Search for T Violation in Resonances of Polarized Compound Nuclei Using Polarized Epithermal Neutrons

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Matter-antimatter asymmetry in the universe

Sakharov Criteria

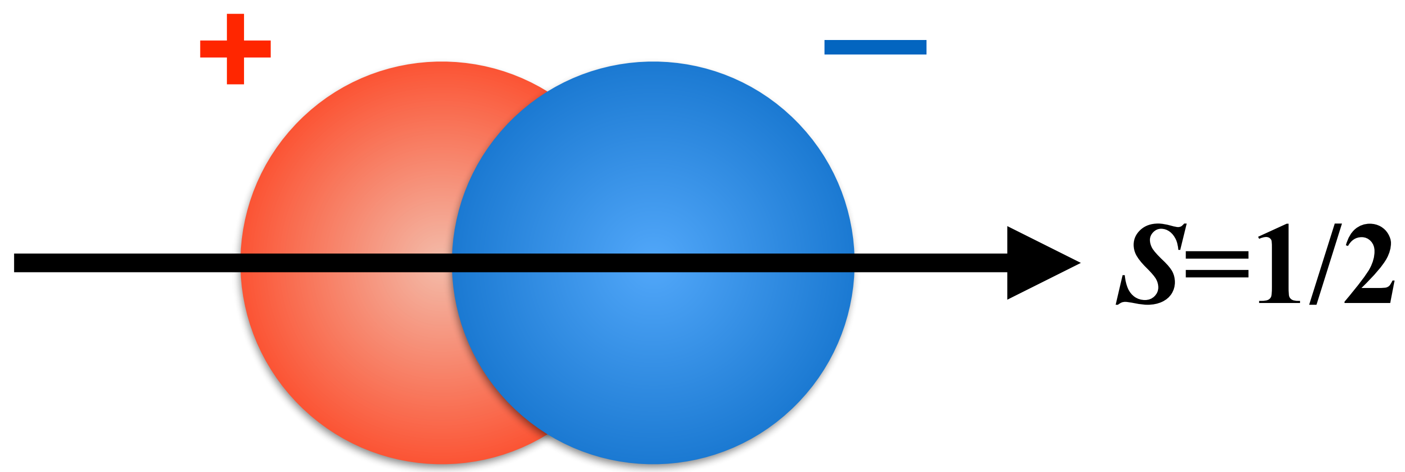
- Conditions out of thermal equilibrium
- Non conservation of baryon number
- C and CP violation (CP$\longleftrightarrow$T)

Searches of TRIV in strongly interacting systems

Complicated theoretical landscape, therefore searches of T violation in different systems, with sensitivity to different possible T-odd mechanisms are necessary:

- Electric Dipole Moments (EDMs)
- T-odd polarized neutron optics

Electric Dipole Moments



$$\vec{d} = \int \vec{x}\rho(x)d^3x = d\ \hat{s}$$

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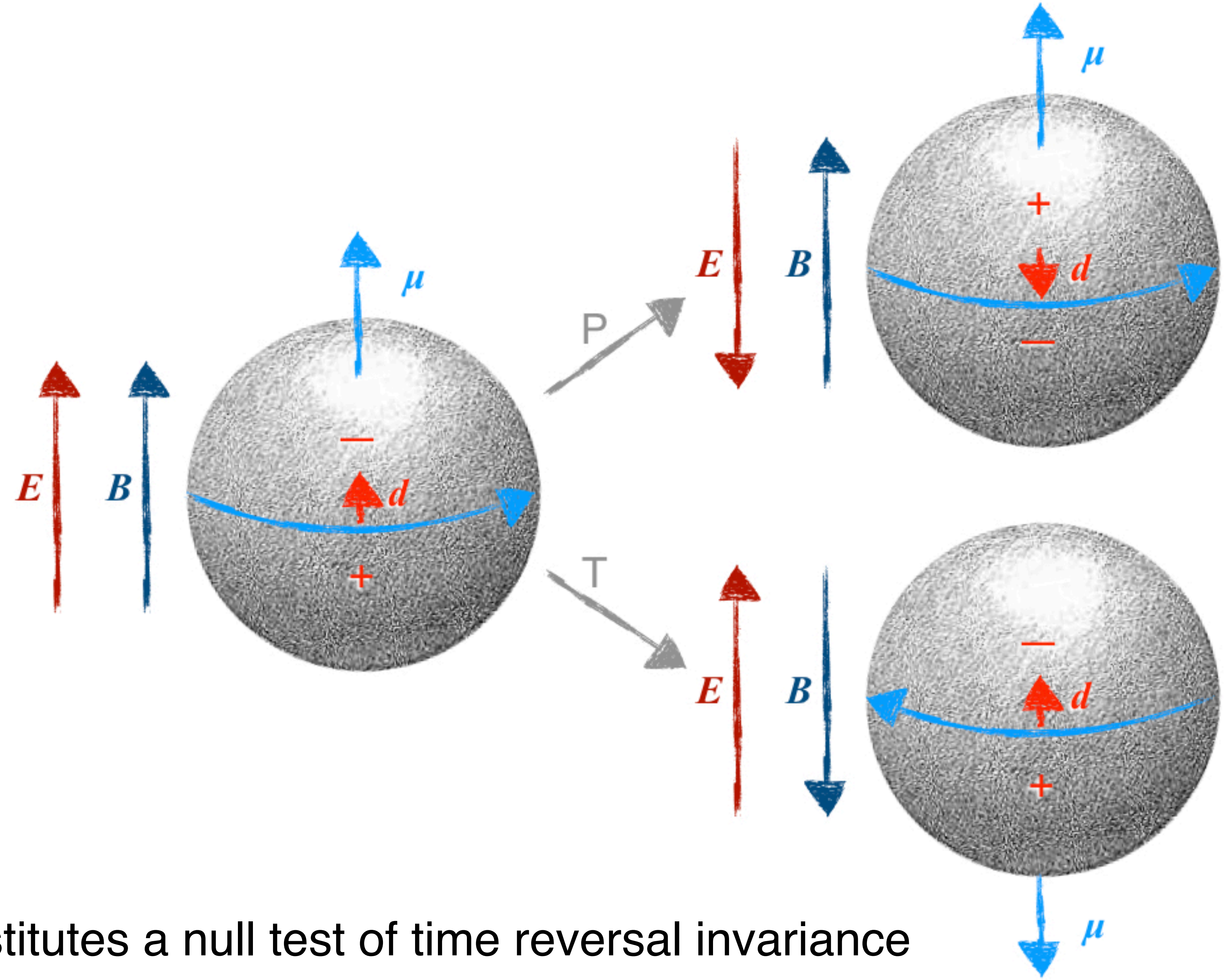
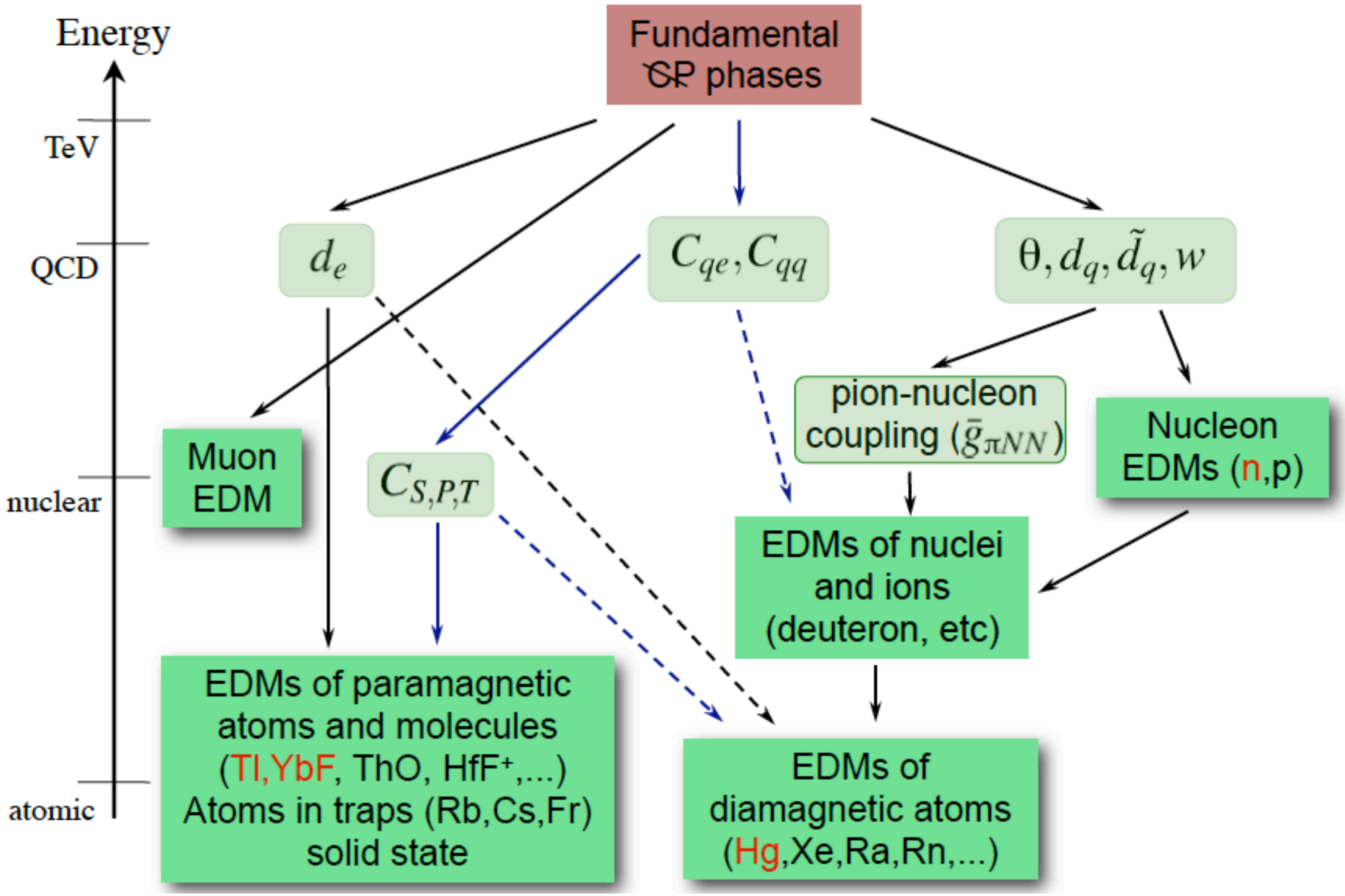
Electric Dipole Moments



$d \neq 0$ constitutes a null test of time reversal invariance

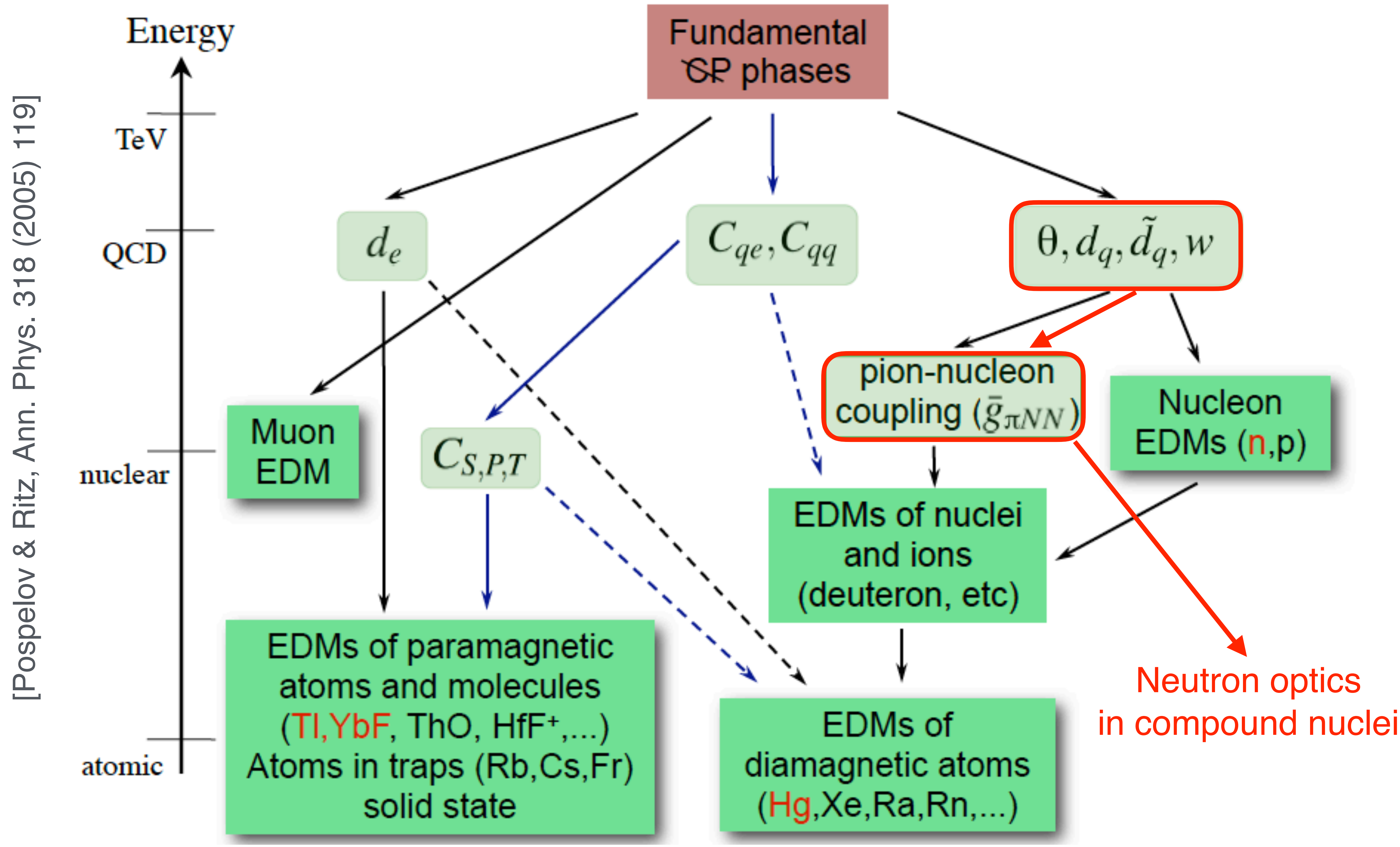
currently for the neutron d_n<3×10^{-26} e·cm

Hierarchy of CP-odd parameters



[Pospelov & Ritz, Ann. Phys. 318 (2005) 119]

Hierarchy of CP-odd parameters



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T violation in p-wave neutron resonances in heavy nuclei

NOPTREX (Neutron Optics Time Reversal Experiment)

For low-energy neutrons ($kR \ll 1$), the neutron-nucleus interaction can be treated within the framework of neutron optics

$$V_F = \frac{2\pi\hbar^2}{m_n} Nf \quad \leftarrow \text{Fermi potential}$$

with m_n the neutron mass, N the number of scattering centers per unit volume and f the forward scattering amplitude (zero angle elastic scattering)

$$f = a_0 + b_0(\vec{\sigma}\cdot\vec{I}) + c_0(\vec{\sigma}\cdot\vec{k}) + d_0[\vec{\sigma}\cdot(\vec{k}\times\vec{I})]$$

where $\vec{I}$ is the polarization of the target and $\vec{\sigma}$ is the neutron spin

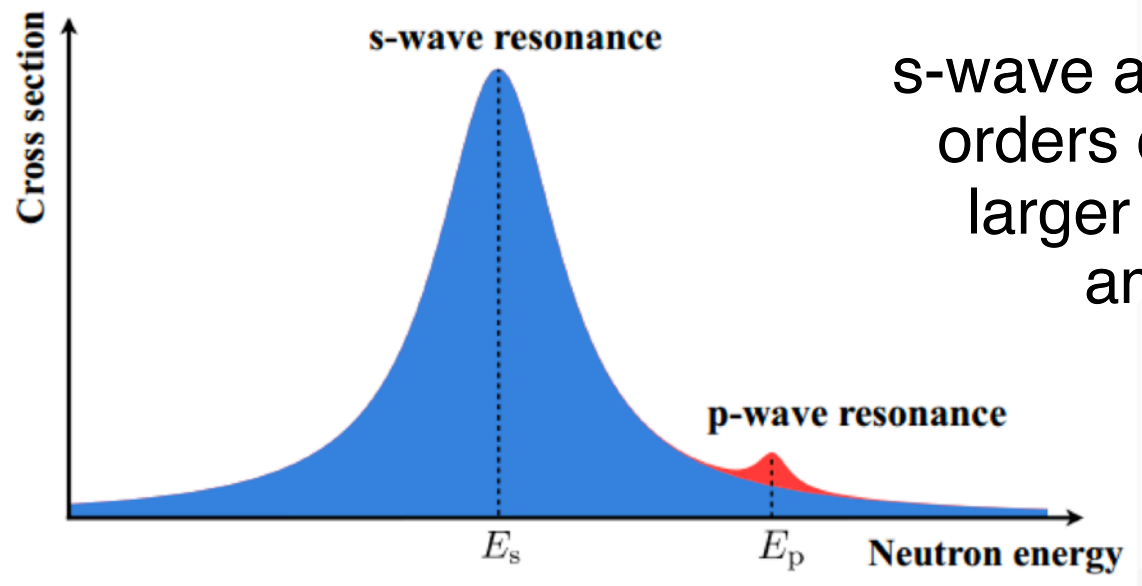
The P-odd amplitude $[c_0(\vec{\sigma}\cdot\vec{k})]$ has been measured in many nuclear systems, with amplifications by factors of 10^5-10^6 due to symmetry mixing in the compound nuclear resonances. [G.E. Mitchell et al. Phys. Rep. 354 (2001) 157]

Enhancement of P-odd (and P, T-odd effects) in p-wave compound resonances

$$P \sim \frac{W_{sp}}{E_s - E_p}\sqrt{\frac{\Gamma^n_s}{\Gamma^n_p}}$$

- A three orders of magnitude enhancement is due to the fact that in a nucleus excited by neutron capture the interval between the chaotic compound states (resonances) of opposite parity is very small.

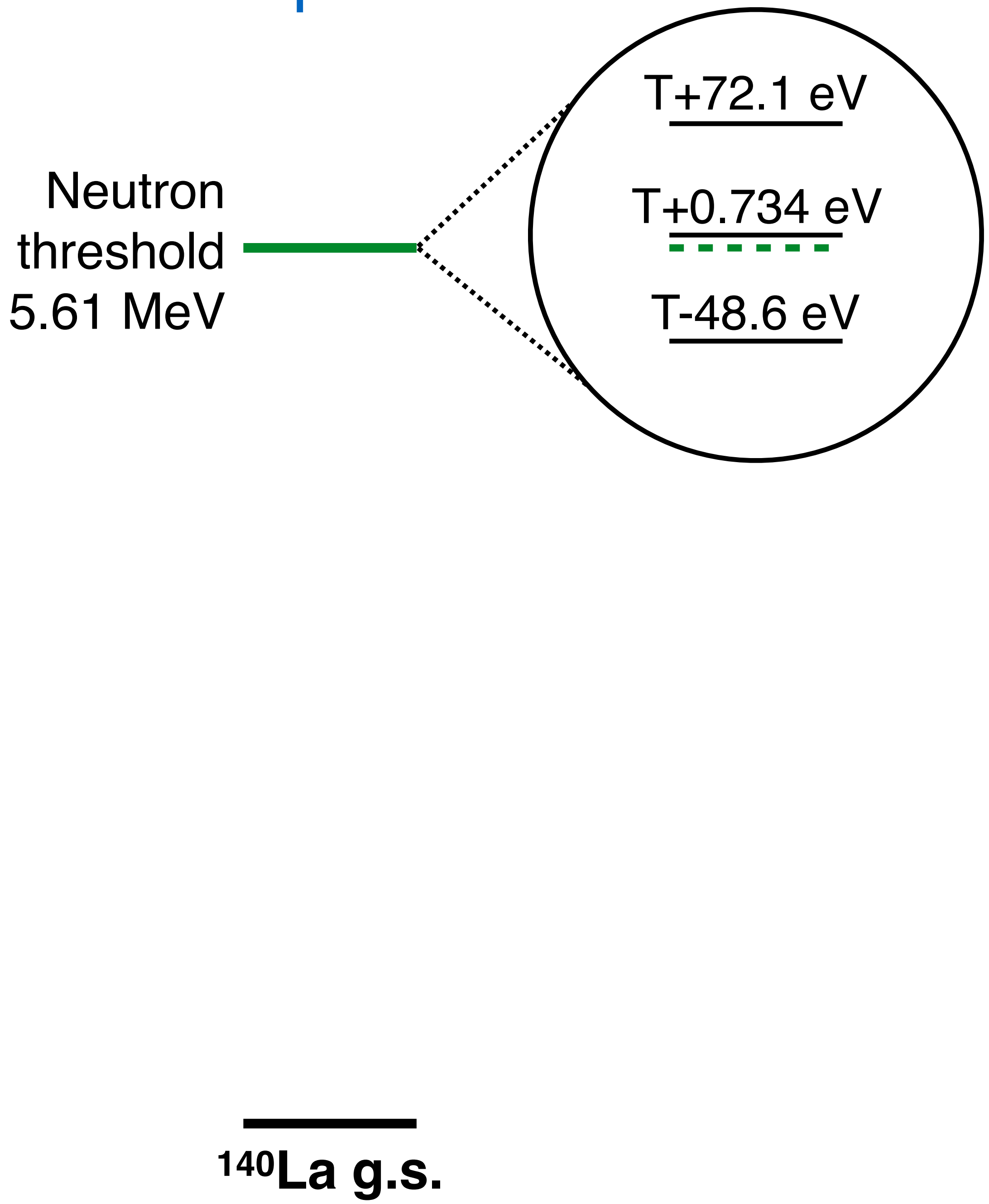
- Admixture of opposite parity states allows the s-wave neutron capture to the p-wave resonance.

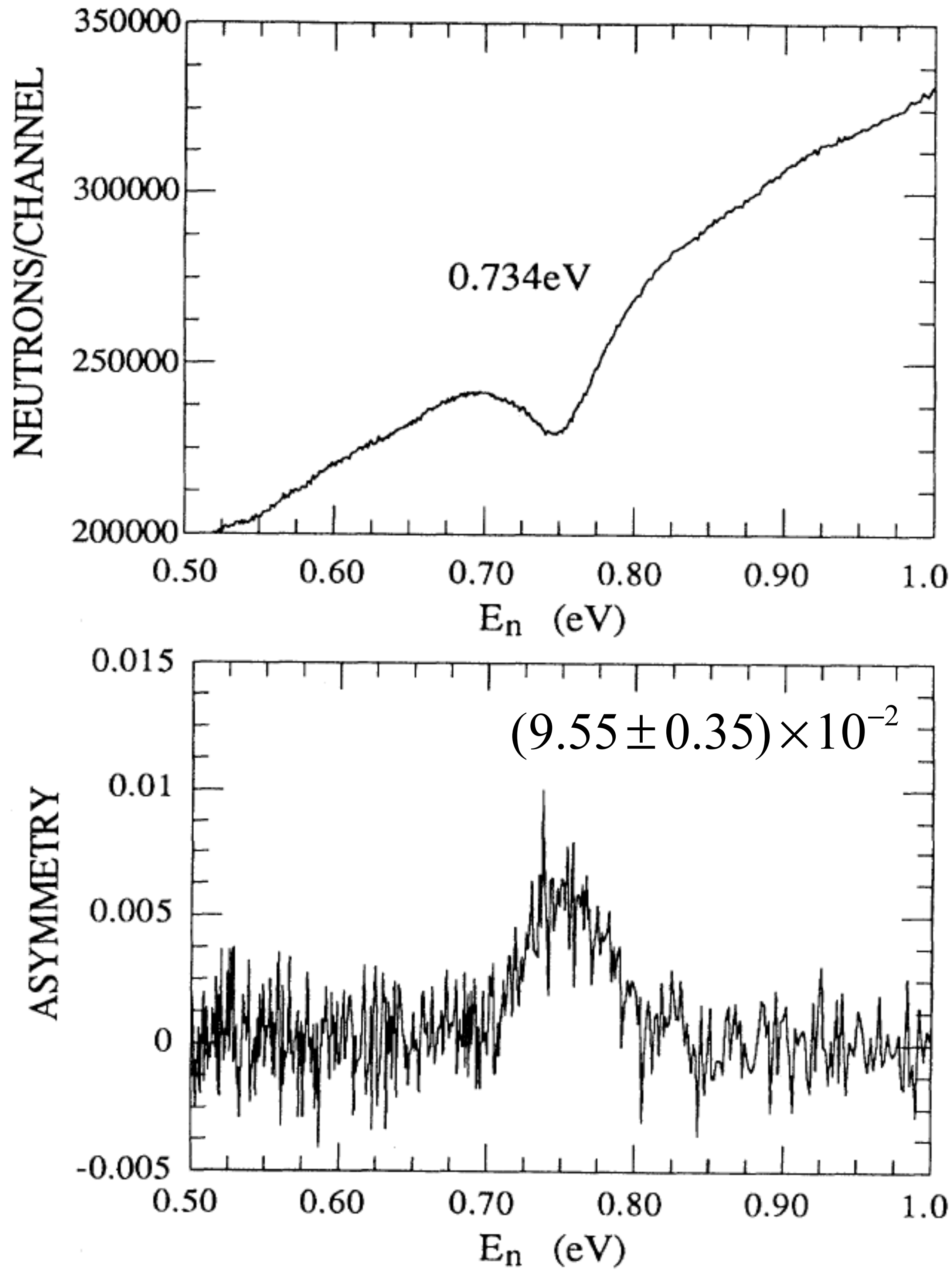


s-wave amplitude three orders of magnitude larger that p-wave amplitude

^{139}La+n system

P-odd amplitude





[V.W. Yuan et al. Phys. Rev. C 44 (1991) 2187]

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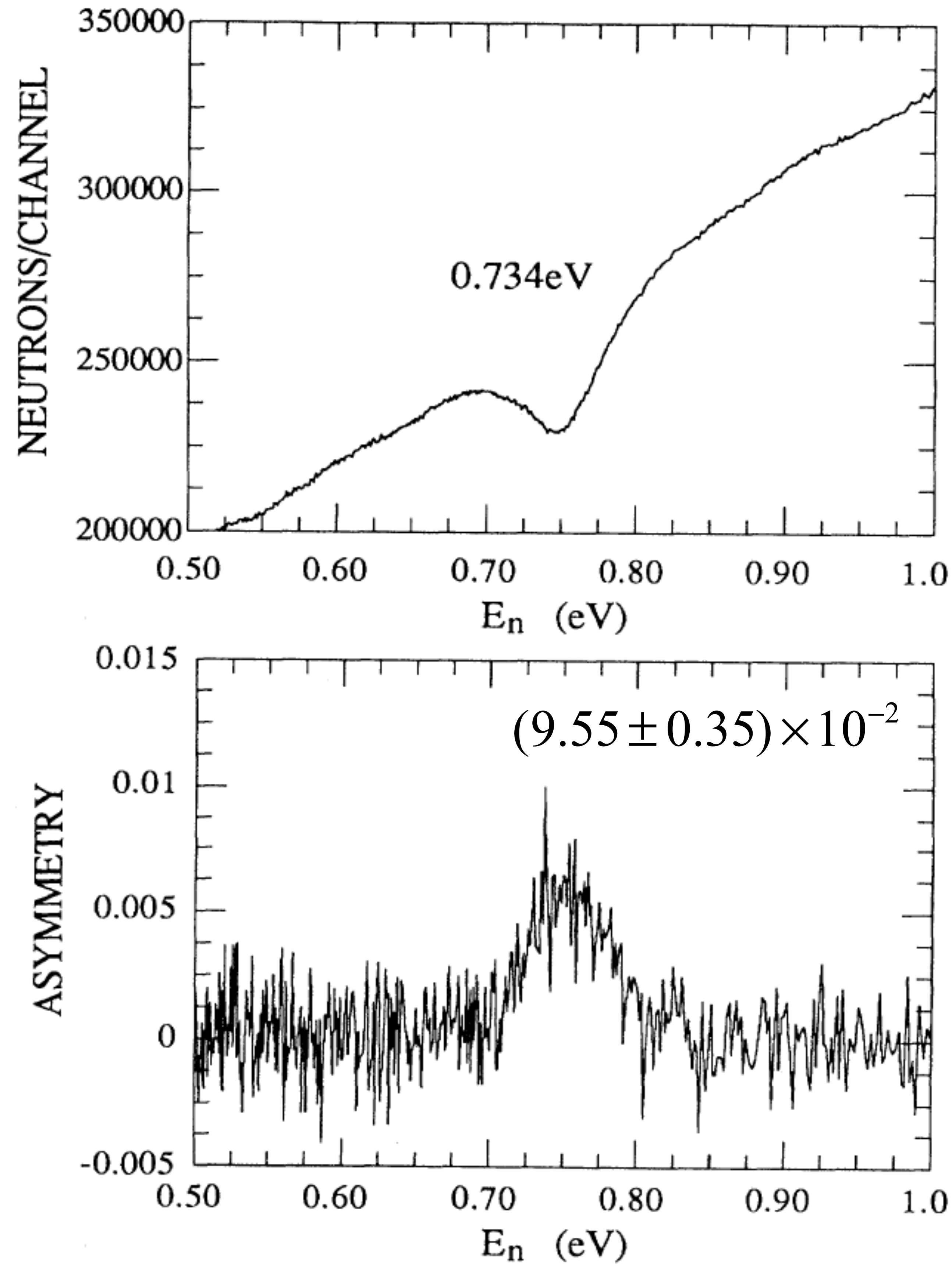
^{139}La+n system

P-odd amplitude

- Highly excited states where residual interaction between particles exceeds the interval between the energy levels.

^{140}La g.s.



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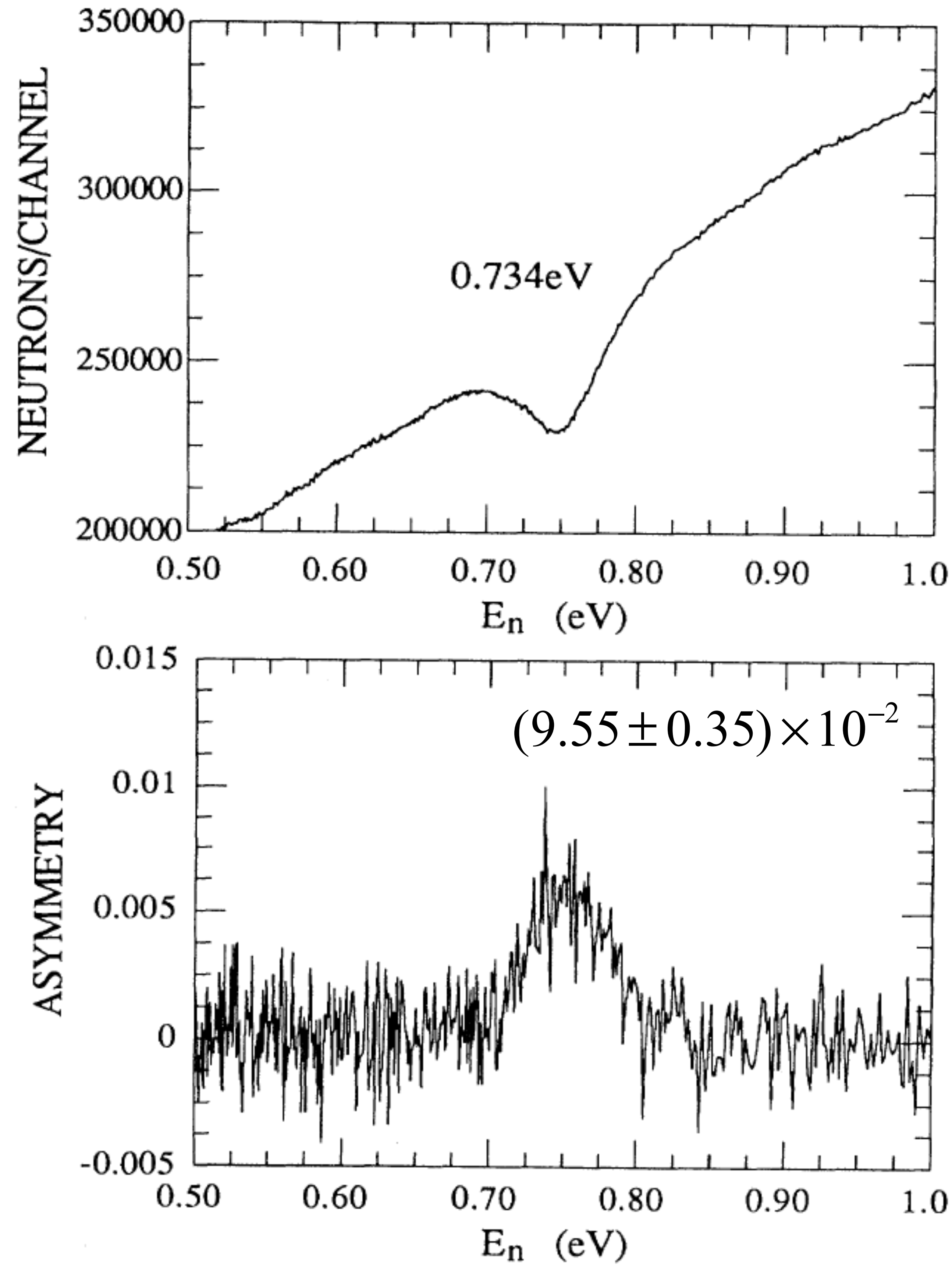
P-odd amplitude

- Highly excited states where residual interaction between particles exceeds the interval between the energy levels.
- Eigenstates are superposition of thousands or millions of Hartree-Fock basic states.



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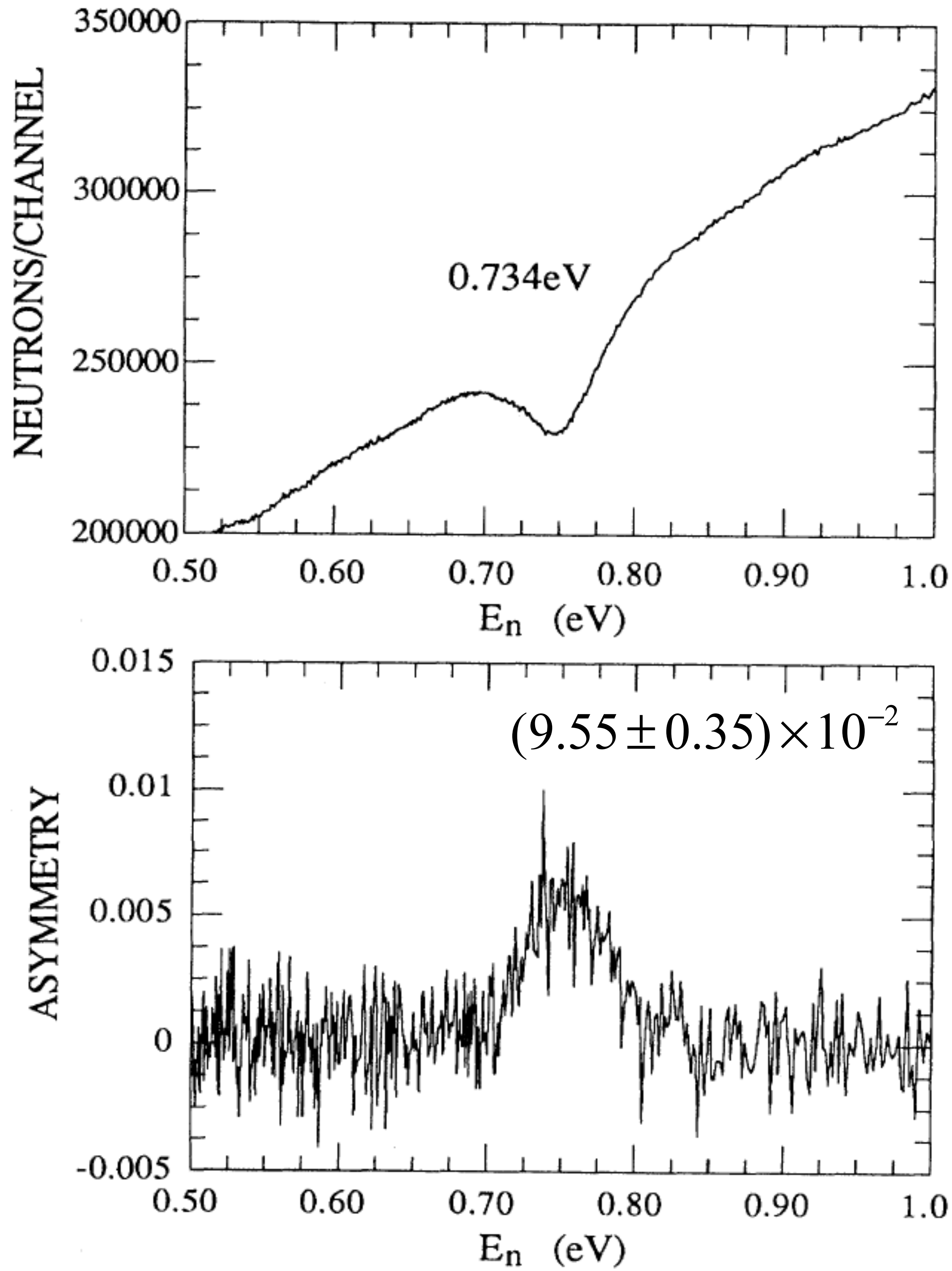
^{139}La+n system

P-odd amplitude

- Highly excited states where residual interaction between particles exceeds the interval between the energy levels.
- Eigenstates are superposition of thousands or millions of Hartree-Fock basic states.
- Heavy nuclei with an open f-shell have chaotic compound resonances.



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T violation in p-wave neutron resonances in heavy nuclei

- The TRIV and PV effects correspond to the real and imaginary part of the same matrix element (calculated with exactly the same wave functions), therefore it is expected that the TRIV effects would have the same enhancement on resonance as the PV ones. Both effects are produced by the PV interaction.

- Because the neutron optics effects in this case involve elastic scattering at zero angle, the initial and final state coincide and therefore there are no Final State Interactions (FSI) that can mimic T-odd correlations originated from TRIV interactions.

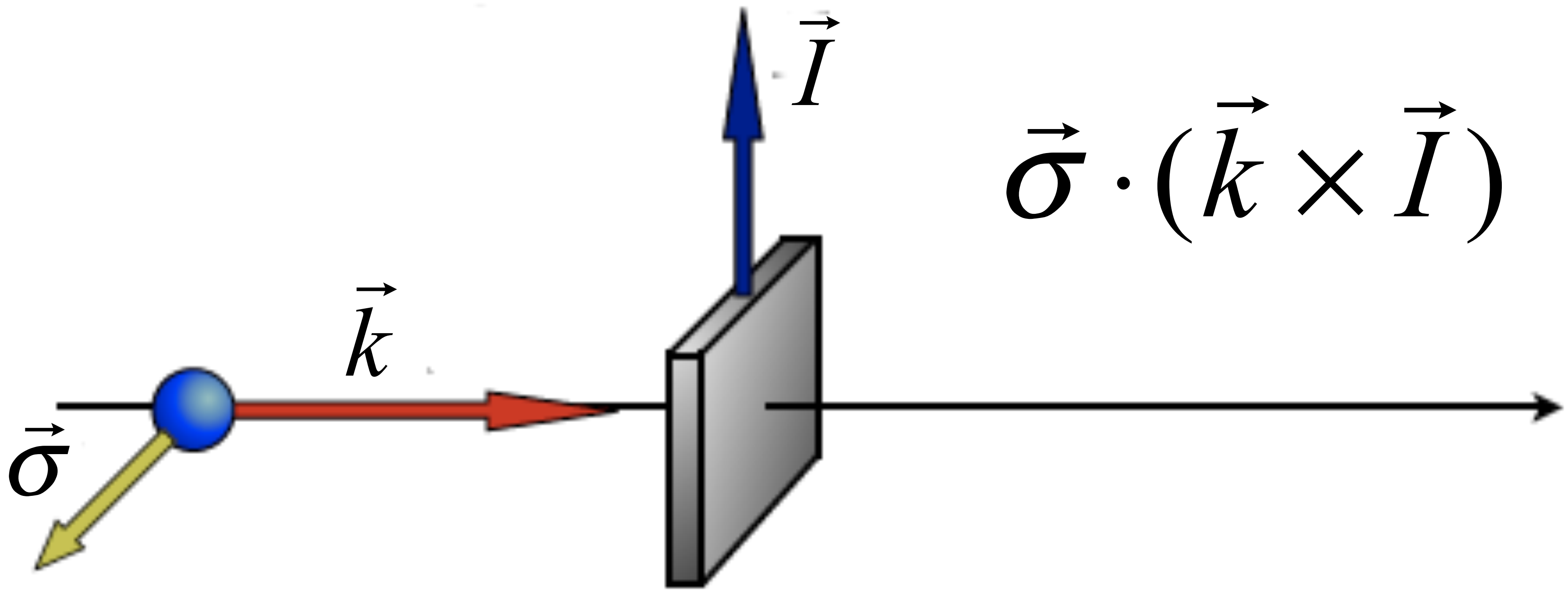
- TRIV effects in neutron transmission on compound nuclei resonances constitute a null test for T invariance.

- The search for TRIV effects in resonances of compound nuclei expands the variety of nuclear systems available (^{139}La, ^{131}Xe, ^{81}Br,…), helping to provide assurance that possible "accidental" cancelation of TRIV effects due to unknown structural factors in particular systems can be avoided.

T violation in p-wave neutron resonances in heavy nuclei

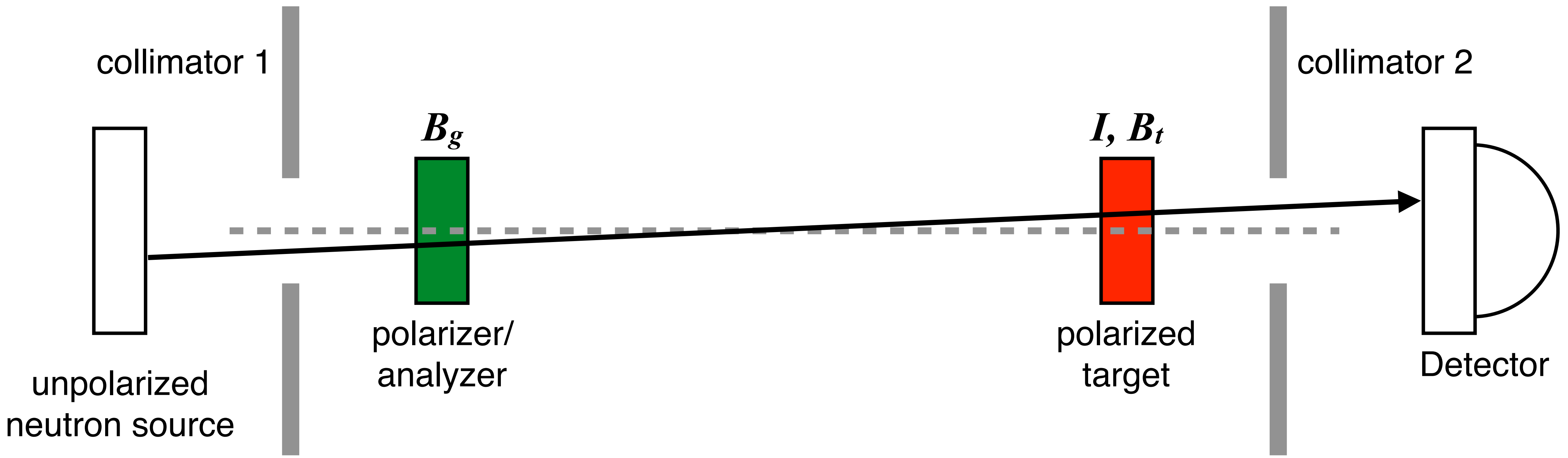
In practice…

$$f = a_0 + b_0(\vec{\sigma}\cdot\vec{I}) + c_0(\vec{\sigma}\cdot\vec{k}) + d_0[\vec{\sigma}\cdot(\vec{k}\times\vec{I})]$$



Measurements of TRIV in this systems is very sensitive to the alignment of the relevant vectors, which are very difficult to control to the required precision.

Model experiment to search for TRIV in resonances of compound nuclei



[Bowman & Gudkov, Phys. Rev. C 90 (2014) 065503,
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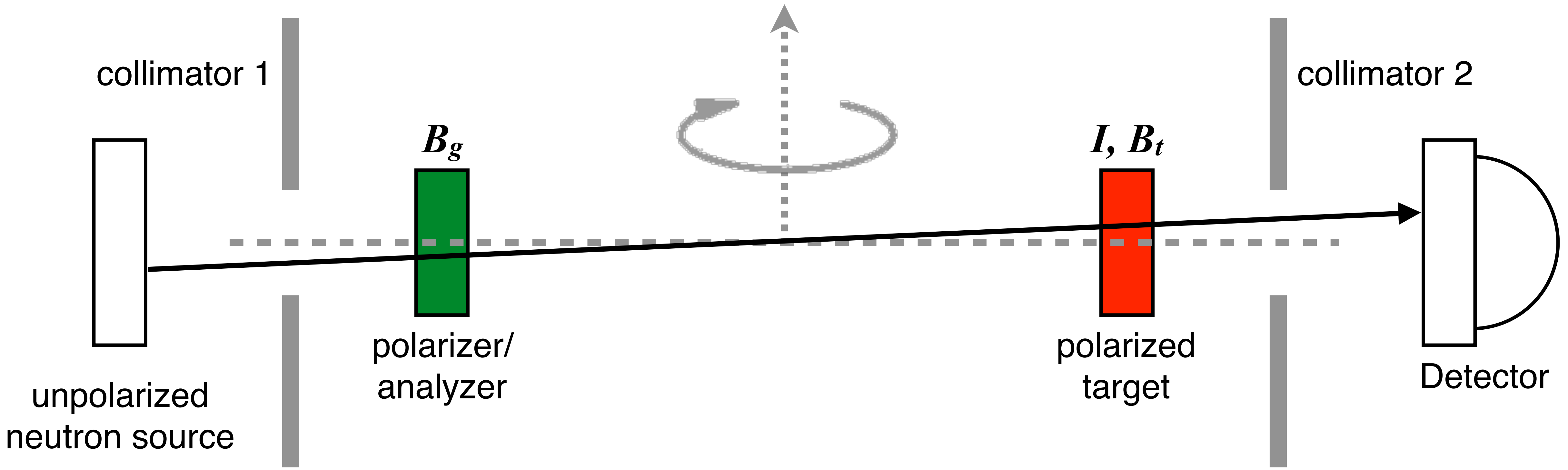

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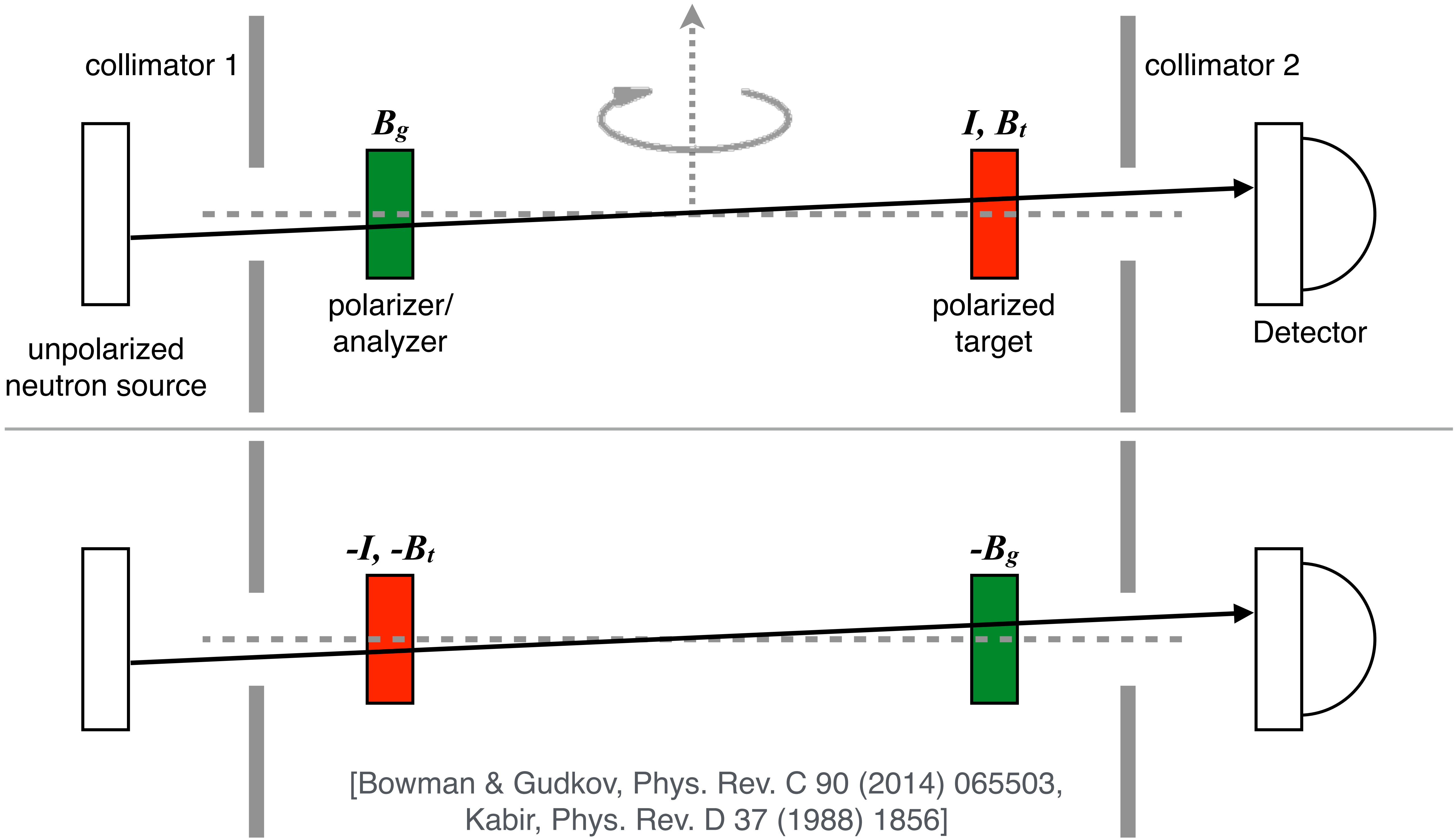

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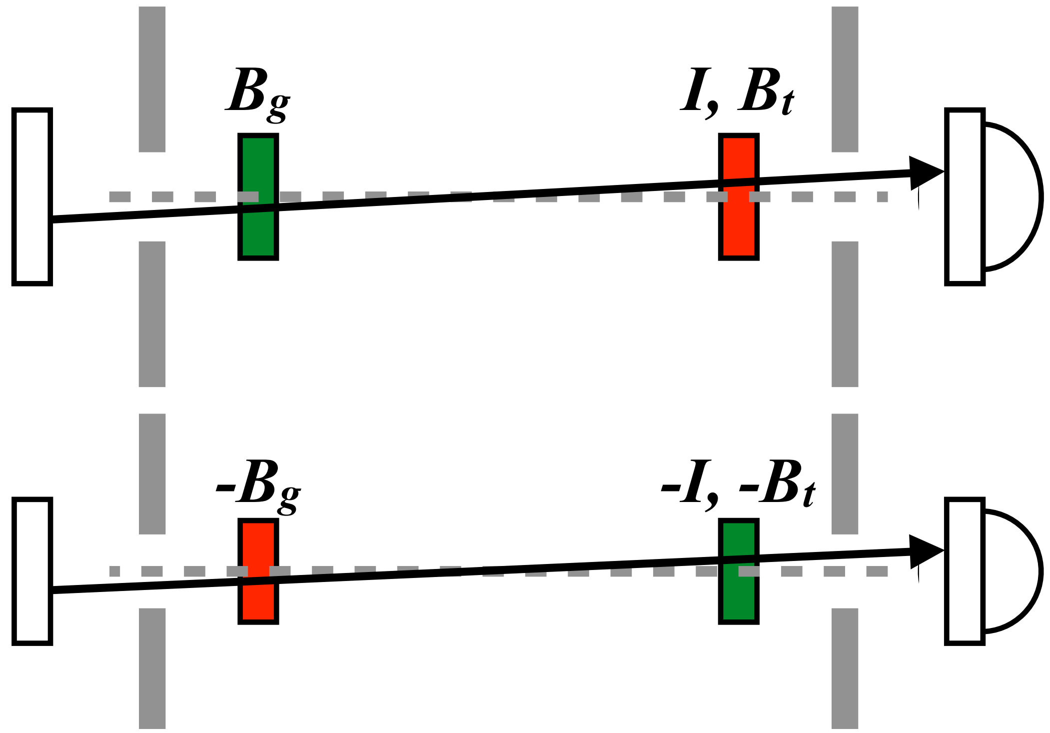


TRIV theorem

[Bowman & Gudkov, Phys. Rev. C 90 (2014) 065503]

$$H = \frac{2\pi\hbar^2}{m_n} Nf - \frac{\mu}{2}(\vec{\sigma}\cdot\vec{B})$$

$$f = a_0 + b_0(\vec{\sigma}\cdot\vec{I}) + c_0(\vec{\sigma}\cdot\vec{k}) + d_0[\vec{\sigma}\cdot(\vec{k}\times\vec{I})]$$

If d_0=0 and the apparatus is rotated, with $\vec{I}$ and $\vec{B}$ being reversed, then the transmission of neutrons in both states are equal.

Any deviation from the equality in the forward and reversed transmission is a clear manifestation of TRIV interactions (nonzero d_0 coefficient).

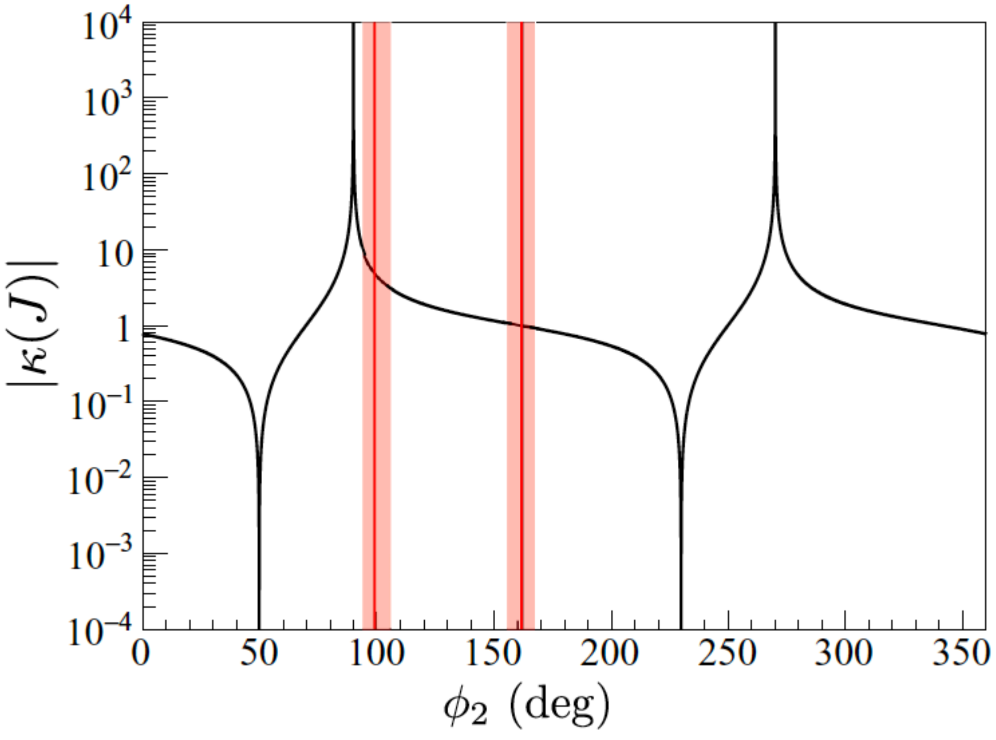
Sensitivity to CP-odd sources: discovery potential

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_{P}} = \kappa(J)\frac{\langle \psi_p | W_{PT} | \psi_s \rangle}{\langle \psi_p | W_P | \psi_s \rangle}$$

$$\kappa(I+1/2) = -\frac{3}{2^{2/3}}\left(\frac{2I+1}{2I+3}\right)^{3/2}\left(\frac{3}{\sqrt{2I+3}}\gamma - \sqrt{I}\right)^{-1}$$

$$\kappa(I-1/2) = -\frac{3}{2^{2/3}}\left(\frac{2I+1}{2I-1}\right)\left(\frac{I}{I+1}\right)^{1/2}\left(-\frac{I-1}{\sqrt{2I-1}}\frac{1}{\gamma} + \sqrt{I+1}\right)^{-1}$$

$$\gamma = \left[\frac{\Gamma_p^n(I+1/2)}{\Gamma_p^n(I-1/2)}\right]^{1/2}$$



Recent γ-ray angular correlation measurements in radiative neutron capture on ^{139}La yield $\kappa(J) \sim 1$

[Okudaira et al., Phys. Rev. C 97 (2018) 034622]

Sensitivity to CP-odd sources: discovery potential

Using the theory of chaotic nuclear compound resonances the ratio w/v has been recently calculated

[P. Fadeev and V.V Flambaum, arXiv: 1903.0893v1 (21 Mar 2019)]

$$v = \sqrt{\overline{\langle \psi_p | W_P | \psi_s \rangle \langle \psi_s | W_P | \psi_p \rangle}}$$

$$w = \sqrt{\overline{\langle \psi_p | W_{PT} | \psi_s \rangle \langle \psi_s | W_{PT} | \psi_p \rangle}}$$

- In terms of the constants of the contact nuclear interaction
- In terms of the meson exchange constants
- In terms of the QCD-θ term
- In terms of the chromo EDMs $\tilde{d}_u$ and $\tilde{d}_d$

Sensitivity to CP-odd sources: discovery potential

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$$\frac{w}{v} = 0.10 \cdot \sqrt{\eta_n^2 + 0.76\eta_p^2} \qquad |\eta_p| = |\eta_n| \qquad \frac{w}{v} = 0.13|\eta_n|$$

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$$-\eta_p = \eta_n = 5 \cdot 10^6 \bar{g} \left(\bar{g}_1 + 0.4\bar{g}_2 - 0.2\bar{g}_0\right)$$

$$\frac{w}{v} = 0.13|\eta_n| = |6.5 \cdot 10^5 \bar{g} \left(\bar{g}_1 + 0.4\bar{g}_2 - 0.2\bar{g}_0\right)|$$

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$$\bar{g}\bar{g}_0 = -0.2108\theta\,, \quad \bar{g}\bar{g}_2 = 0, \qquad \bar{g}\bar{g}_1 = 46.24 \cdot 10^{-3}\theta$$

$$\frac{w}{v} = 5.7 \cdot 10^4|\theta|$$

$$|\theta| < 10^{-10} \qquad w/v < 10^{-5}$$

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$$\bar{g}\bar{g}_1 = 4 \cdot 10^{15}\left(\tilde{d}_u - \tilde{d}_d\right)/\text{cm}\,, \qquad |\tilde{d}_u - \tilde{d}_d| < 6 \cdot 10^{-27}\text{cm}\,,$$

$$\bar{g}\bar{g}_0 = 0.8 \cdot 10^{15}\left(\tilde{d}_u + \tilde{d}_d\right)/\text{cm} \qquad |\frac{1}{2}\tilde{d}_u + \tilde{d}_d| < 3 \cdot 10^{-26}\text{cm}\,,$$

$$w/v < 2 \cdot 10^{-5}$$

Sensitivity to CP-odd sources: discovery potential

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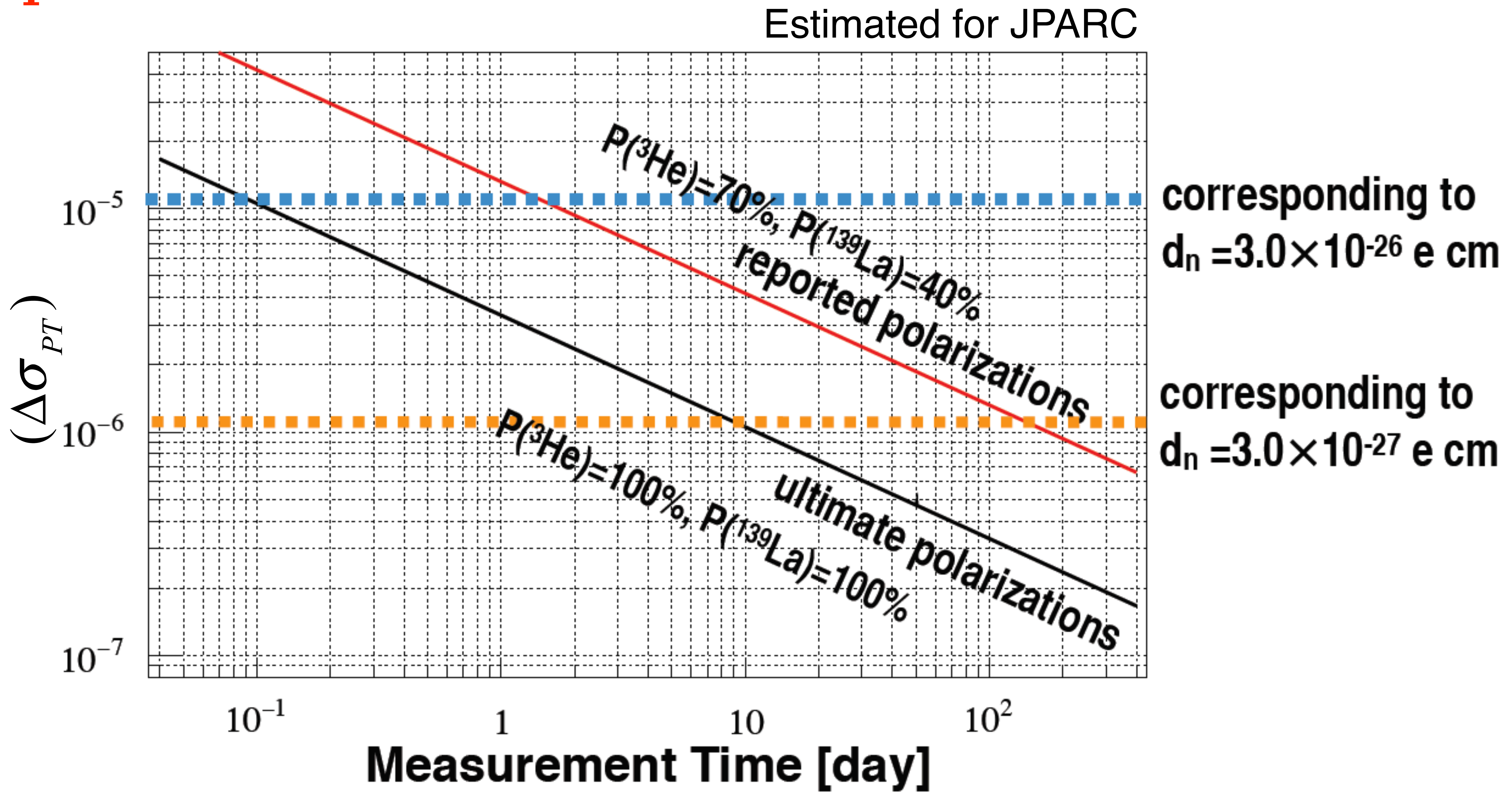
$$w/v < 2 \cdot 10^{-5}$$

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} \lesssim 2 \cdot 10^{-5} \qquad \frac{\Delta\sigma_{PT}}{\Delta\sigma_P}_{exp.sensitivity} < 10^{-6}$$

Sensitivity to CP-odd sources: discovery potential



Slide by H.M. Shimizu

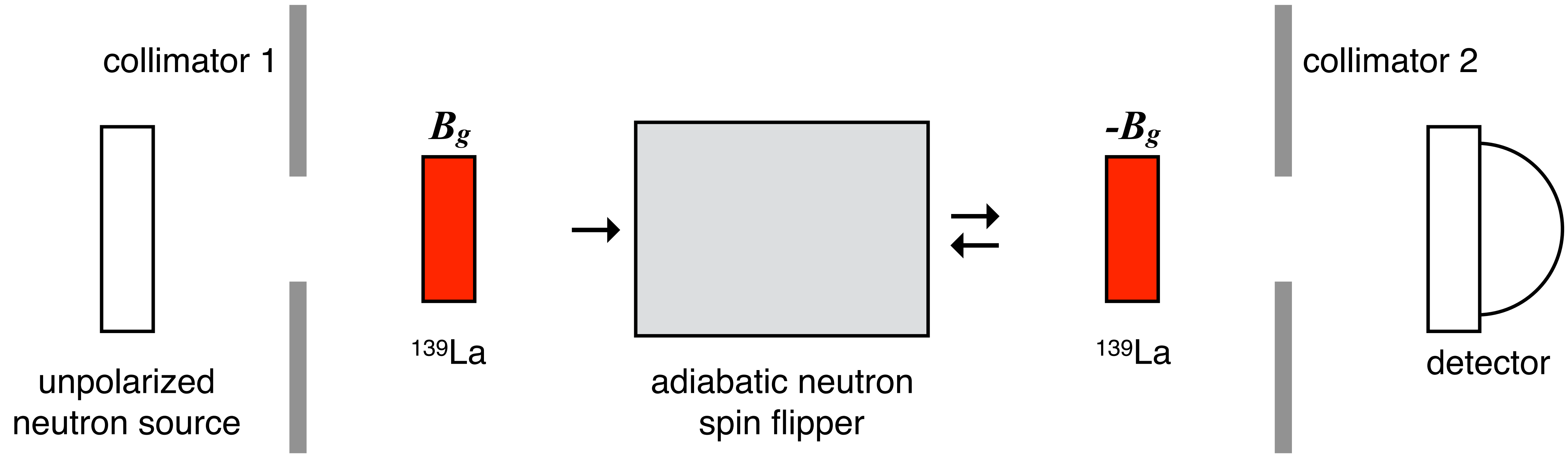
Complementarity of TRIV searches

- EDMs are ground state properties, while highly excited states in heavy nuclei are involved in neutron optics TRIV effects, which offer a quantitatively different environment with different sensitivity to the many possible sources of CP violation.

- Any single type of TRIV search cannot be equally sensitive to all possible CP violation mechanisms, so it is essential to pursue any experiments in different systems which can be realized with sufficient sensitivity.

Ongoing and future efforts

Improved precision on ^{139}La PV asymmetry



- Currently taking place al FP12 of LANSCE
- 1% accuracy goal (currently almost 4%)

Ongoing and future efforts

Polarizer for epithermal neutrons

- Epithermal neutron polarizers based on ^{3}He spin filters have been developed. Polarizations of the order of 70% can be achieved.

Targets of heavy nuclei and their polarization

- In the fall of 2018 we plan to perform precision PV asymmetry measurements on ^{81}Br (0.88 eV resonance) and ^{131}Xe (3.2 eV resonance), making use of a ^{3}He neutron polarizer. Searches for PV effects in other nuclei (^{235}U for example) are also planned with this setup.
- A proposal has been submitted to LANSCE to search for P-odd effects in never-measured heavy nuclei (Tl, Ir, Re, W, Ta, Hf, Tm, Er, Ho, Dy, Tb, Gd, Eu, Sm, Om, Nd, Ba, Te, Rh, Mo, Sr, As, Co and Mn) using polarized epithermal neutrons.
- Progress has been made in obtaining polarized ^{139}La targets (KEK, Kyoto U., PSI). Polarizations of the order of 40% have been achieved in lanthanum aluminate crystals.
- The SIU group is working on considerable improvements in ^{131}Xe polarized cells.

Conclusions

- Neutron optics on p-wave resonances in compound nuclei offer a possibility to search for TRIV effects. These effects are free of FSI and constitute a null test for T invariance.

- TRIV effects, just as PV effects, can be enhanced by a factor of 10^6 in compounds nuclei, due to symmetry mixing on the resonance. This creates a potential for TRIV effects in nuclear resonances to be sensitive enough to improve the constraints on TRIV meson-nucleon couplings.

- TRIV in neutron optics experiment are complementary to EDMs since they constitute quantitatively different systems and can, in principle, access different sources CP violation.

- A complicated theoretical landscape makes it important to perform experiments with different sensitivities to possible CP violation sources.

NOPTREX collaboration

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SIU Southern Illinois University CARBONDALE

THE UNIVERSITY OF BRITISH COLUMBIA

INDIANA UNIVERSITY

OAK RIDGE National Laboratory

山形大学 YAMAGATA UNIVERSITY

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