What can be learned from complex atomic spectra in strong magnetic fields?

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Questions

1. Why not to use simple atoms?
2. How magnetic field can help to study complex spectra?
3. How magnetic field can help to look for new physics?
4. How magnetic field changes statistical properties of complex spectra?

Why do we need to use atoms as probes for new physics?

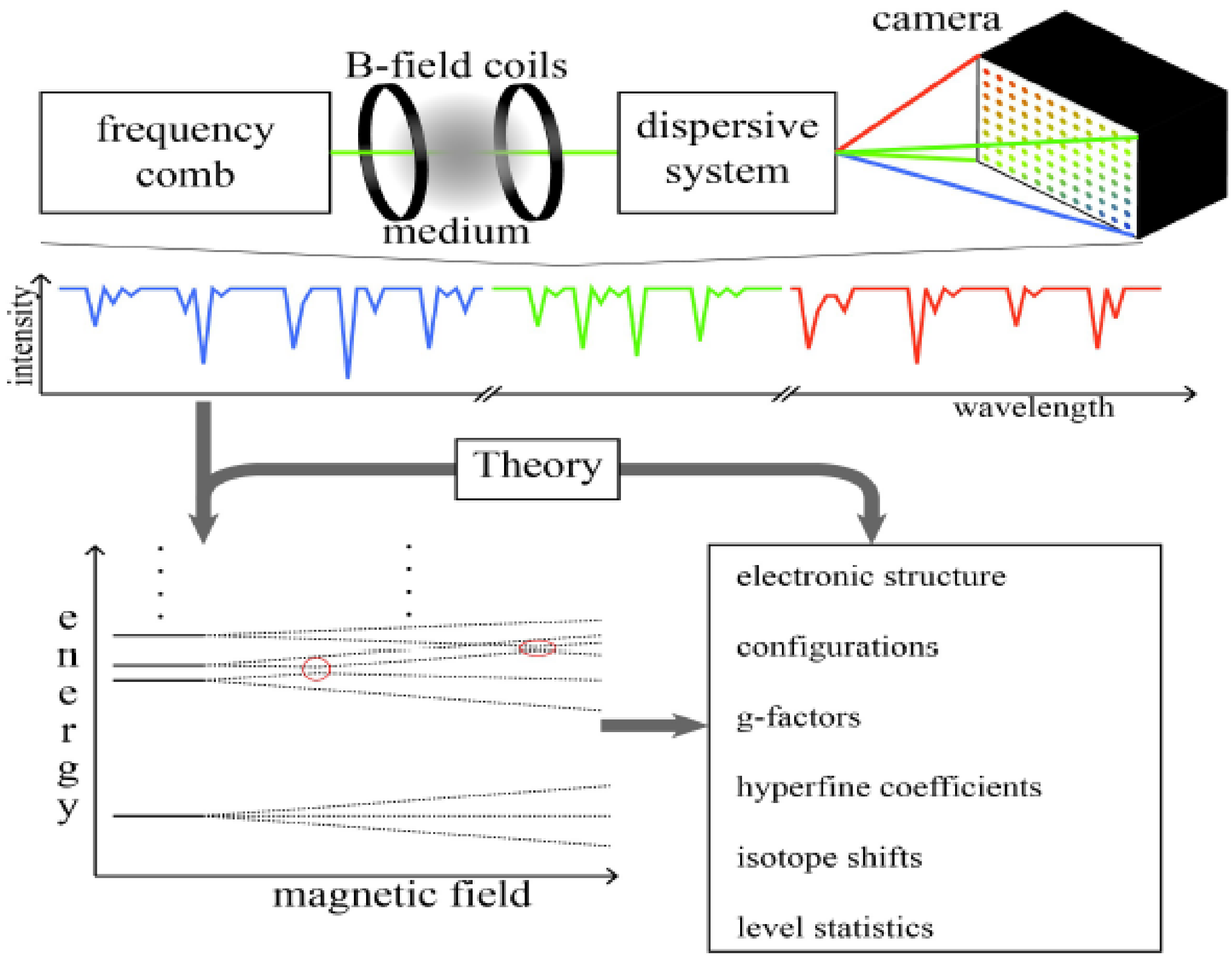
- *High precision* ⇒narrow lines, metastable states, convenient wavelengths.
- *High sensitivity* ⇒ close levels with different properties (parity, α-dependence, density at the origin, etc.) ⇒ accidental degeneracies.
- *Not easy to find perfect combination!* ⇒ *Need to have where to choose from.*

Do we know spectra of all complex atoms?

- There are large gaps in atomic spectral tables.
- Dense spectra are very difficult to analyze.
- The progress in acquiring data on complex spectra is very slow.
- $\Rightarrow$ We need new experimental techniques and analytical methods to improve situation.

Spectroscopy 2.0

Proposal JGU-HIM-PNPI



Broadband high resolution spectral system

How magnetic field may help to analyze broadband spectra?

Broad anticrossing

- Atomic g-factors were always used for level identification.
- In dense spectra level cross in magnetic field.
- M1 operator does not mix different configurations, ⇒ *broad anticrossings happen only between levels of the same configuration*.

Same configuration!

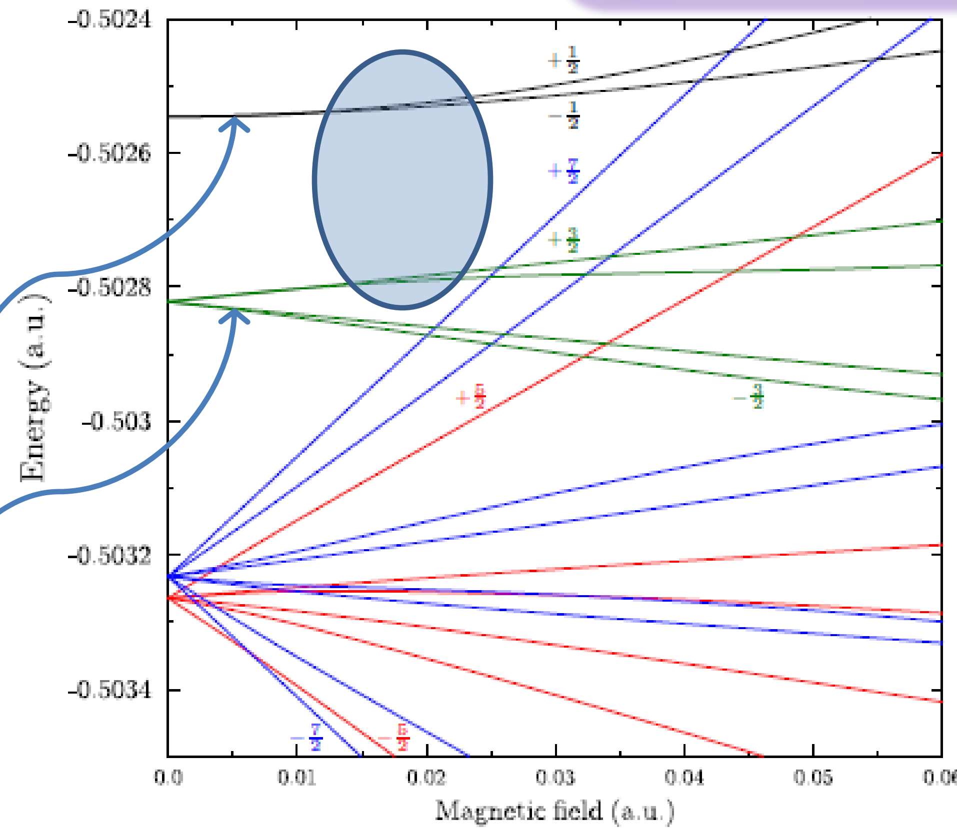
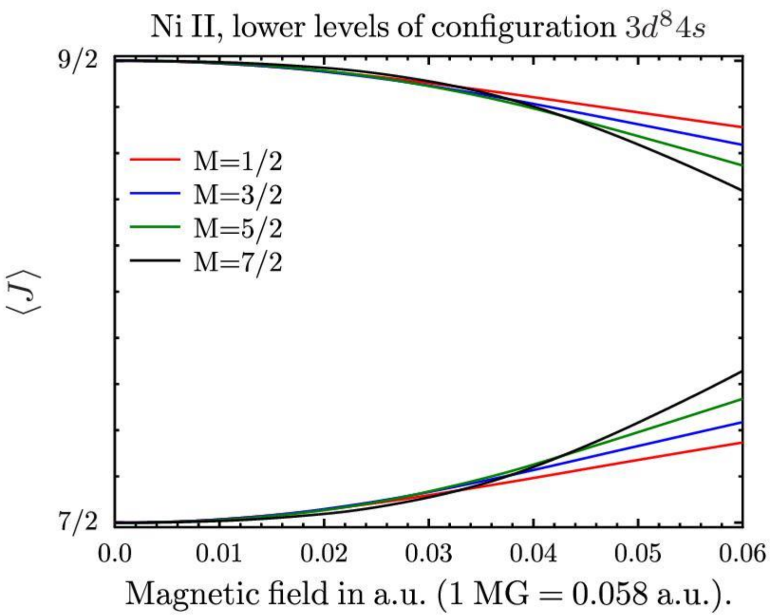
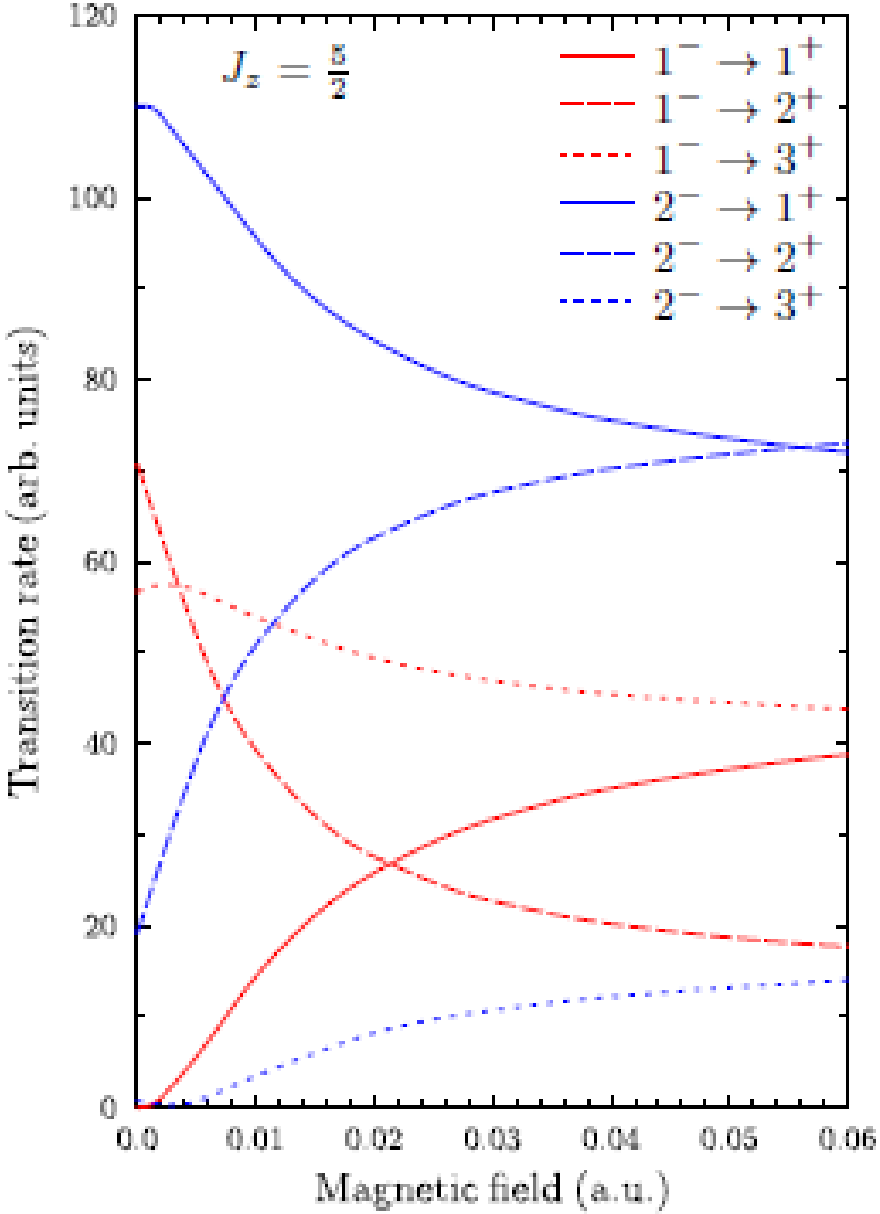


FIG. 1: Level crossings between odd levels of Ni^+.

Intensity of spectral lines

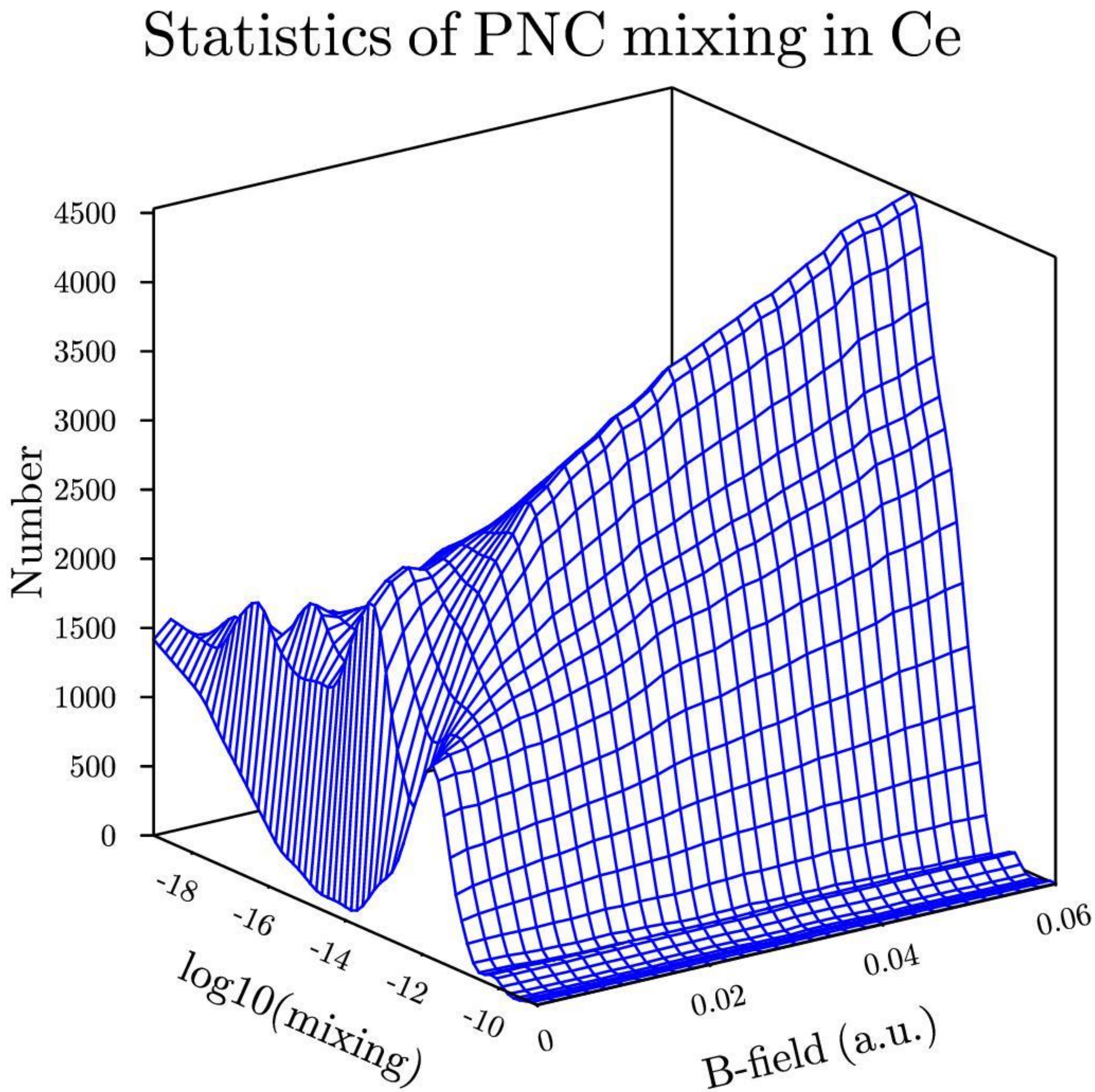
- Magnetic field mixes levels with different total angular momenta J and removes selection rule $\Delta J = 0, \pm 1$.
- $\Rightarrow$ Many forbidden transitions appear.





Search for new fundamental interactions

- If we have two close levels of opposite parity, we can use magnetic field to bring them to crossing. This gives additional enhancement to the PNC mixing.
- If we look for DM in the form of cosmological classical field, which oscillates at some unknown frequency $\omega = mc^2/\hbar$, we can scan magnetic field and try to catch the resonance.
- Magnetic field:
  - removes selection rules in J;
  - increases probability of accidental level crossings;
  - $\Rightarrow$ *leads to statistical enhancement of all small perturbations*.

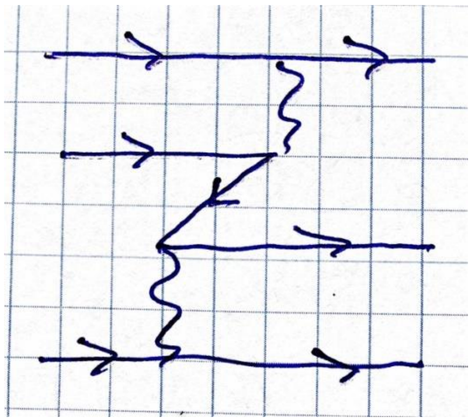


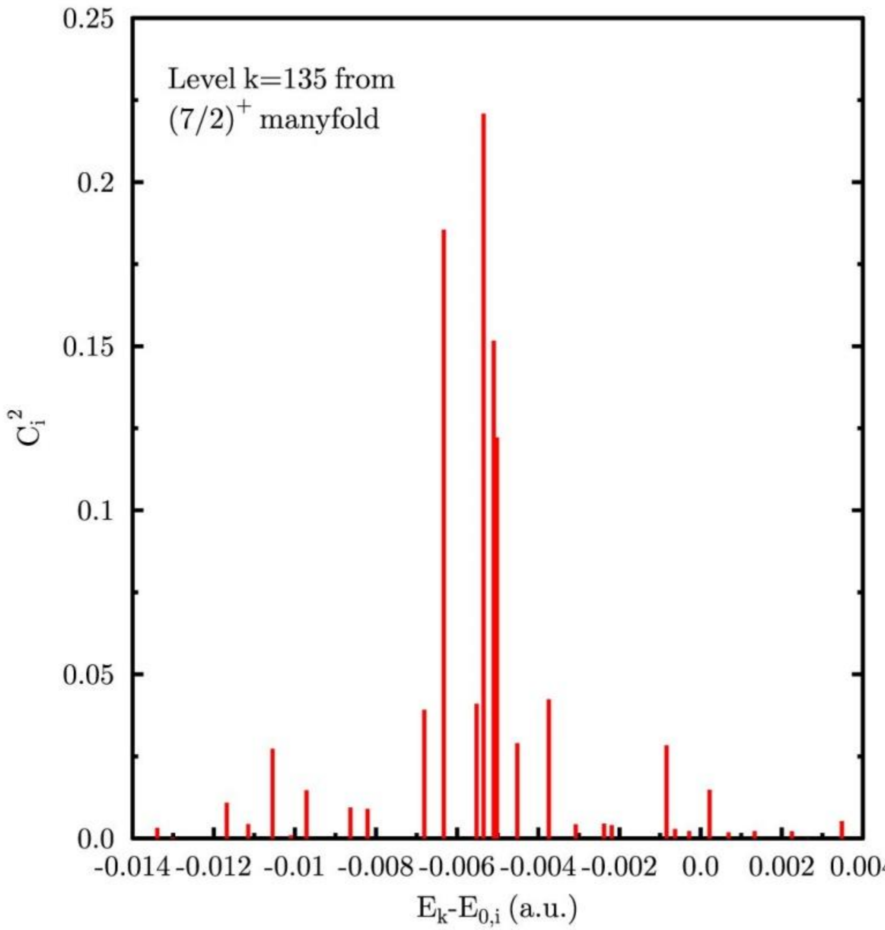
Statistics of PNC mixing in Ce
Number
4500
4000
3500
3000
2500
2000
1500
1000
500
0
-18
-16
-14
-12
-10
log10(mixing)
0
0.02
0.04
0.06
B-field (a.u.)

Quantum chaos

- In systems with dense spectra all small perturbations are statistically enhanced.
- Enhancement depends on the level density and grows as $(N)^{1/2}$, where N is number of principle components in the wavefuction (Sushkov & Flambaum).
- This leads to violation of all approximate symmetries and selection rules.
- Hierarchical structures in the spectrum disappear and system becomes chaotic.

Effective three-electron interaction (TEI)





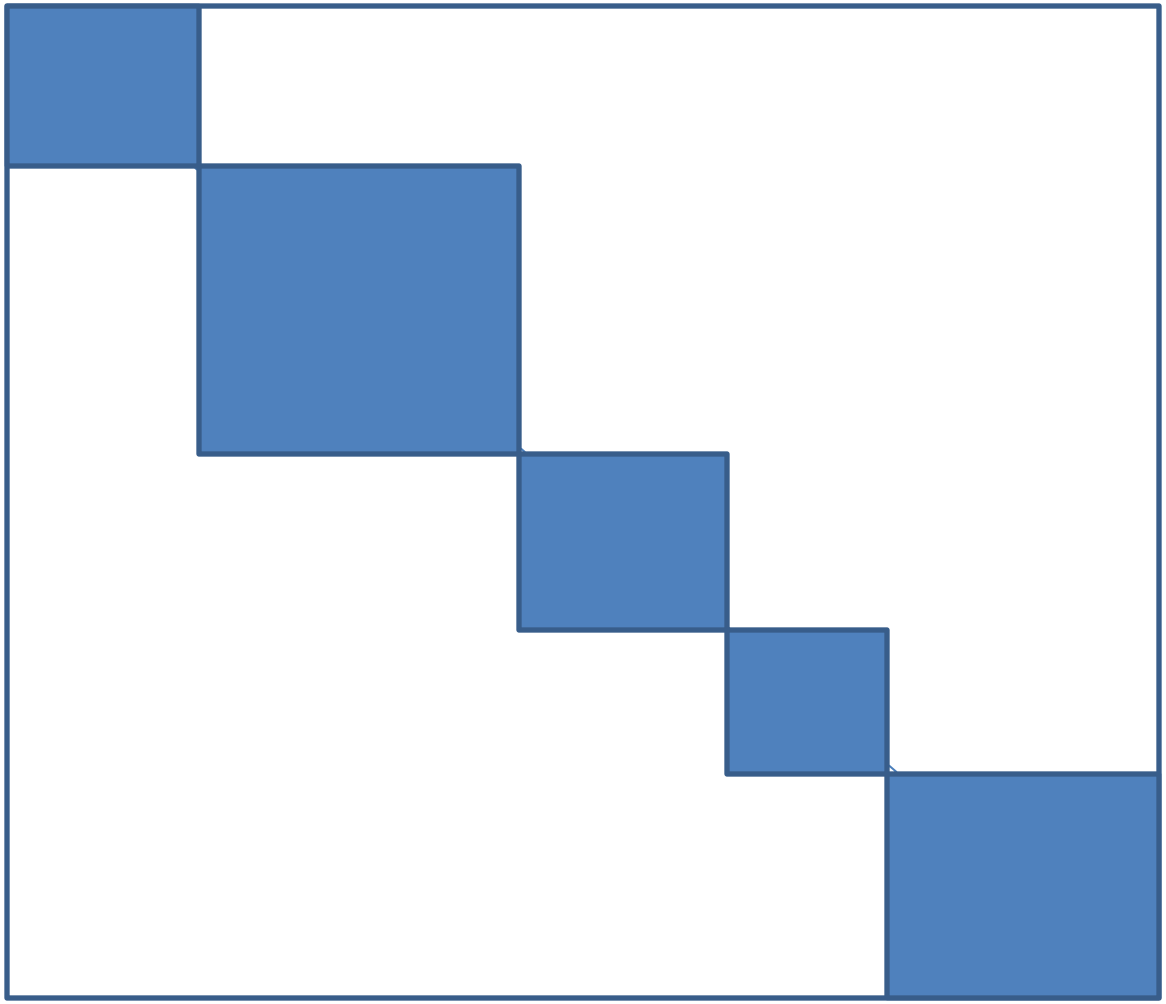
Effective TEI between valence electrons is induced by the exchange with the core.

Typically it is very small, but is enhanced in atoms with filling f-shell.

Even there it is about 1000 cm^{-1}, or less.

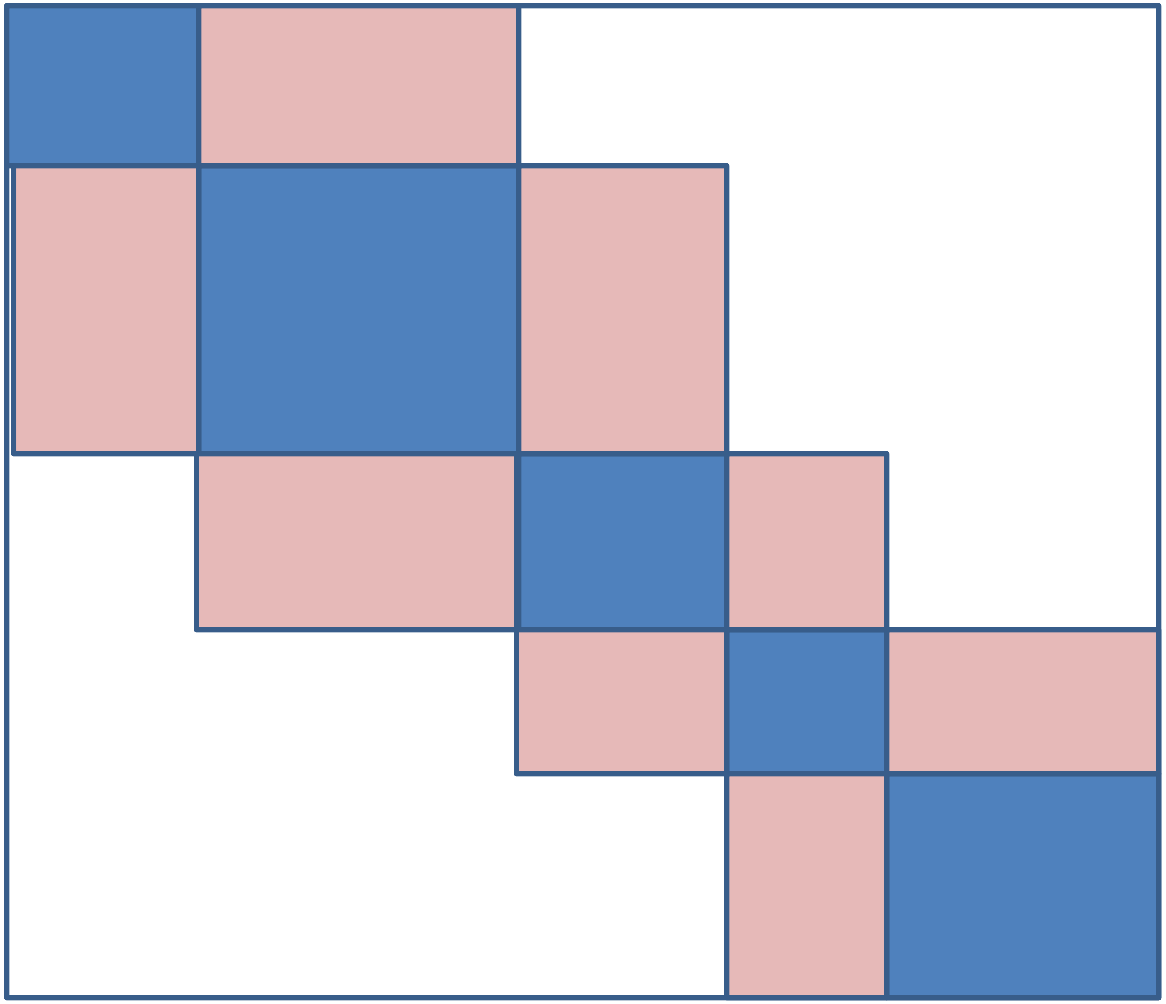
Mixing of states with TEI in Protactinium (Z=91)

Atomic Hamiltonian in zero field



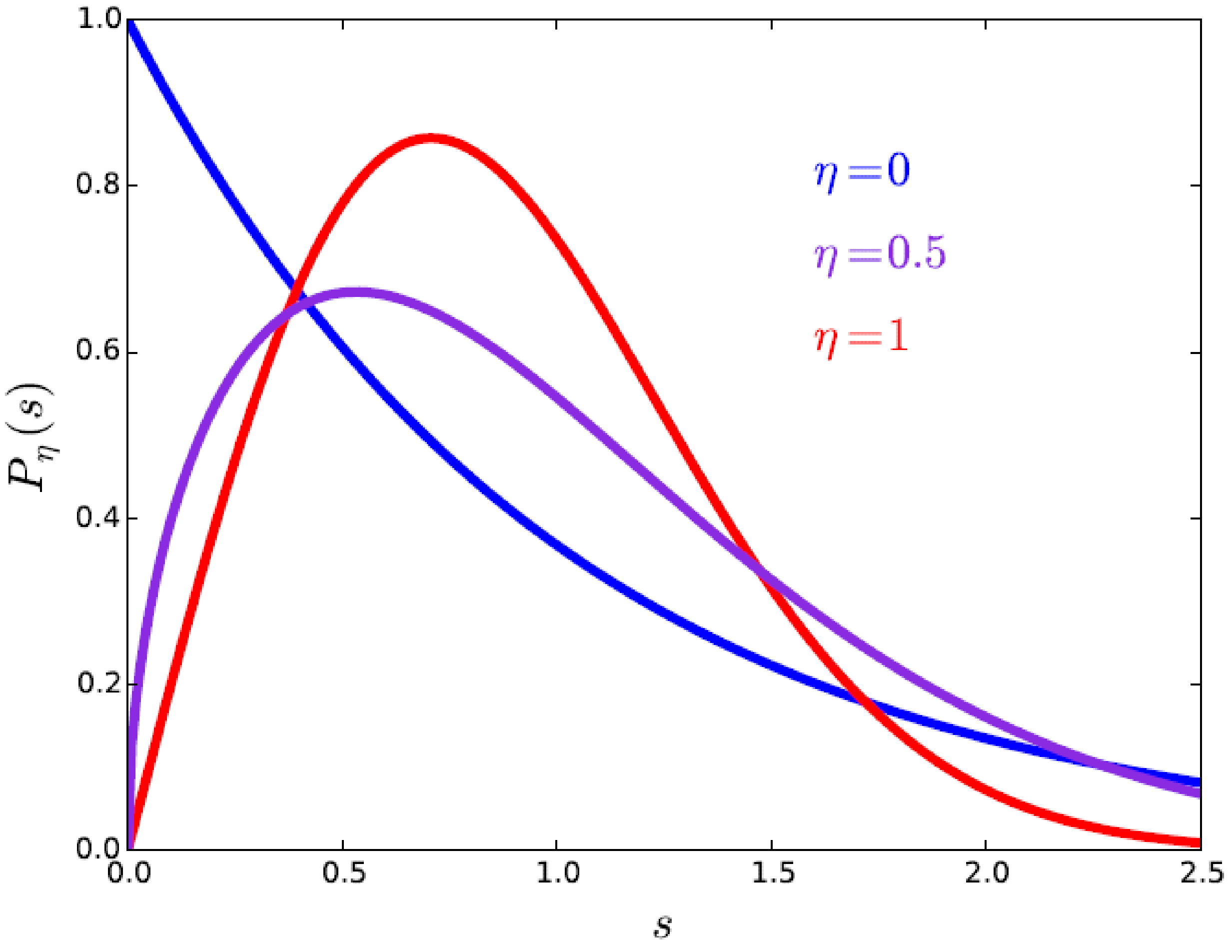
Each block corresponds to particular J.
Atomic spectrum is combination of independent spectra of blocks.

Atomic Hamiltonian in non-zero field



Independent spectra merge in a single spectrum with increased level density.

Nearest-neighbor spacing distribution



Poisson

intermediate

Wigner

Level spacing for $J^{\pi}=4^{+}$ subspace in Ce

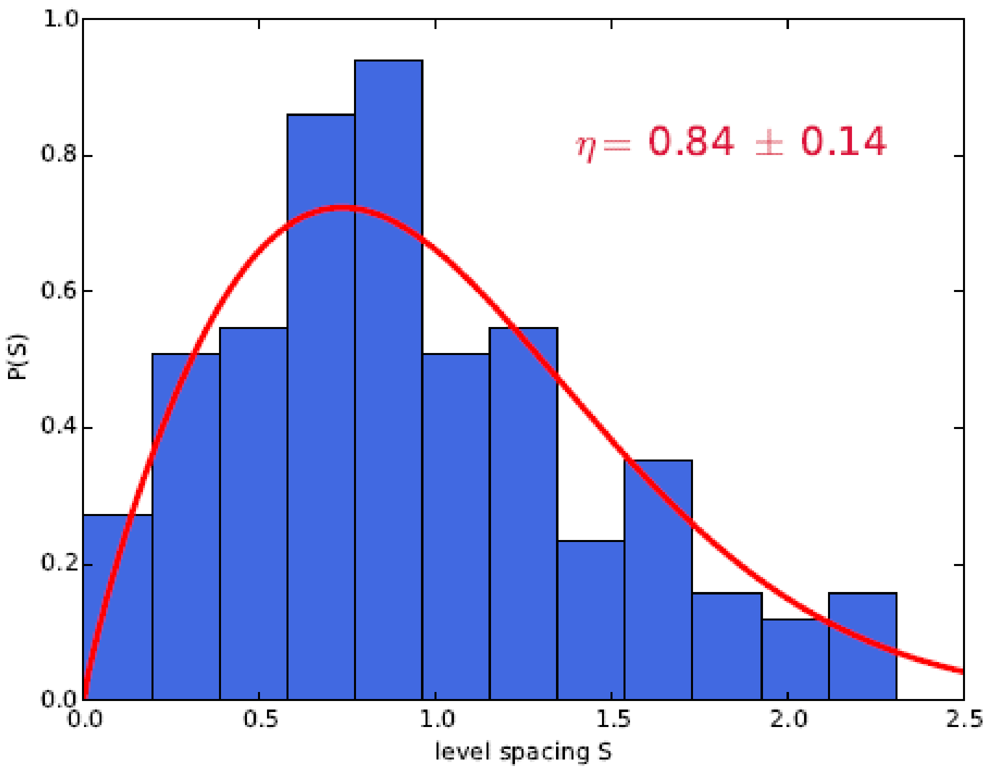
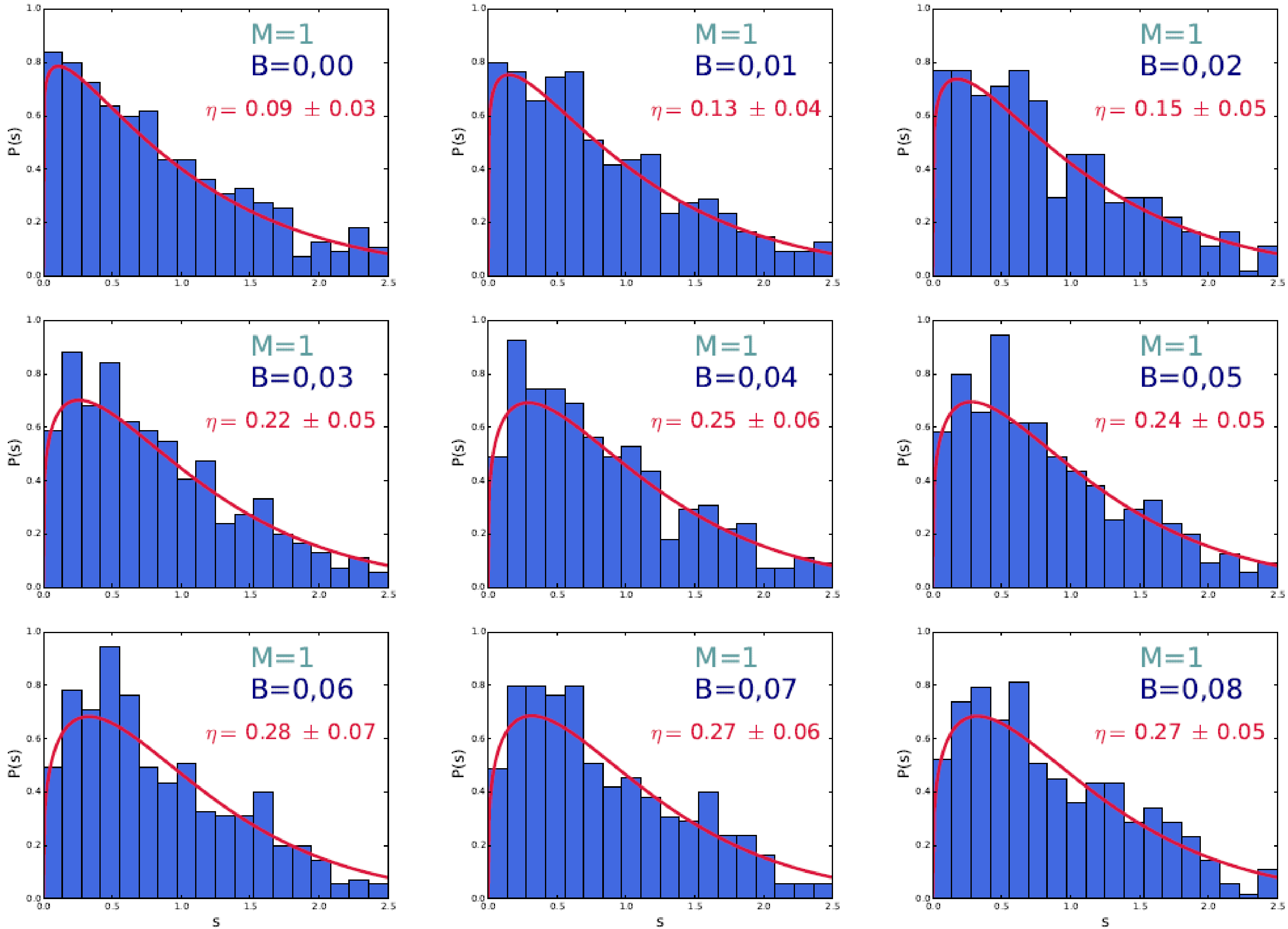
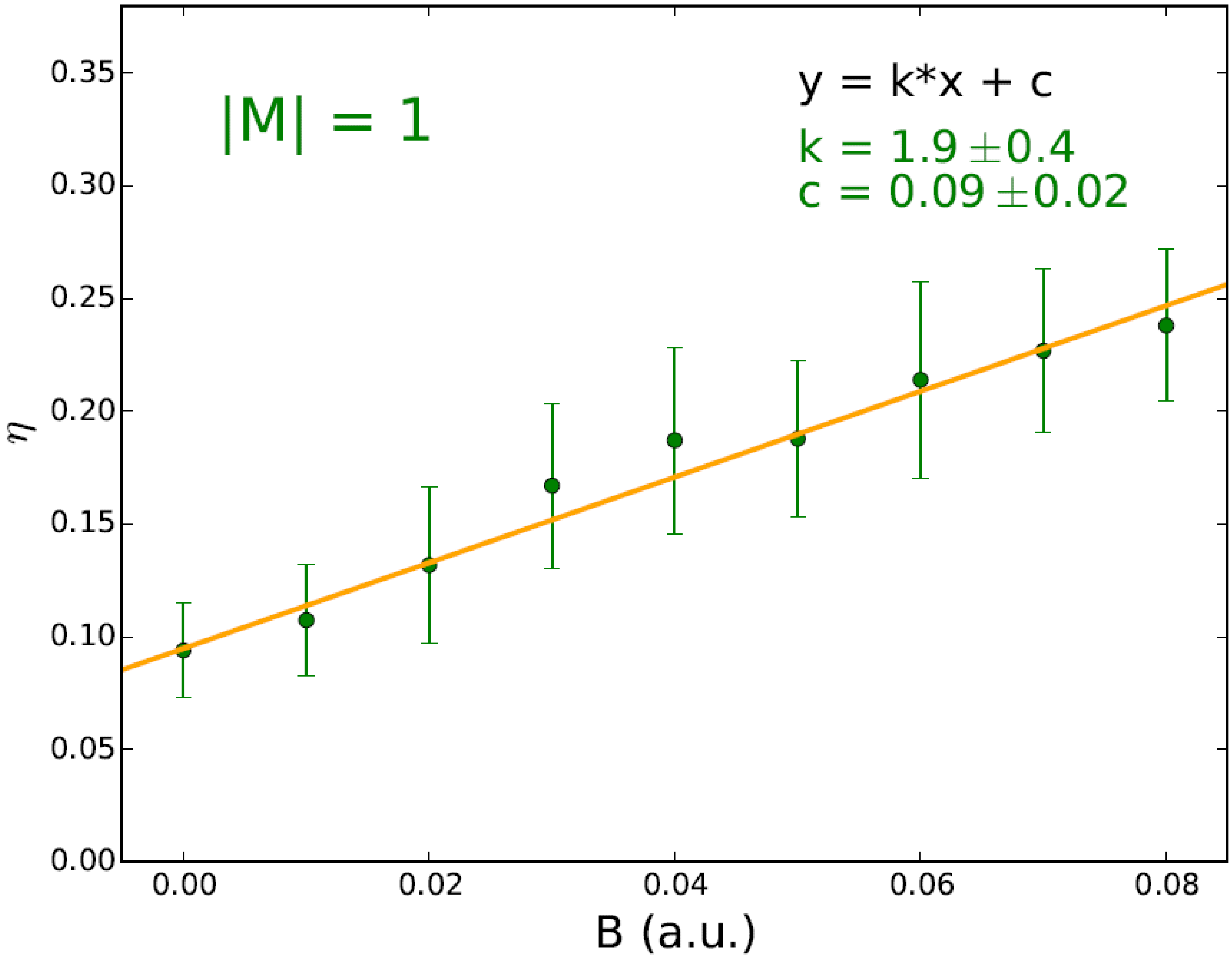


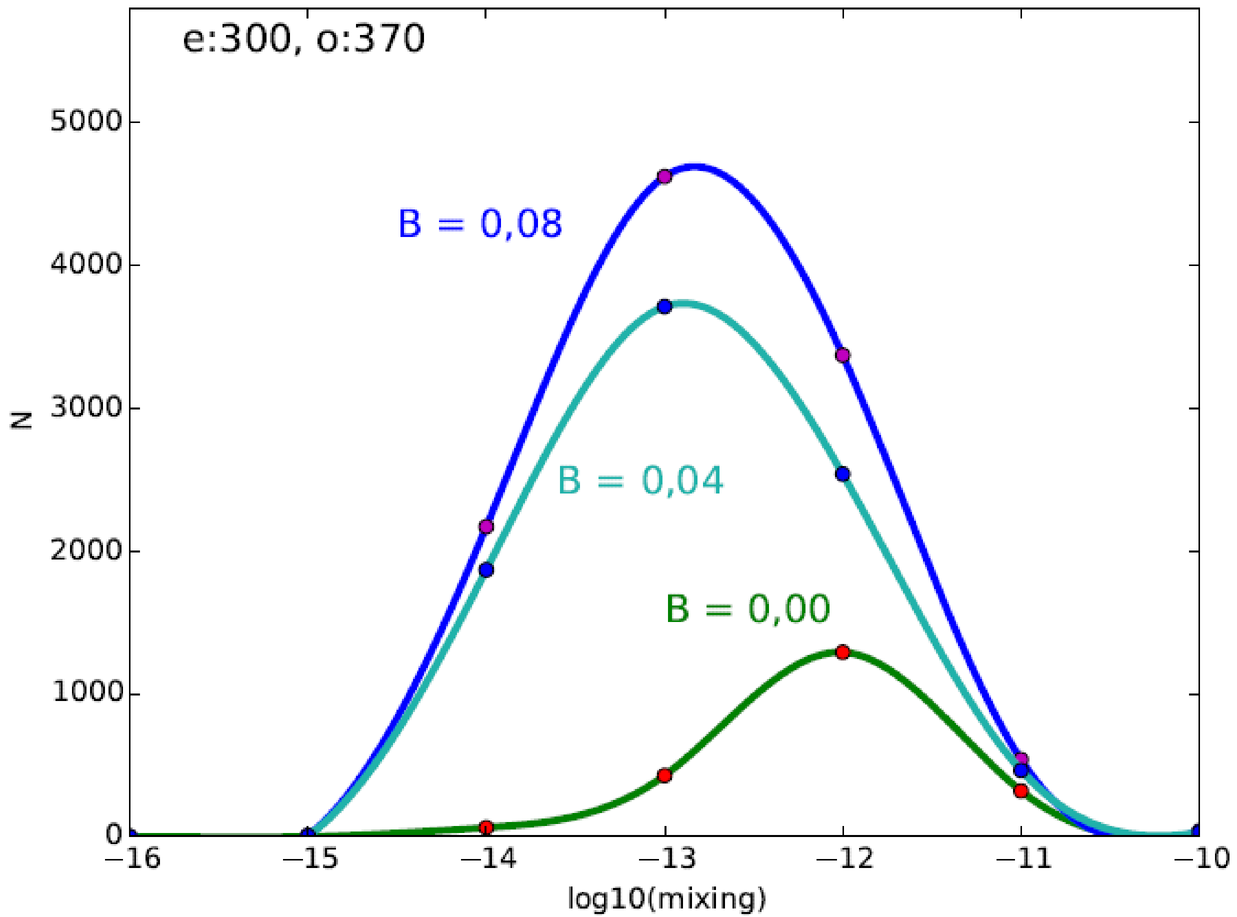
Рис.: Level spacing distribution for the $J^{\pi} = 4^{+}$ levels of Ce: calculated for 15-153 even levels. Fitted with Brody function.


M=1
B=0,00
η= 0.09 ± 0.03
M=1
B=0,01
η= 0.13 ± 0.04
M=1
B=0,02
η= 0.15 ± 0.05
M=1
B=0,03
η= 0.22 ± 0.05
M=1
B=0,04
η= 0.25 ± 0.06
M=1
B=0,05
η= 0.24 ± 0.05
M=1
B=0,06
η= 0.28 ± 0.07
M=1
B=0,07
η= 0.27 ± 0.06
M=1
B=0,08
η= 0.27 ± 0.05
P(s)
s

η as a function of B for Ce



PNC mixing in Ce



Package for CI+MBPT calculations

[MK, S G Porsev, M S Safronova, and I I Typitsyn
Computer Physics Communications, **195**, 197 (2015)]

- Dirac-Coulomb Hamiltonian in no-pair approximation.
- No spherical symmetry assumed – easy to include magnetic field in non-perturbative manner .
- H_{eff} is formed within second order MBPT.
- 13 effective operators for observables in RPA approximation include:
  (a) hyperfine constants A & B
  (b) P-odd & P,T-odd interactions (PNC, AM, eEDM, MQM)
  (c) transition amplitudes *E1-E3* & *M1-M3*
  (d) easy to include other operators

Conclusions

- Strong magnetic field can help in analysis of complex spectra.
  - Anti crossings between levels of the same configuration.
  - More levels are accessible from the ground state due to the violation of the ΔJ selection rule.
- Level crossings lead to enhancement of the weak perturbations and allow to scan through the mass of the potential bosonic DM candidates.
- Magnetic field increases effective level density in the spectrum, which may lead to the “controlled quantum chaos”.

Collaborators

- Anna Viatkina
- Victor Flambaum
- Dmitry Budker
- Nathan Leefer
- Ilya Tupitsyn

Thank you!