Time Reversal Violating Resonance Energy Shifts Revisited

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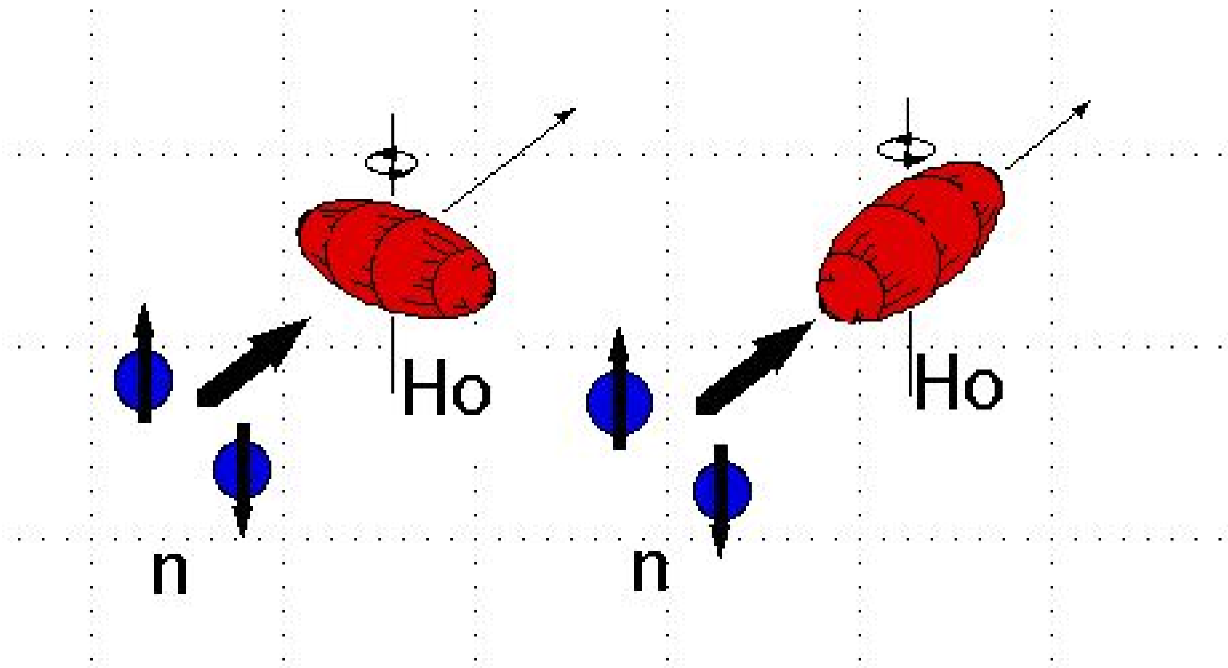
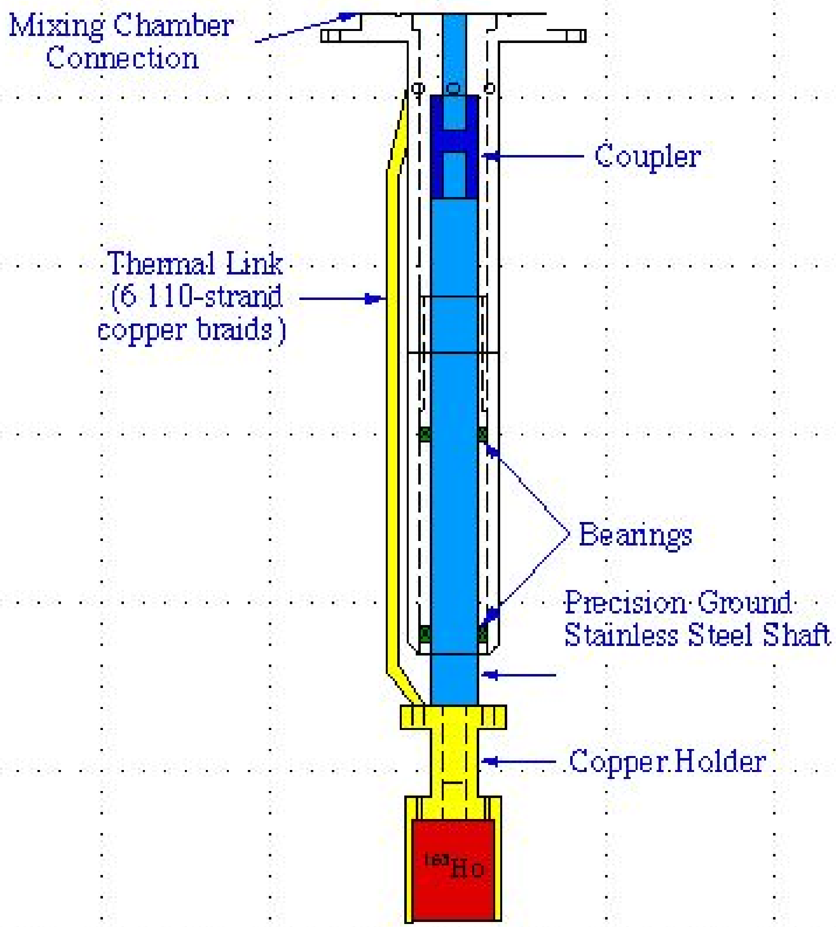
Outline

- ***Polarized neutron transmission tests of TRV***
- ***TRV and resonance energy spacings –early work***
- ***Polarized neutron capture energy shifts – another way?***
- ***T even "fake" energy shifts***
- ***Statistical issues and ultimate bounds***

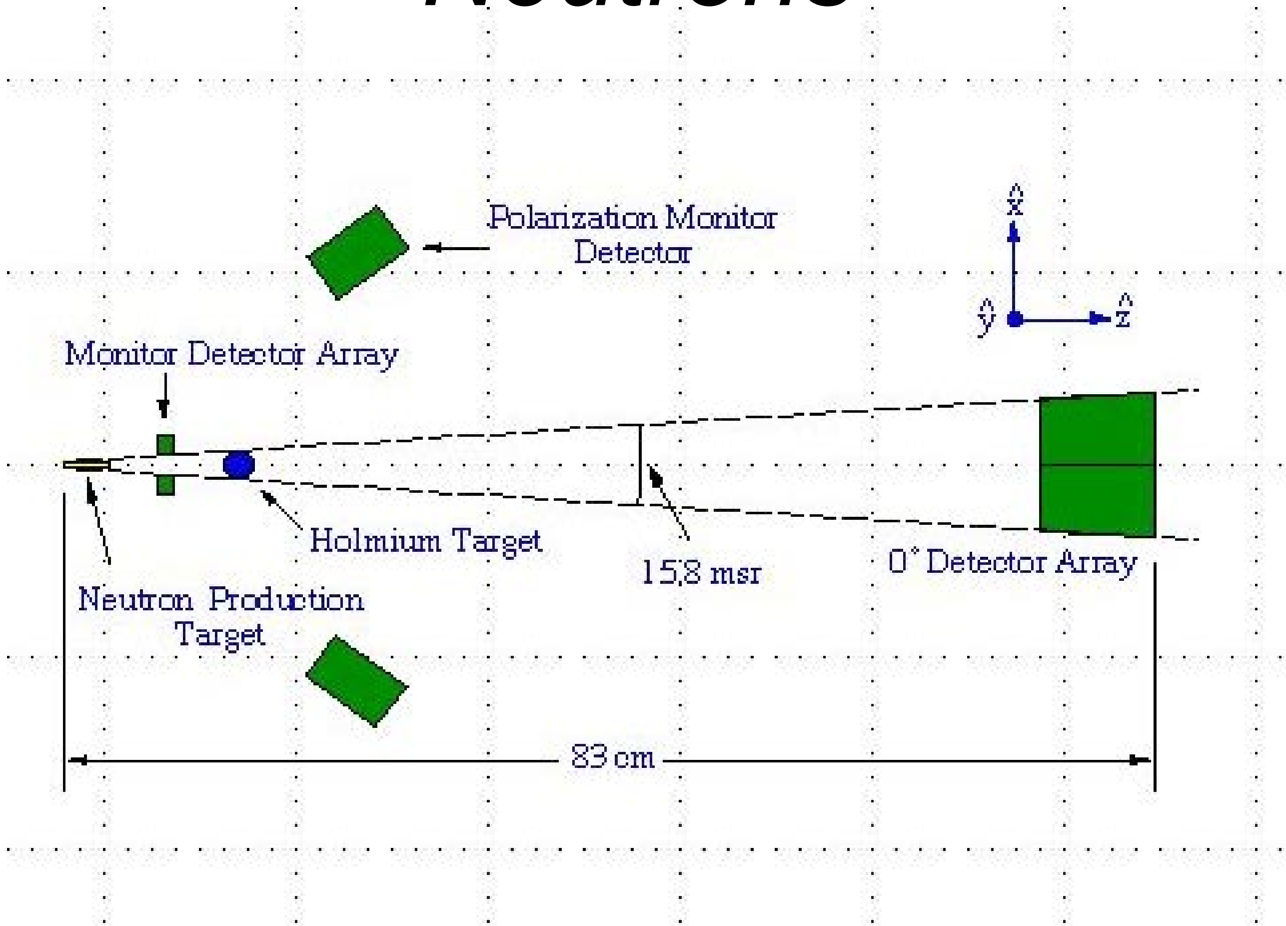
FC Test with polarized neutrons and aligned holmium nuclei



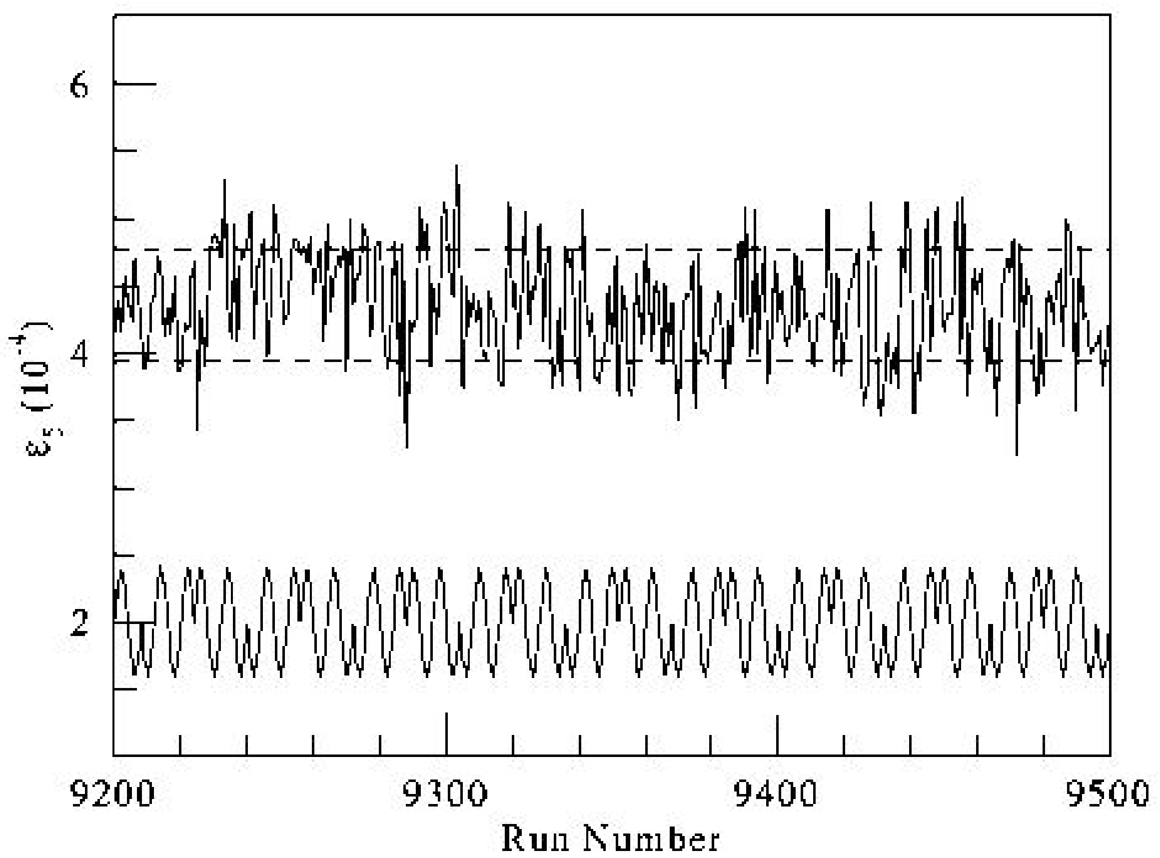
Mounting Apparatus



TUNL FC Test with 6 MeV Neutrons



P-even TRV transmission asymmetry



Results for MeV neutron tests

TC (89) 7,11 MeV $\varepsilon \leq 10^{-3}$

FC (91,97) 6 MeV $\varepsilon = 1.1 \pm 1.0 \times 10^{-6}$ *(400×TDB)*

1/A suppression $\rightarrow$ $\breve{g}_{\rho} = 2.3 \pm 2.1 \times 10^{-2}$

edm's rule, but for a P-even TRV scenario where they set no bounds, see Kurylov et al (PR D63, 2001)

COSY plans 200 MeV test in p-d scattering (2004)

Why no resonance tests?

- *TC – sequential interactions mimic the signal: strong rotation by F_M followed by weak attenuation by F_P –target problem*

- *FC – sequential interactions not a problem: need a beam line and a holmium target!*

- *"for whatever reason this field has been dead in the water for some time" (R. Golub on edm's)*

Is there another way?

- *T-odd energy shifts in neutron capture correlations*
- *Do not need a polarized target!*
- *P-odd with polarized neutrons (Flambaum and Sushkov 85)*
- *P-even with unpolarized neutrons (Barabanov 93)*
- *But (caution) not a null test*

Early ideas on P-even TRV from energy level spacings

French et al (87) shell model study of GOE versus GUE:

H = H + i U, = |<v$_t$>/<v>| ratio of residual interaction 2 body matrix elements

=0 : GOE (no T-violation)
=1 : GUE (maximal T-violation)

From analysis of Th energy levels, they conclude

$\leq 2\times10^{-3}$ *(99% CL)* => $\breve{g}_\rho \leq 2\times10^{-1}$

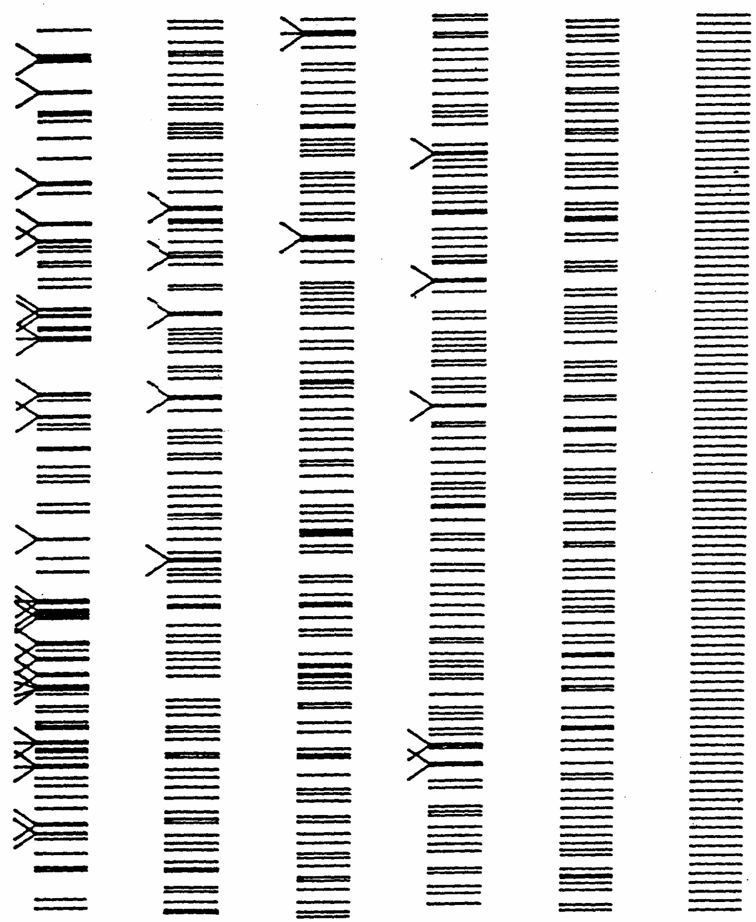
where $\breve{g}_\rho \approx$ *Haxton et al 94), is dimensionless ratio of T-odd to T-even ρ coupling constants*

Match the spectra contest!

- Six spectra* – only one is "real"

1. Poisson
2. Uniform
3. GOE
4. GUE -
5. Shell model study of (s-d)6 2+ levels
6. Thorium

*Thanks to A. Pandey



Only #3 is real

P-even TRV energy shift study from Dubna

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Testing *T*-Odd, *P*-Even Interactions with γ Rays from Neutron *p*-Wave Resonances

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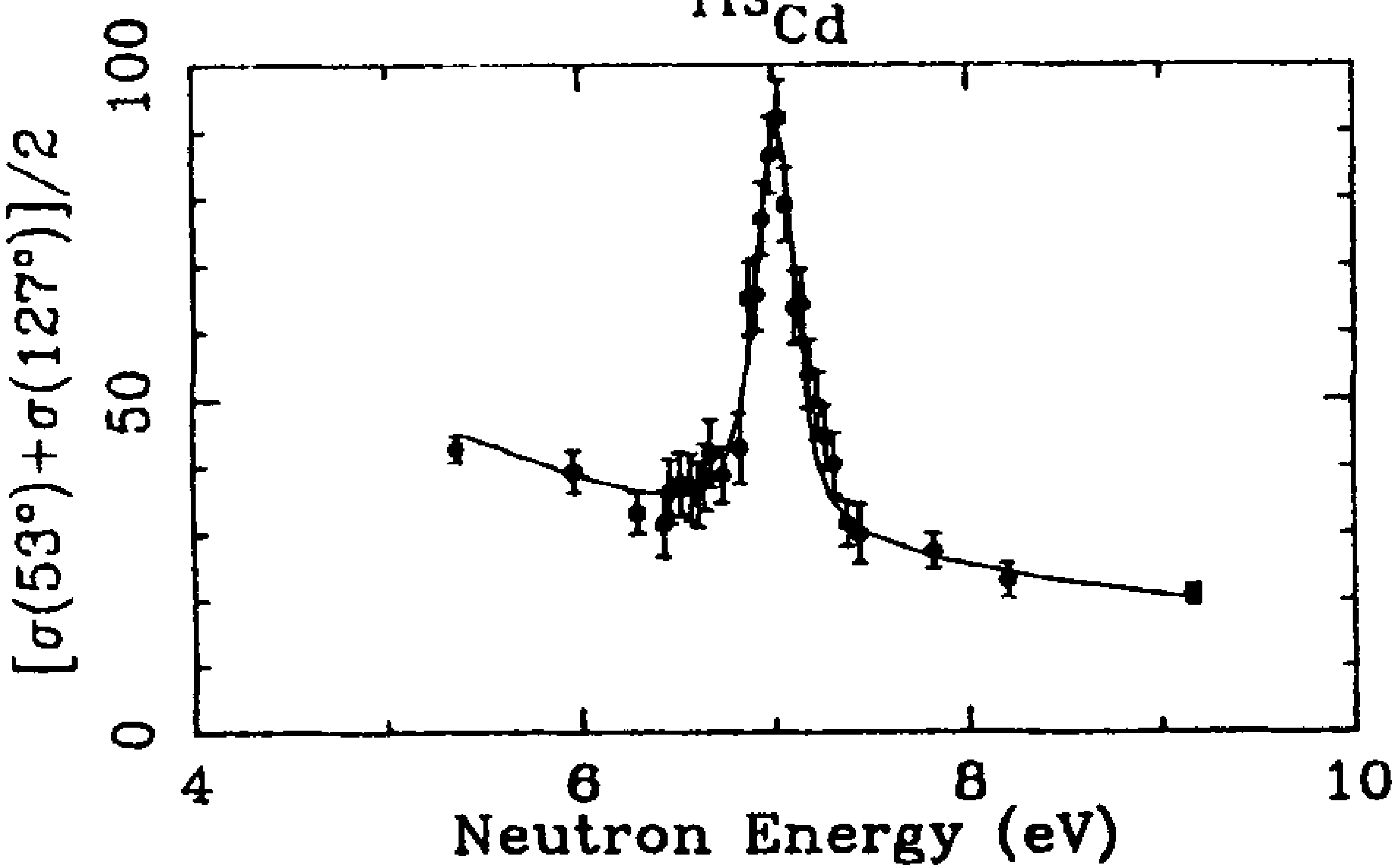
(Received 13 October 1992)

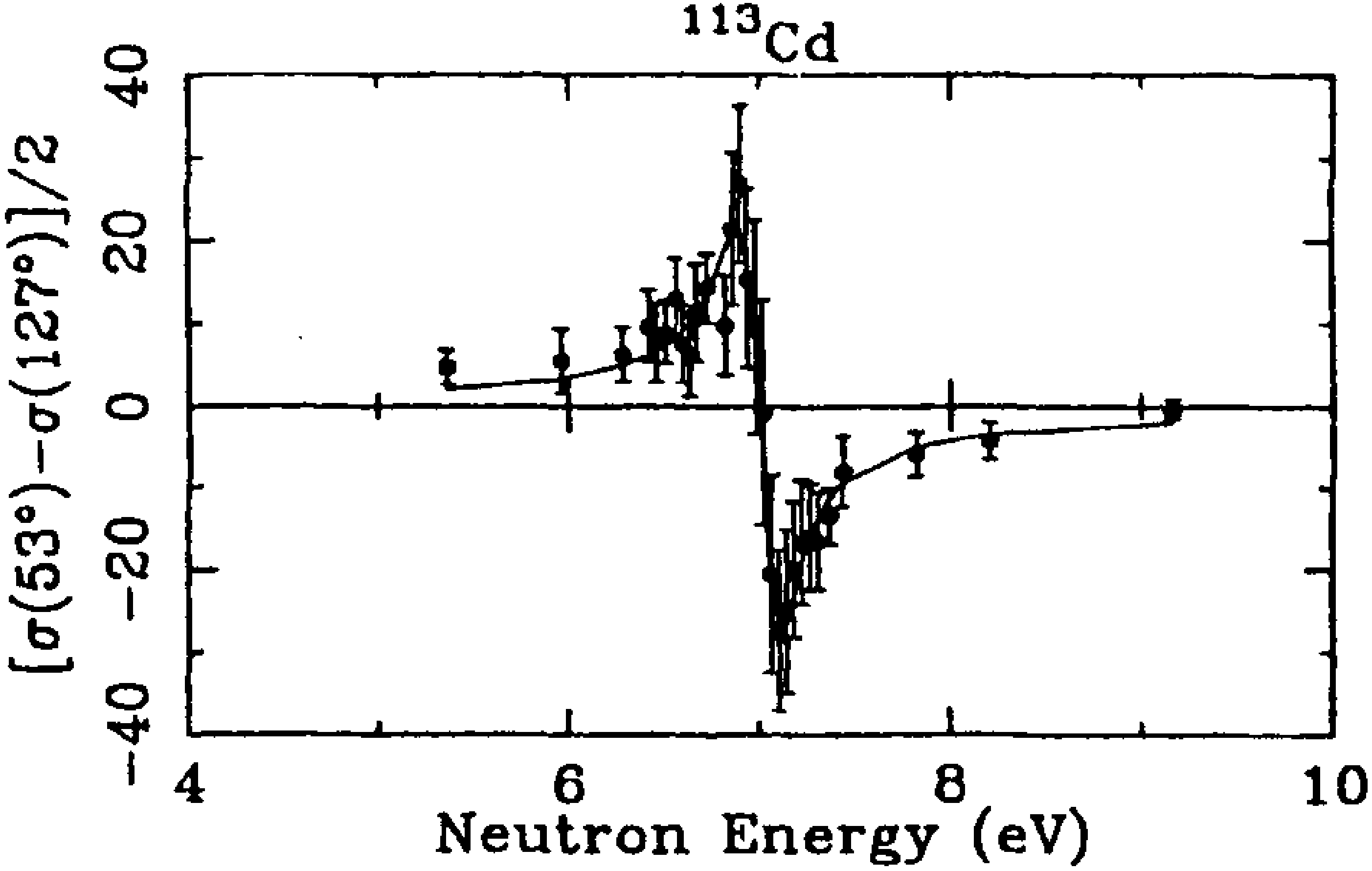
A new method for the study of time reversal violation is described. It consists of measurements of the forward-backward asymmetry in individual gamma-ray transitions resulting from unpolarized neutron capture in *p*-wave resonances. An experiment with a ^{113}Cd target performed at the Dubna pulsed neutron source has been analyzed and a limit on the time reversal odd, parity even interaction extracted. The possibility of experiments using the powerful pulsed neutron source at Los Alamos is considered.

PACS numbers: 25.40.Ny, 11.30.Er

Resonance energy from the yield curve



Zero crossing of the fore-aft asymmetry



Results in 113Cd

- $E = 7.0412 \pm 0.0073$ eV
- $\Delta E = -0.0016 \pm 0.0062$ eV

- Conclusion is $\alpha < 10^{-4}$ (good precision)

- But single case, so difficult to draw a statistically meaningful bound

Energy shift signature of P-odd TRV

F and S proposal NP A435(84) p 363

Seventeen angular and polarization correlations (8 P-even 7 P-odd) in (n,) reactions near threshold (s and p waves, E1 and M1 amplitudes), coefficients a_i.

Focus on $\boldsymbol{s_n}$ $\boldsymbol{k}$ *ray asymmetry with a transversely polarized neutron beam (cf NPDG apparatus) at a p-wave resonance showing large P violation*

P-odd TRV energy shift

Given the ratio of T-odd to T-even matrix elements

$= |\langle s|v_{pt}|p\rangle / \langle s|v_p|p\rangle|$

Then TRV shifts the zero crossing of the correlation term from $E=E_p$ *by an amount proportional to*

$a_9 \sim Re\ 1/(E - E_p + i\ \ {}_p/2) + \quad Im\ 1/((E - E_p + i\ \ {}_p/2)$

Also true for circular polarization measured with an unpolarized beam

FS conjecture is surprising- is it true?

Revisit this issue by considering in order:

Two resonance model
Complex phases for neutron and -ray
Role of distant states
Statistical issues
Experimental issues

In FS notation, focus on $a_9^{'} = a_9 - a_{12}/3$

Main conclusion: result is correct, but what are limitations?

Assume equal s and p wave amplitudes at $E=E_p$ *(a requirement for large parity mixing)*

Definitions

$= (E - E_p)/(\ {}_p/2)$

$= |<s|v_{pt}|p>/<s|v_p|p>|$

Findings so far

Correction term b ~ O(/D) even in two resonance approximation: $a_9' \sim$ + + b
Corrections due to complex phases in channel are negligible O(/D)/√N, N number of open channels
Corrections due to mixing of distant s-wave states are O(/D)
Corrections due to mixing of distant p-wave states are suppressed by extra factor O(/D) over s wave mixing
Probability distribution for is a convolution of a Gaussian and a Cauchy distribution – Voigt profile- Bayesian analysis underway (EDD). Need multiple cases!

Experimental Issues

- *NPDG apparatus exists – ideal for this measurement (measure transverse to avoid fore-aft P-even asymmetries)*
- *Ultimate sensitivity bounded by Γ/D – of order 10^{-3}?*
- *Best experimental precisions quoted at Dubna and LANSCE are of order 6 meV – Q: is 1 meV possible?*

Conclusions

Energy shifts ARE a signature of P-odd TRV; a TRV neutron resonance experiment without a polarized target is feasible

However it's not a null test; correction terms (cf FSI) exist to $O(\ /D) \sim 10^{-3}$

Bring on the SNS?

The Fundamental Neutron Physics Beamline at the Spallation Neutron Source

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Contest: Identify the level diagrams

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CP nonconservation or T (time reversal) noninvariance was observed in the decay of neutral kaons long ago [1]. Attempts to search for this phenomenon in other processes have failed. Recently some possible tests using neutron optics experiments were discussed in a paper by Weidenmuller [2] and references therein. Interest in the neutron-nucleus interaction was stimulated by the discovery [3,4] of large P- (parity-) nonconserving effects near neutron p-wave resonances. These effects appeared to be enhanced by 3 to 6 orders of magnitude compared to the single-particle estimate $Gm_\pi^2 \sim 10^{-7}$ (in units of $\hbar = c = 1$ and $G = 10^{-5} m_p^{-2}$). The enhancement was explained in terms of the P-nonconserving mixing of compound nuclear states with opposite parity (mixing of the p-wave resonance with the nearest s-wave resonances [5,6]). The concept of the spreading width of the weak interaction was brought into practice based on recent experimental results [7].

It was shown by Bunakov and Gudkov [8,9] that possible T-noninvariant effects may be enhanced near p-wave resonances in the same manner as P-nonconserving effects. It has been suggested that a serach be made for P-conserving, T-noninvariant effects in polarized neutron transmission through aligned nuclear targets [10–12]. Such an effect would occur due to an $\mathbf{s}\cdot[\mathbf{k}\times\mathbf{I}](\mathbf{k}\cdot\mathbf{I})$ term in the neutron-nucleus elastic forward scattering amplitude. Here $\mathbf{s}$ and $\mathbf{I}$ are the neutron and nucleus spins and $\mathbf{k}$ is neutron momentum. Bunakov [9] showed that the maximum value of the experimental polarization asymmetry in the cross section β is connected to the T-noninvariant matrix element v_p^T and to the p-wave resonance level spacing D_p by the approximate relation

$$\beta \approx v_p^T / D_p \,. \qquad (1)$$

Here $i v_p^T = \langle H^T \rangle_{12} = -\langle H^T \rangle_{21}$ is the purely imaginary matrix element of the T-noninvariant, P-conserving interaction between compound nuclear wave functions of the considered p-wave resonance (labeled 1) and its nearest-neighboring p-wave resonance (labeled 2). Estimates given by Bunakov [9] indicate the enhancement factor may be as big as 10^3. The estimate is that $v_p^T/D_p \sim 10^3 \phi$, where ϕ is roughly the strength of the T-noninvariant, P-conserving nuclear interaction relative to the T-invariant one. The new theoretical limits on ϕ are very low [13]. The experimental upper limit on ϕ is between 10^{-3} and 10^{-4}, e.g., as given in Ref. [9] or in the recent aligned target experiment [14]. Therefore, in the framework of Bunakov's hypothesis, any experimental measurement of β near a p-wave resonance with accuracy better than 10^{-1} may decrease this limit.

It has been noted [15] that the value of v_p^T/D_p in p-wave resonances may be obtained from a quite different kind of experiment, namely, from the measurement of the forward-backward asymmetry in the yield of gamma rays from individual transitions in unpolarized neutron capture reactions. Such measurements have already been made [16–18] for p-wave resonances in targets of ^{113}Cd and ^{117}Sn. Here we present the results of our analysis of the ^{113}Cd capture experiment after giving the details of our approach to the analysis which is based on the hypothesis of Ref. [9].

In our approach to the calculation of experimental observables we will use an S-matrix scattering formalism. We wish to start from the expression

$$\delta S_J = S_J(1\tfrac{1}{2} \to 1\tfrac{3}{2}) - S_J(1\tfrac{3}{2} \to 1\tfrac{1}{2}) \,,$$

where $S_J(lj, l'j')$ is the scattering matrix element which corresponds to the transition of p-wave neutrons ($l = l' = 1$) in a resonance with spin J from a channel with neutron total angular momentum $j = \frac{1}{2}$ to a channel with $j' = \frac{3}{2}$ and vice versa. Using the explicit forms for the scattering matrix elements of Ref. [19] we get

$$\delta S_J = \frac{2\,\mathrm{Im}[g_n(1\tfrac{1}{2})\, g_n^*(1\tfrac{3}{2})]}{E - E_p + i\Gamma_p/2} \,. \qquad (2)$$

Here E_p and Γ_p are the energy and the total width of the p-wave resonance and $g_n(lj)$ is the neutron partial width amplitude $[\Gamma_n(lj) = |g_n(lj)|^2]$. By definition

$$g_n = \alpha \langle \varphi_{JMlj} | \Psi_{JM} \rangle \,, \qquad (3)$$

