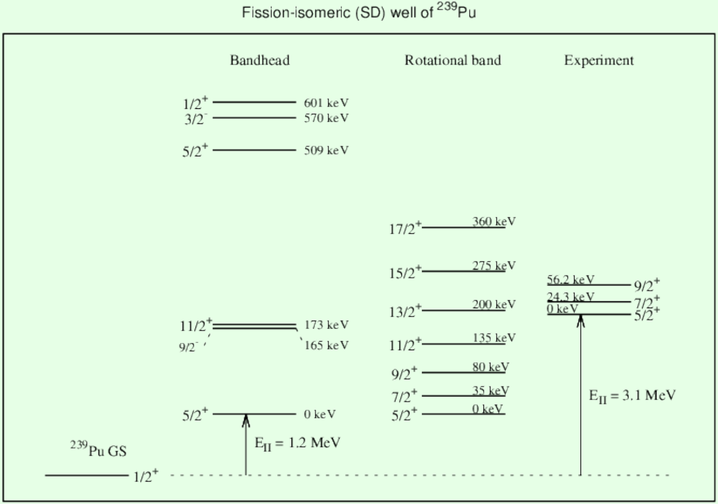
RESULTS

ONE-QUASIPARTICLE BANDHEADS IN ^{239}PU GS WELL



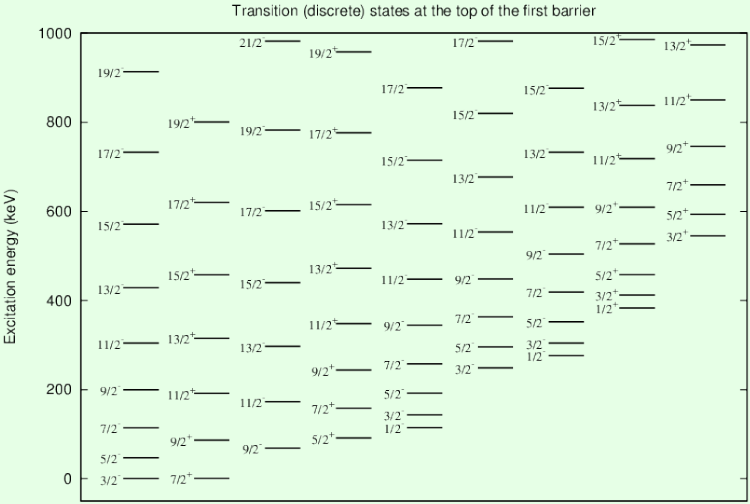
RESULTS

ONE-QUASIPARTICLE BANDHEADS IN ^{239}PU SD WELL



Results

Rotational bands at ^{239}Pu first saddle

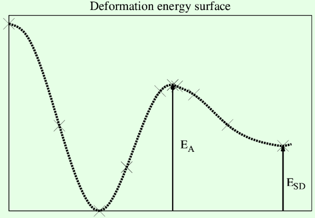


Results

Fission barriers for fixed K^π

Relative energies of first saddle point and second (SD) minimum with respect to GS minimum for various K^π:

	^{235}U		^{239}Pu	
K^π	E_A	E_{SD}	E_A	E_{SD}
$1/2^+$	6.6	2.6	7.4	1.7
$7/2^-$	6.8	2.5	7.9	2.5
$5/2^+$	5.8	1.4	7.0	0.9
$7/2^+$	–	–	5.9	1.6



Results

Effect of time-reversal symmetry breaking

Difference between first-fission-barrier heights without (EFA) and with (SCB) time-reversal symmetry breaking in the selfconsistent blocked HFBCS solution for various K^π:

K^π	$E_A(SCB) - E_A(EFA)$ (keV)
$1/2^+$	20
$7/2^-$	20
$5/2^+$	0

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CONCLUSIONS

1. The calculated spectra compare favorably with experimental data in GS and SD wells
$\Rightarrow$ reasonable class-I, class-II and transition states of rotational character

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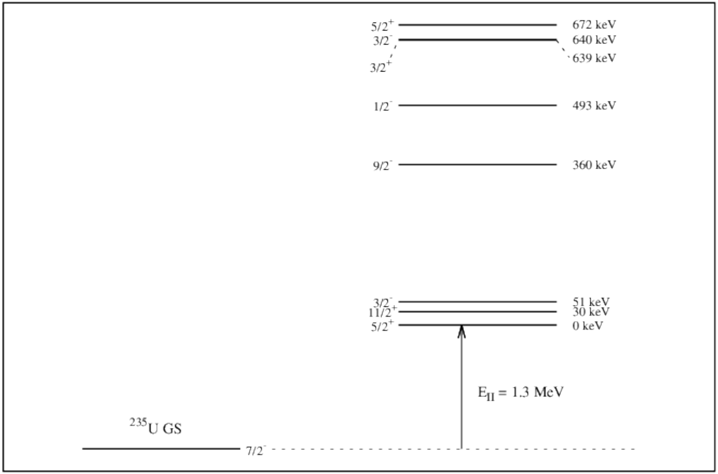
1. The calculated spectra compare favorably with experimental data in GS and SD wells
   $\Rightarrow$ reasonable class-I, class-II and transition states of rotational character
2. The inner barrier height can vary significantly with K^{π}
3. EFA seems justified for calculations of fission-barrier heights (not for spectroscopic properties like magnetic moments)

Perspectives

- Extend study to second saddle point (outer fission barrier)
- Improve moment of inertia for the core:
  - core polarization
  - pairing quenching because of unpaired nucleon (blocking)
- Restore particle-number symmetry broken by BCS
  $\Rightarrow$ Highly Truncated Diagonalization Approach (HTDA)
  $\approx$ highly truncated shell model based on a mean-field solution
- Account for vibrational degrees of freedom, for example in the HTDA approach
- Extension to odd-odd compound nuclei

Fission-isomeric (SD) well of ^{235}U



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