NOPTREX Topics

Mike Snow
Indiana University/CEEM
IU Center for Spacetime Symmetries

Unique features of NOPTREX collaboration

TRIPLE collaboration history

Search for P violation in Unmeasured Nuclei

P-even/T-odd NOPTREX search

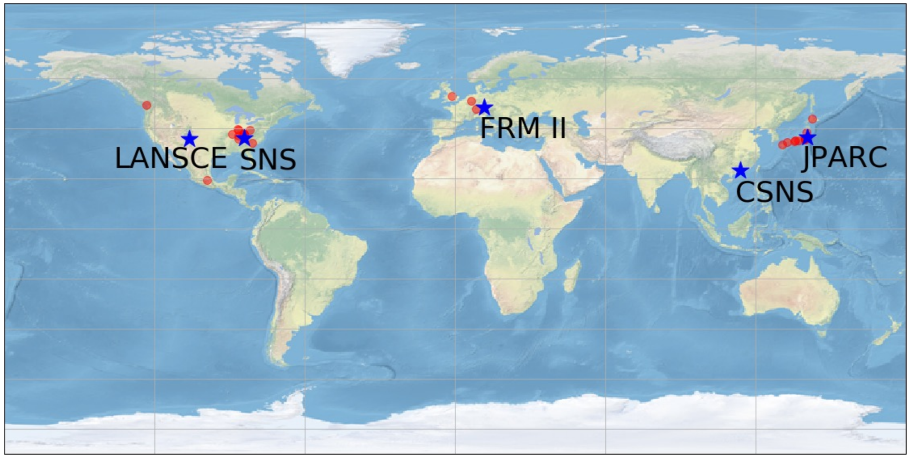
Thx: D. Bowman, V. Gudkov, H. Shimizu, P. Schmidt-Wellenburg, V. Cirigliano, Y. Uzikov, …

NSF PHY-2209481
NSF PHY-1913789

NOPTREX Collaboration

C. Auton[16], E. Babcock[29], M. Barlow[30], L. Barron-Palos[27], J. D. Bowman[18], J. Carini[16], L. E. Charon-Garcia[27], E. **Y.** Chekmenev[32], C. Crawford[19], J. Curole[16], K. Dickerson[16], J. Doskow[16], D. Eigelbach[20], S. Endoh[1,3], R. Fan[15], J. Fry[24], H. Fujioka[7], B. M. Goodson[22], V. Gudkov[17], C. Haddock[21], K. Hagino[11], H. Harada[3], P. Hautle[28], M. Hino[11], K. Hirota[1], I. Ide[1], M. Iinuma[6], H. Ikegami[10], T. Ino[4], R. Ishiguro[13], S. Ishimoto[4], K. Ishizaki[1], T. Iwata[9], C. Jiang[18], W. Jiang[15], K. Kameda[7], G. N. Kim[14], A. Kimura[3], P. King[23], M. Kitaguchi[1], Y. Kiyanagi[1], J. Koga[2], H. Kohri[8], A. Komives[31], S. W. Lee[14], H. Lu[16], G. Luan[34], D. Lutes[16], M. Luxnat[16], T. Matsushita[1], M. McCrea[36], J. Mills[24], K. Mishima[4], Y. Miyachi[9], T. Momose[5], T. Morishima[1], Y. Niinomi[1], I. Novikov[25], T. Okudaira[1], K. Ogata[8], T. Oku[3], G. Otero[16], J. Peck[19], S. Penttila[18], A. Perez-Martin[27], B. Plaster[19], X. Ruan[34], D. Sahibnazarova[19], K. Sakai[3], S. Samiei[16],D. Schaper[20], R. Shchepin[33] ,T. Shima[8], H. M. Shimizu[1], W. M. Snow[16], D. Spayde[35], H. Tada[1], J. Tang[37], Z. Tang[20], Y. Tani[7], S. Takada[2], Y. I. Takahashi[11], D. Takahaski[12], K. Taketani[8], K. Tateishi[10], X. Tong[15], T. Uesaka[10], J. Vanderwerp[16], M. Veillette[26], G. Visser[16], N. Wada[1], Y. Wang[19], T. Yamamoto[1], Y. Yamagata[10], H. Yoshikawa[8], T. Yoshioka[2], M. Yosoi[8] , M. Zhang[15,16], Q. Zhang[34], G. Ziemyte[19]

[1]Nagoya, [2]Kyushu, [3]JAEA, [4]KEK, [5]British Columbia, [6]Hiroshima, [7]Tokyo Inst. Tech., [8]Osaka, [9]Yamagata, [10]RIKEN, [11]Kyoto, [12]Ashikaga, [13]Japan Women's, [14]Kyungpook, [15]CSNS, [16]Indiana, [17]South Carolina, [18]ORNL, [19]Kentucky, [20]LANL, [21]Phase III Physics, [22]Southern Illinois, [23]Ohio, [24]Eastern Kentucky, [25]Western Kentucky, [26]Berea, [27]UNAM, [28]PSI, [29]Juelich, [30]Nottingham, [31]DePauw, [32]Wayne State, [33]SDSM&T, [34]CIAE, [35]Hendrix, [36]Manitoba, [37]USTC



NOPTREX

Neutron Optical Parity and Time-Reversal EXperiment

One experiment:
Five neutron sources

NOPTREX MS/PhD Theses

Takuya Okudaira, PhD, Nagoya University (2018)
Tomoki Yamamoto, PhD, Nagoya University (2021)
Yuika Tani, MS, Tokyo Institute of Technology (2021)
Jun Koga, PhD, Kyushu University (2021)
Danielle Schaper, PhD, University of Kentucky (2021)
S Takada, PhD, Kyushu University (expected 2022)
R Abe. MS, Nagoya University (expected 2022)
Jonathan Curole, PhD, Indiana University (2023)
Hao Lu, PhD thesis, Indiana University (expected 2023)
Luis Charon-Garcia, PhD, UNAM (expected 2023)
Kento Kameda, MS, Tokyo Institute of Technology (???)
Hiromoto Yoshikawa, PhD, RCNP/Osaka (???)
Benjamín Salazar-Ángeles, MS, UNAM (???)
Kylie Dickerson, PhD, Indiana University (???)
Gabe Otero, PhD, Indiana University (???)
Clayton Auton, PhD, Indiana University (???)
Mofan Zhang, PhD, Indiana University (???)
Tobi Abdulgafar, PhD, Southern Illinois University (???)
Md Shahabuddin Alam, PhD, Southern Illinois University (???)
Sepehr Samiei, PhD, Indiana University (???)

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S Takada, PhD, Kyushu University (2022)
Shunsuke Endo, MS, Nagoya University (2019), PhD Nagoya Univ. (expected 2024)
Kohei Ishizaki, MS Nagoya University (2019)
Ryota Abe, MS, Nagoya University (2021)
Ikuo Ide, MS, Nagoya University (2021), return to Doctor Course, PhD (expected 2025)
Hiroki Hotta, MS, Nagoya University (2021)
Yuki Ito, MS, Nagoya University (2023)
Kento Kameda, MS, Tokyo Institute of Technology (2023)
Rintaro Nakabe, PhD, Nagoya University (expected 2024)
Hiromoto Yoshikawa, PhD, RCNP/Osaka (expected 2024)
Shiori Kawamura, MS, Nagoya University (expected 2024)
Yu Goto, MS, Nagoya University (expected 2024)
Mao Okuizumi, MS, Nagoya University (expected 2025)
Taro Nambu, MS, Nagoya University (expected 2025)

Danielle Schaper, PhD, University of Kentucky (2021)
Jonathan Curole, PhD, Indiana University (2023)
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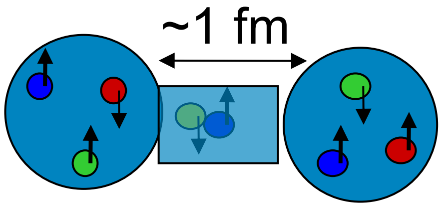
Sepehr Samiei, PhD, Indiana University (???)

N- N Weak Interaction: Size and Mechanism

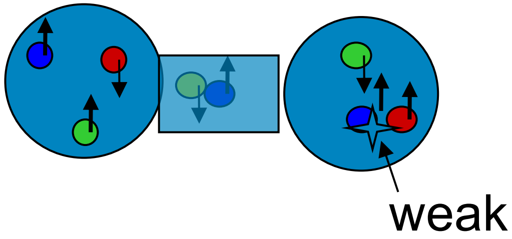


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = valence + sea quarks + gluons + …

interacts through NN strong force, mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings → conserves parity



Both W and Z exchange possess
much smaller range [~1/100 fm]

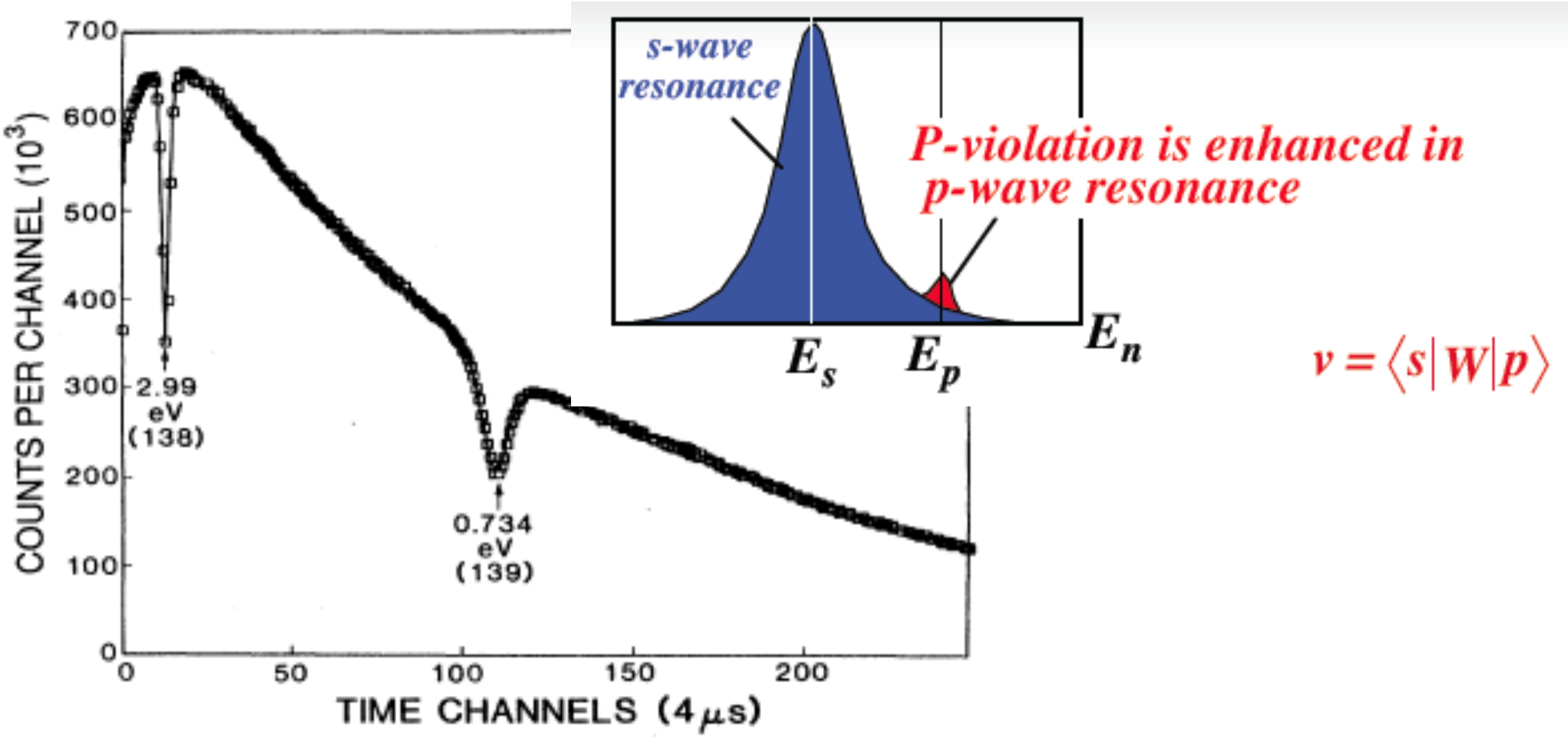
Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{{m_W}^2}\right)/\left(\frac{g^2}{{m_\pi}^2}\right) \approx 10^{-6}$

Use parity violation to isolate the weak contribution to the NN interaction.

NN strong interaction at low energy largely dictated by QCD chiral symmetry.
Can be parametrized by effective field theory methods.

Parity Violation in ^{139}La .734 eV $\Delta\sigma/\sigma$ =0.097±.005.

10^6 amplification!

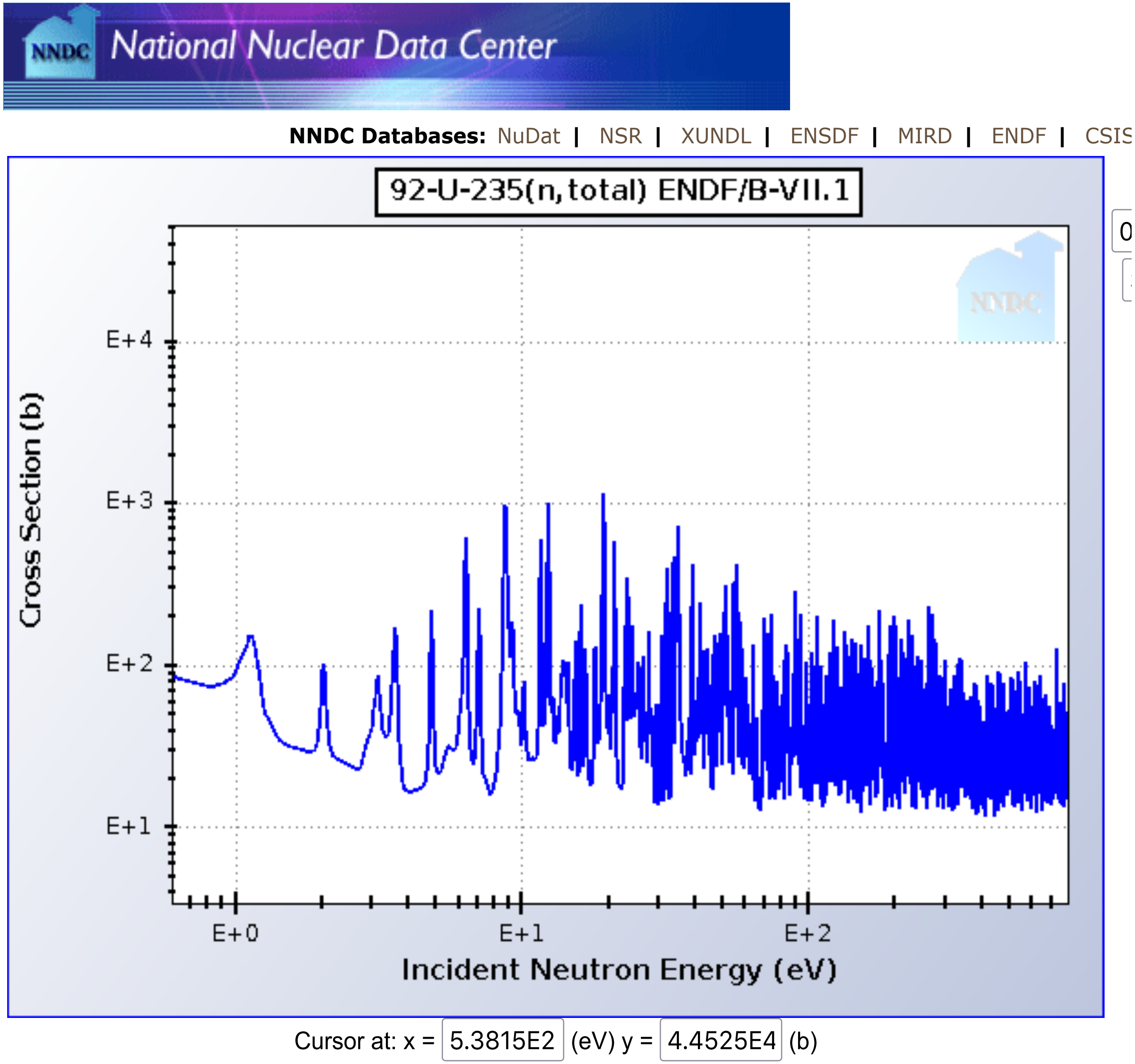


P-violation is enhanced in p-wave resonance

$$v = \langle s | W | p \rangle$$

Discovered in Dubna 1980. Theory BEFORE experiment!

Neutron-Nucleus Resonances



NNDC Databases: NuDat | NSR | XUNDL | ENSDF | MIRD | ENDF | CSIS

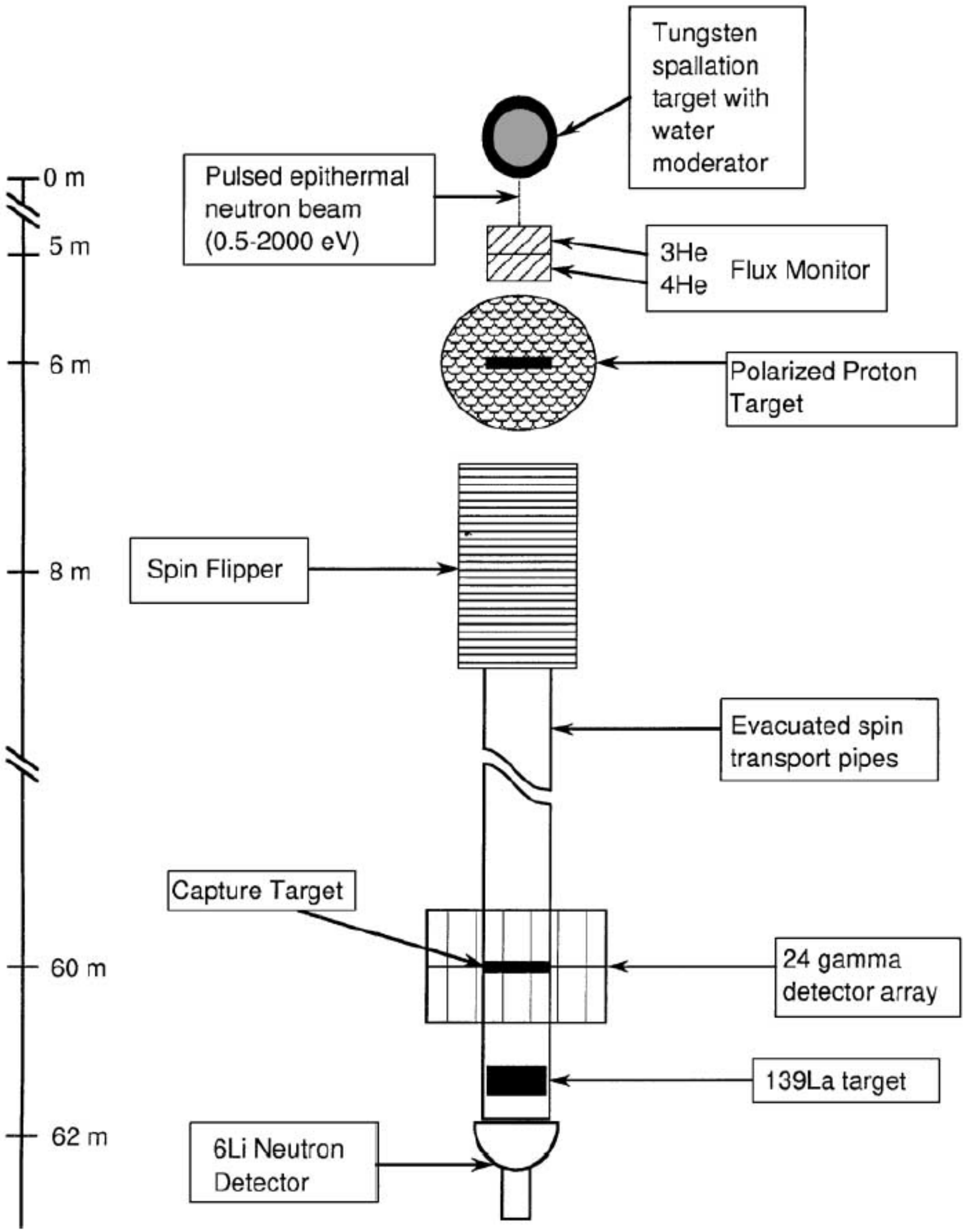
Cursor at: x = 5.3815E2 (eV) y = 4.4525E4 (b)

Heavy nuclei possess a very dense set of resonances just above the neutron separation energy

No Coulomb barrier -> neutrons can easily excite them

Mainly L=0 resonances, but lots of L=1 resonances

P-even/T-odd interactions can mix pairs of different L=1 resonances

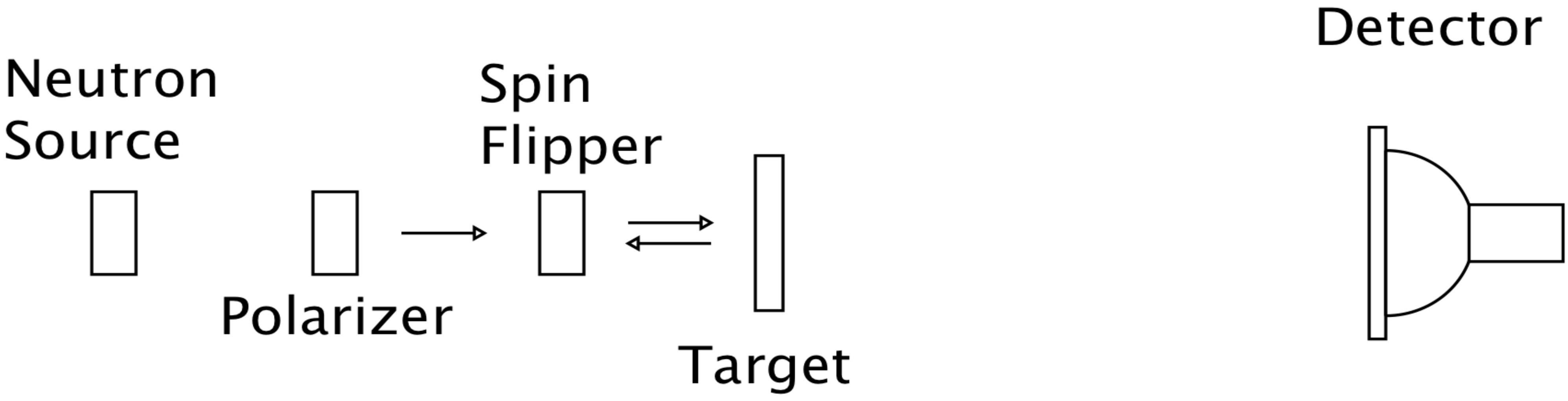


Apparatus for PV at a spallation neutron source

Polarized proton target to make polarized neutrons

Look for σ.k dependence of total cross section

TRIPLE $\sigma \cdot k$ P violation work in heavy nuclei



Measure P-odd neutron helicity dependence of total cross section $\Delta\sigma/\sigma$

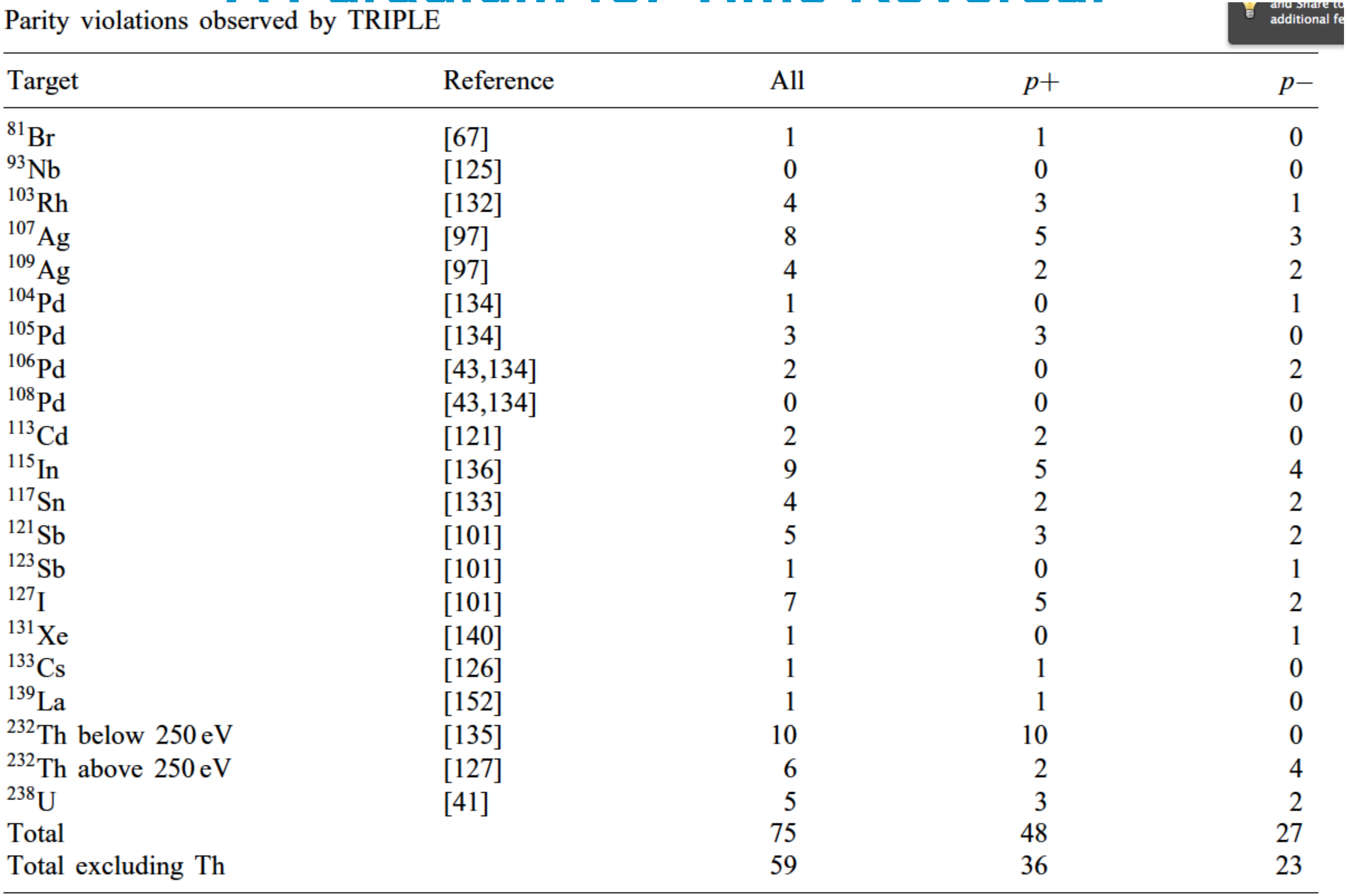
20 meter flight path

TRIPLE collaboration measured ~75 parity-odd asymmetries in p-wave resonances in heavy nuclei in eV-keV energies G. M. Mitchell, J. D. Bowman, S. I. Penttila, and E. I. Sharapov, Phys. Rep. 354, 157 (2001).

Quantitative analysis of distribution of parity-odd asymmetries conducted using nuclear statistical spectroscopy S. Tomsovic, M. B. Johnson, A. Hayes, and J. D. Bowman, Phys. Rev. C 62, 054607 (2000).

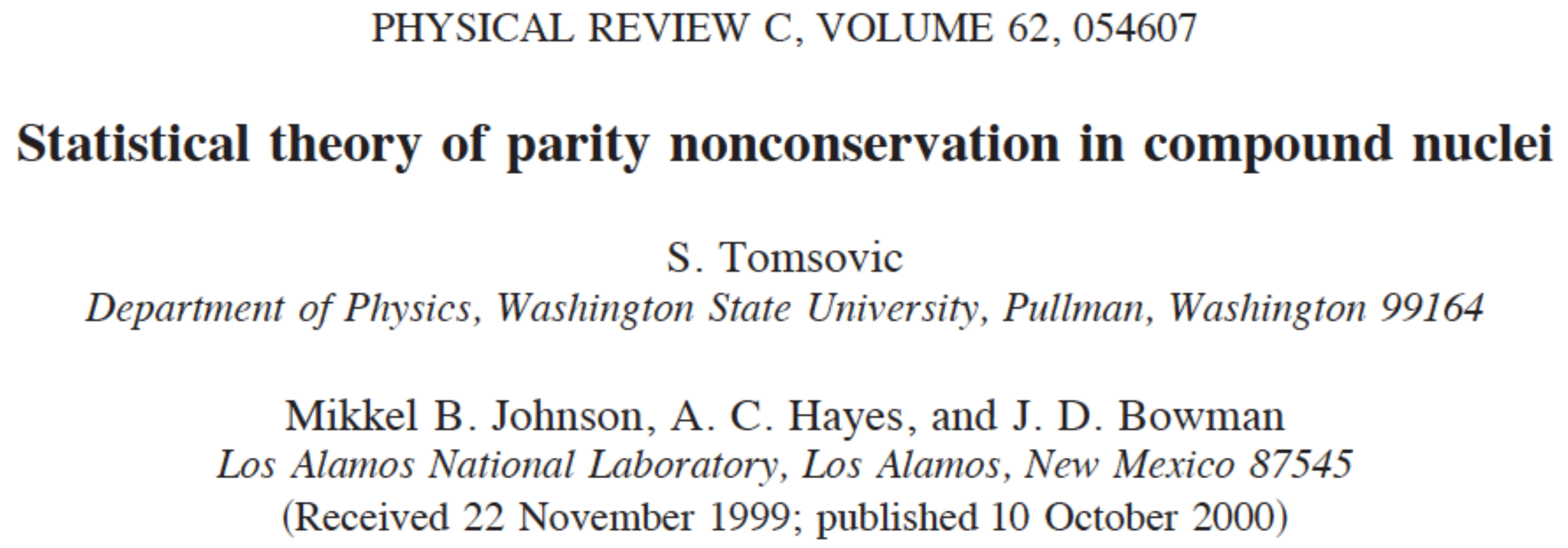
D. Bowman

Study of Parity Violation in the Compound Nucleus
A Paradigm for Time Reversal



Parity violations observed by TRIPLE

Target	Reference	All	$p+$	$p-$
^{81}Br	[67]	1	1	0
^{93}Nb	[125]	0	0	0
^{103}Rh	[132]	4	3	1
^{107}Ag	[97]	8	5	3
^{109}Ag	[97]	4	2	2
^{104}Pd	[134]	1	0	1
^{105}Pd	[134]	3	3	0
^{106}Pd	[43,134]	2	0	2
^{108}Pd	[43,134]	0	0	0
^{113}Cd	[121]	2	2	0
^{115}In	[136]	9	5	4
^{117}Sn	[133]	4	2	2
^{121}Sb	[101]	5	3	2
^{123}Sb	[101]	1	0	1
^{127}I	[101]	7	5	2
^{131}Xe	[140]	1	0	1
^{133}Cs	[126]	1	1	0
^{139}La	[152]	1	1	0
^{232}Th below 250 eV	[135]	10	10	0
^{232}Th above 250 eV	[127]	6	2	4
^{238}U	[41]	5	3	2
Total		75	48	27
Total excluding Th		59	36	23



PHYSICAL REVIEW C, VOLUME 62, 054607

Statistical theory of parity nonconservation in compound nuclei

S. Tomsovic
Department of Physics, Washington State University, Pullman, Washington 99164

Mikkel B. Johnson, A. C. Hayes, and J. D. Bowman
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 22 November 1999; published 10 October 2000)

Comparison of experimental CN matrix elements with Tomsovic theory using DDH “best” meson-nucleon couplings: agreement within a factor of 2

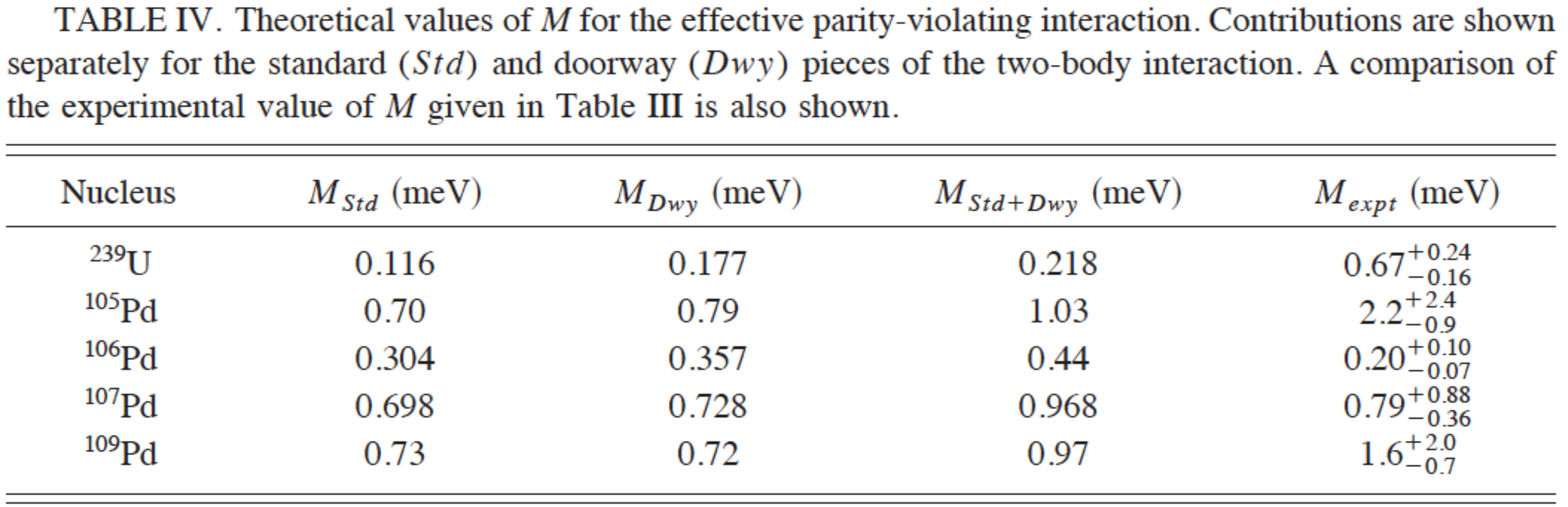
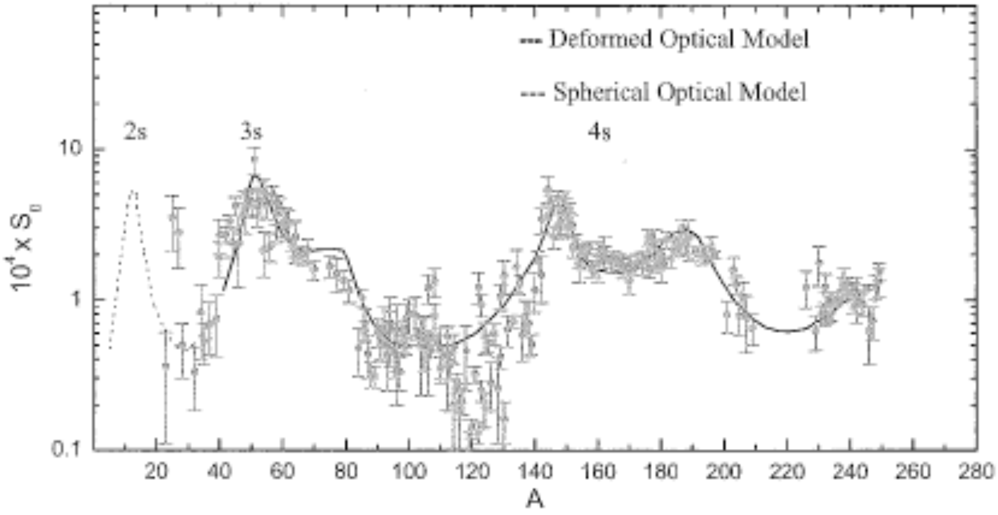
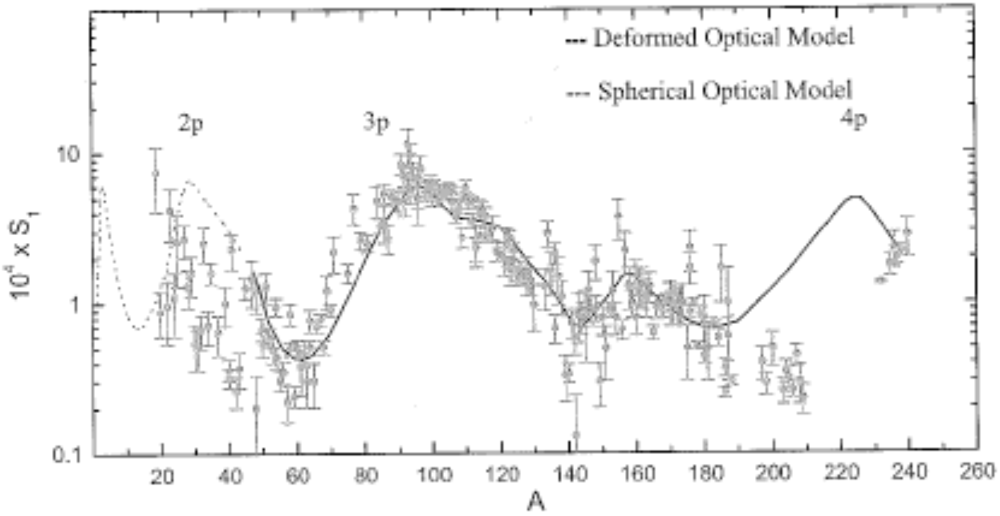


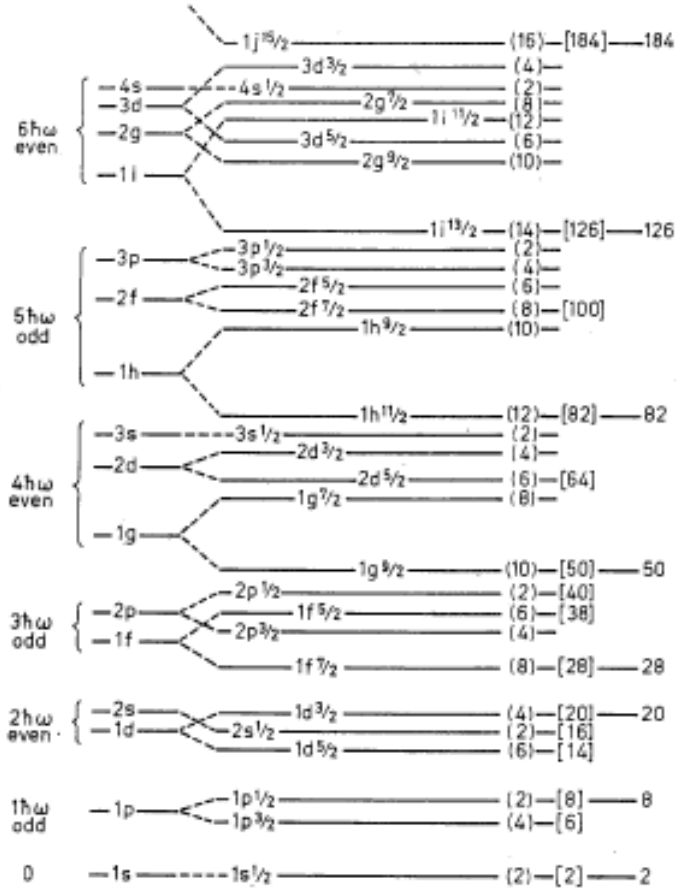
TABLE IV. Theoretical values of M for the effective parity-violating interaction. Contributions are shown separately for the standard (Std) and doorway (Dwy) pieces of the two-body interaction. A comparison of the experimental value of M given in Table III is also shown.

Nucleus	M_{Std} (meV)	M_{Dwy} (meV)	$M_{Std+Dwy}$ (meV)	M_{expt} (meV)
^{239}U	0.116	0.177	0.218	$0.67^{+0.24}_{-0.16}$
^{105}Pd	0.70	0.79	1.03	$2.2^{+2.4}_{-0.9}$
^{106}Pd	0.304	0.357	0.44	$0.20^{+0.10}_{-0.07}$
^{107}Pd	0.698	0.728	0.968	$0.79^{+0.88}_{-0.36}$
^{109}Pd	0.73	0.72	0.97	$1.6^{+2.0}_{-0.7}$

Systematics of S and P resonances





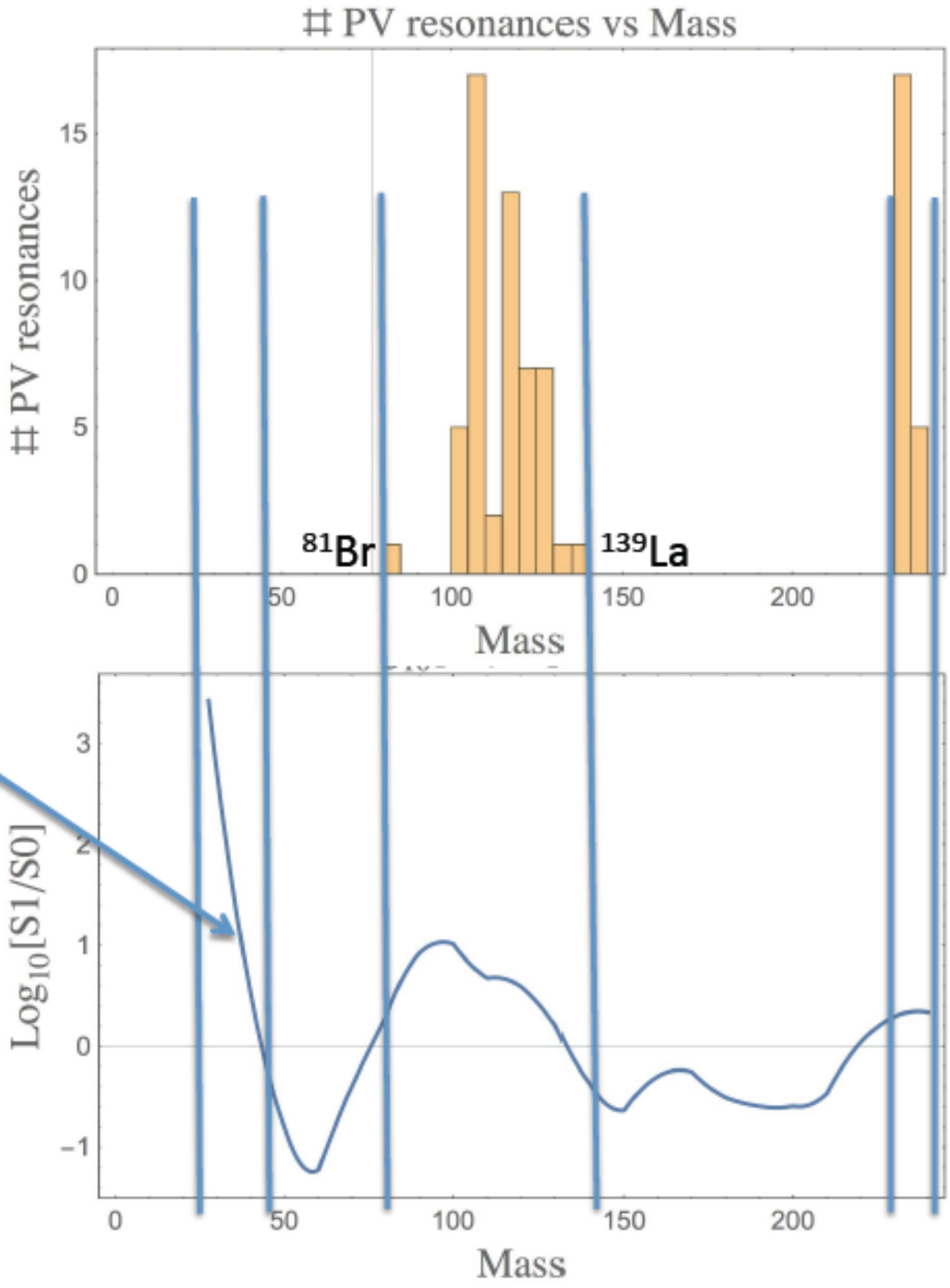


-23 Sequence of one-particle orbits. The figure is taken from M. G. Ma Jensen, *Elementary Theory of Nuclear Shell Structure*, p. 58, Wiley, New Yor

Shell model explains systematics of S and P strength functions.

D. Bowman

PV resonances found by TRIPLE



Look at
30<A<50

PV resonances occur
If S1/S0 is between
1/3 and 10. The best
TRIPLE resonances
Have S1/S0 ~ 1

What about 140<A<180?
No data!

S1/S0 not so different from
^{139}La, ^{81}Br, ^{131}Xe

It only takes one discovery
to be useful for NOPTREX

many I>0 nuclei in this range

Stable 140<A<180 Nuclei, I>0 (abundance)

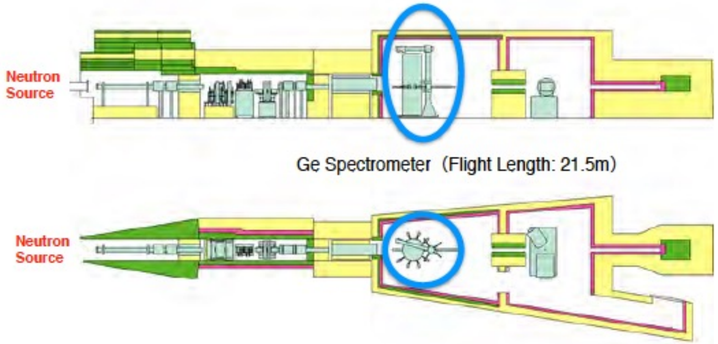
^{141}Pr, I=5/2 (100%)
^{143}Nd, I=7/2 (12.2%)
^{145}Nd, I=7/2 (8.5%)
^{147}Sm, I=7/2 (15%)
^{149}Sm, I=7/2 (13.8%)
^{151}Eu, I=5/2 (47.8%)
^{153}Eu, I=5/2 (52.2%)
^{155}Gd, I=3/2 (14.8%)
^{157}Gd, I=5/2 (15.7%)
^{159}Tb, I=3/2 (100%)
^{161}Dy, I=5/2 (18.9%)
^{163}Dy, I=5/2 (24.9%)
^{165}Ho, I=7/2 (100%)
^{167}Er, I=7/2 (22.9%)
^{169}Tm, I=1/2 (100%)
^{171}Yb, I=1/2 (14.1%)

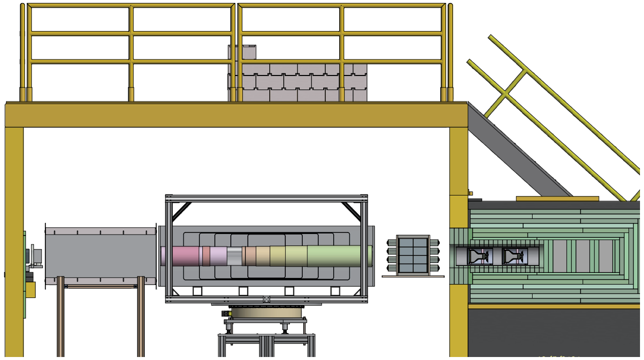
^{173}Yb, I=5/2 (16.3%)
^{175}Lu, I=7/2 (97.4%)
^{179}Hf, I=9/2 (13.8%).

<u>**Especially interesting for NOPTREX:**</u>

^{169}Tm, I=1/2 (100%), DNP possible in a diamagnetic salt
^{171}Yb, I=1/2 (14.1%), has been hyperpolarized
^{149}Sm, ^{151}Eu, ^{167}Er, ^{165}Ho, polarizable using internal hyperfine fields

Where to Measure: JPARC, LANSCE, CSNS





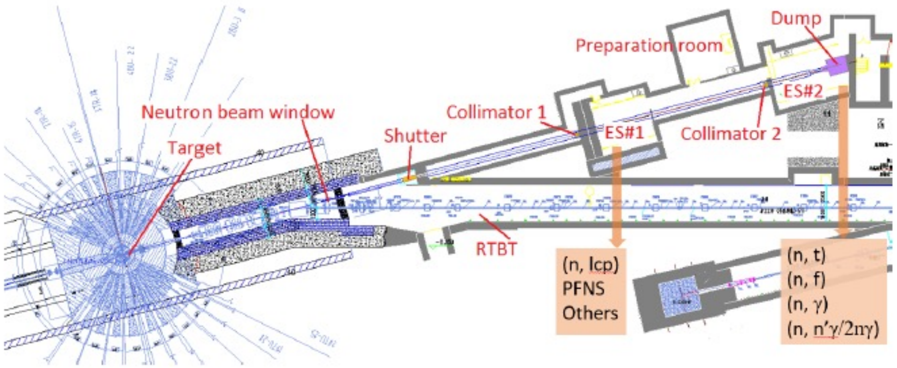


Figure 1. Back-n white neutron beam line and spectrometers.

Toward A Search for P-even/T-odd NN interactions in n-A resonances

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2 ways to violate T (+conserve CPT): P-odd/T-odd , P-even/T-odd

MANY search for P-odd/T-odd (EDMs,…), VERY few for P-even/T-odd

P-odd/T-odd effect can come from:
BSM P-odd/T-odd or [BSM P-even/T-odd][SM P-odd]

Experimental limits on P-even/T-odd NN interactions are quite poor

Neutron optics on n-A resonances could improve limits by ~10^2-10^3

Thx: D. Bowman, V. Gudkov, H. Shimizu, P. Schmidt-Wellenburg, V. Cirigliano, Y. Uzikov, …

NSF PHY-2209481
NSF PHY-1913789

Neutron Spin Filter using polarized protons can work up to ~100 keV

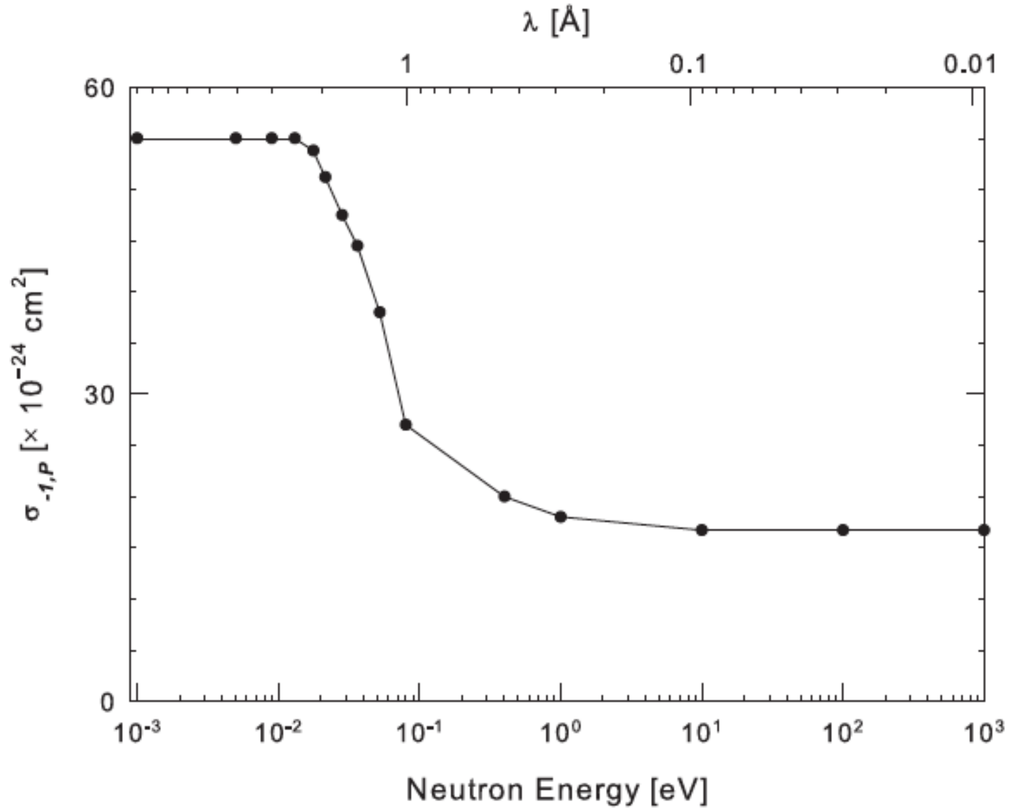


Figure 6.3: Plot of the general trend for the normalized polarization cross section σ_P as a function of the neutron wavelength and energy. The data points are a compilation of literature values [4, 59, 60, 62].

Desirable for P-even/T-odd search (with N p-waves, search ~N^2 pairs!)

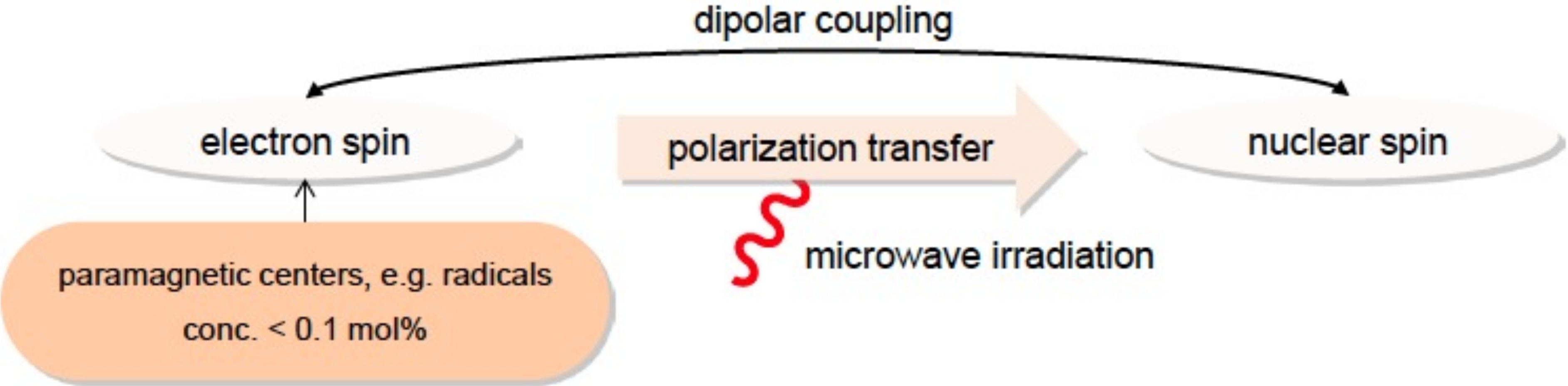
How to make a polarized proton spin filter?

Dynamic Nuclear Polarization (DNP)

spin polarization for spin 1/2 – particles: $P = \frac{N^{+} - N^{-}}{N^{+} + N^{-}} = \tanh\left(\frac{\mu B}{2kT}\right)$

static polarization @ 1K and 5 T : P (proton) ≈ 0.5 %
P (electron) ≈ 99 %

polarization transfer from electron spins to surrounding nuclei



dipolar coupling

electron spin

polarization transfer

nuclear spin

microwave irradiation

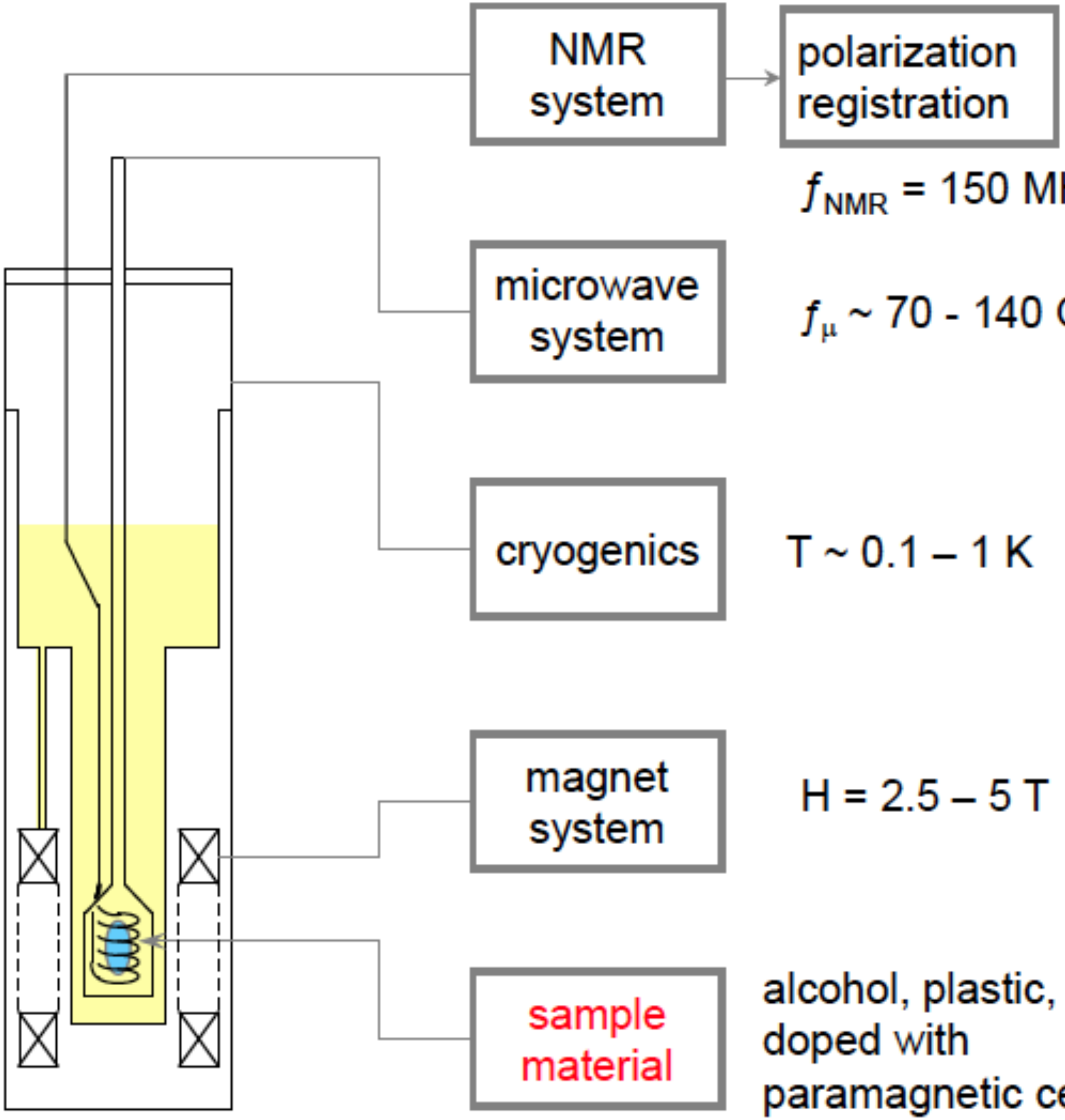
paramagnetic centers, e.g. radicals
conc. < 0.1 mol%

"classical" DNP: create electron polarization thermally

➡ **low temperature** (typically 1 K and below)

➡ **high magnetic fields** (typically 5 Tesla)

Components of a classical DNP system



NMR system → polarization registration

f_{NMR} = 150 MHz

microwave system

$f_{\mu} \sim 70 - 140$ GHz

cryogenics

T ~ 0.1 – 1 K

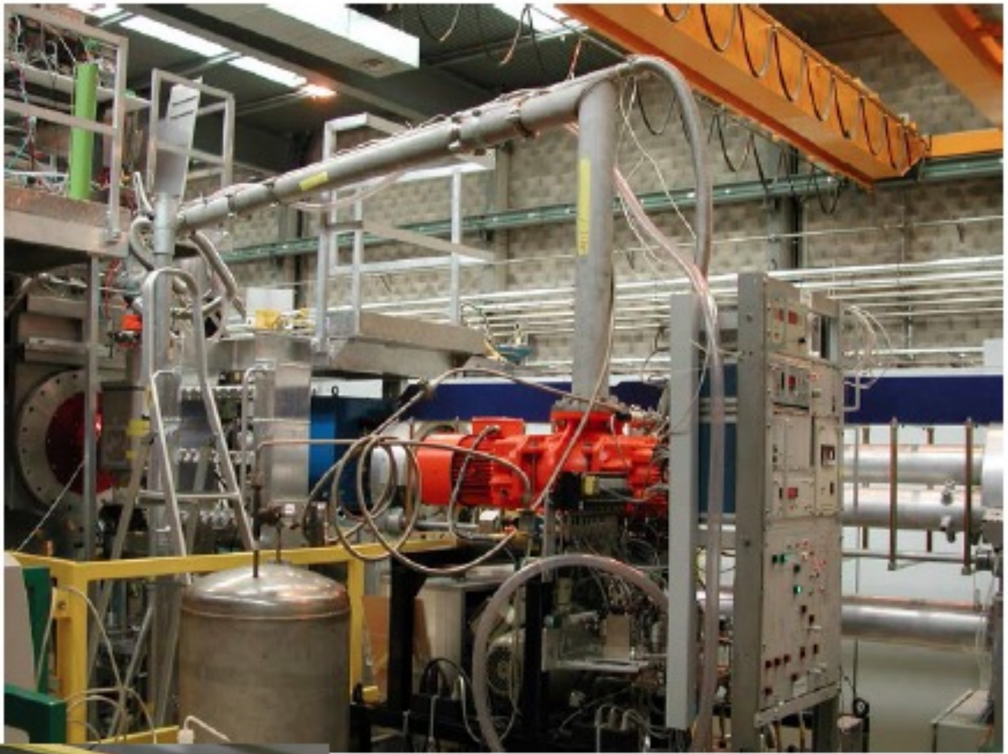
magnet system

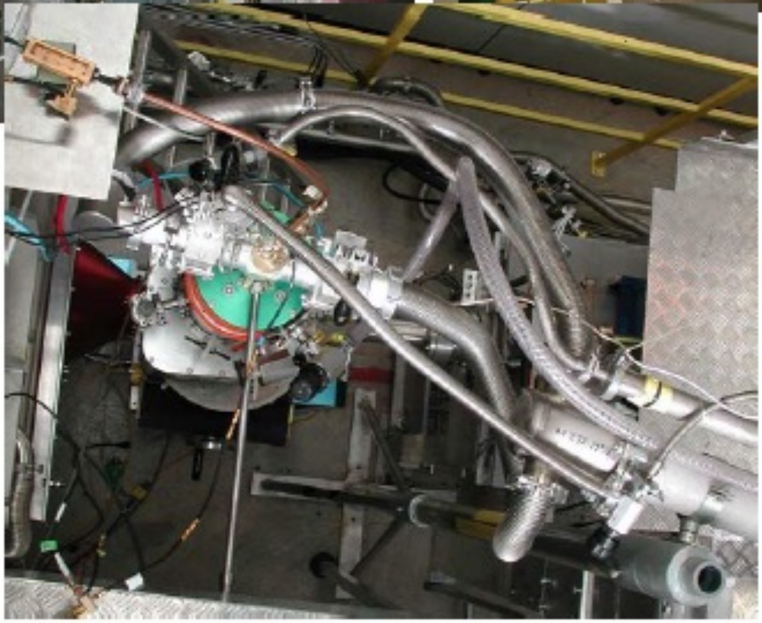
H = 2.5 – 5 T

sample material

alcohol, plastic, $LaAlO_3$
doped with
paramagnetic centers

Classical DNP systems





This is a compact system !!

Target volume ~ 5 ccm

1 K ^{4}He cryostat
(~ 50 l LHe per day)

1000 m^3/ h + 250 m^3/ h
roots blower pumping system

2.5 / 3.5 T magnet system

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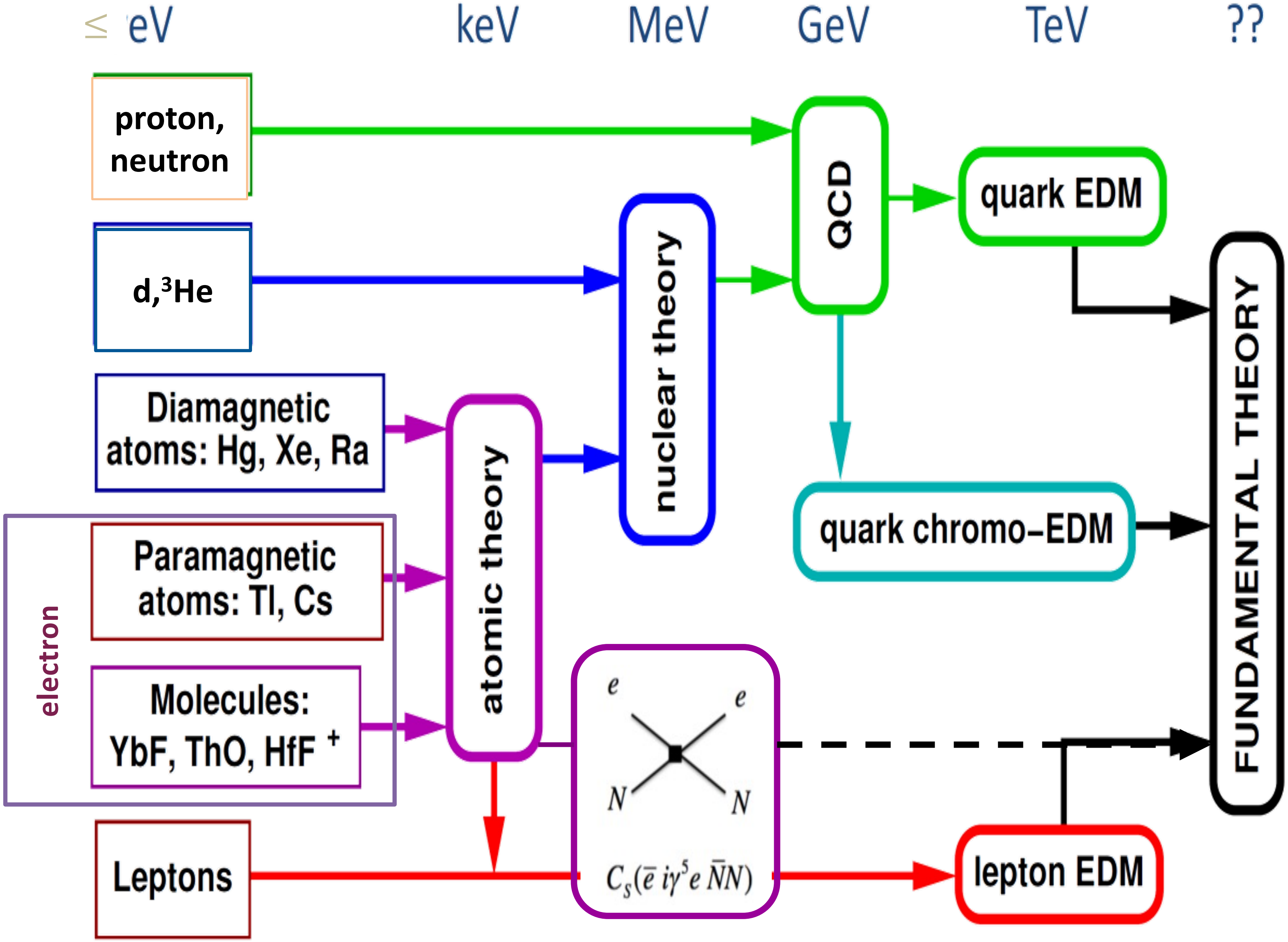
EDM searches in atomic/nuclear systems



QCD, nuclear, and atomic theory input also needed!

P. Schmidt-Wellenburg

For EDMs see: T. Chupp et al, Rev. Mod. Phys. **91**, 015001 (2019)

Scheme: adapted from Rob G. E. Timmermans

What About P-even/T-odd NN?

No P-even/T-odd effects in Standard Model: CKM, $\boldsymbol{\theta}$ both P-odd/T-odd

Lowest mass meson exchange from $\boldsymbol{\rho}^{+/-}$ [C-odd, J≥1]

[Herczeg Nucl. Phys. **75**, 655 (1966), Simonius PLB **58**, 147 (1975)]

VERY few experiments:

Detailed balance: [E. Blanke et al PRL **51**, 355 (1983); J. P. French et al PRL **54**, 2313 (1985)]: $g_{\rho}<2x10^{-1}$

Charge symm. breaking [Simonius PRL **78**, 4161(1997)]: $g_{\rho}<7x10^{-3}$

N transmission aligned Holmium (P. R. Huffman et al, PRC 55, 2684 (1997): $g_{\rho}<6x10^{-2}$

Comparing with EDM P-odd/T-odd: $g_{\pi}<10^{-11}$

Direct constraints on P-even/T-odd NN interactions are poor

Y. Uzikov

(Some) P-even/T-odd Theory Work (flavor conserving)

$$\frac{G_F}{\sqrt{2}}\frac{q_1}{2m_p}\bar{\psi}_1 i\gamma_5\sigma^{\mu\nu}(p_1'-p_1)_\nu\psi_1\bar{\psi}_2\gamma_\mu\gamma_5\psi_2 ,$$

$$C_7\left(\frac{1}{\Lambda^3}\right)\bar{q}_1\gamma_5 D^\mu q_2\bar{q}_3\gamma_5\gamma_\mu q_4 + H.c.,$$

$$C_7'\left(\frac{1}{\Lambda^3}\right)\bar{q}\sigma_{\mu\nu}\lambda^A q G^{A\mu\rho}F^\nu_\rho ,$$

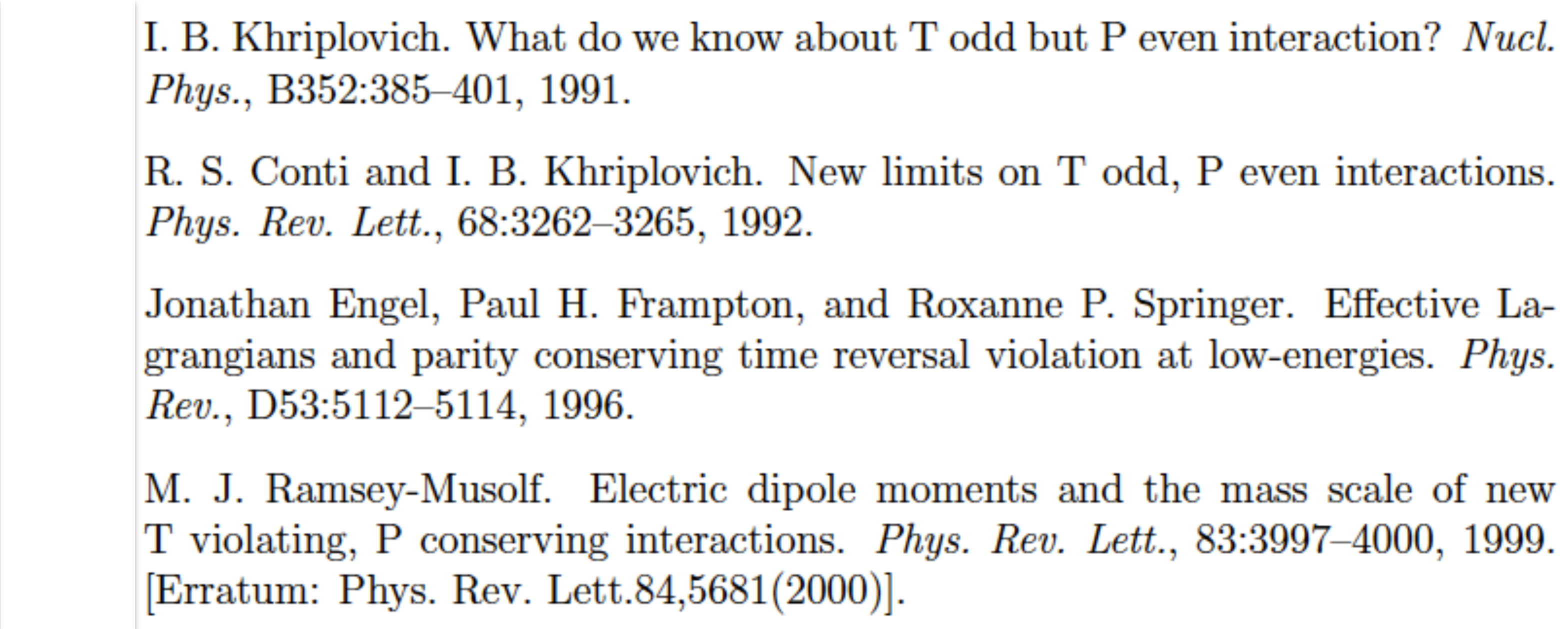
$$C_7^{\gamma Z'}\bar{\psi}\sigma_{\mu\nu}\psi F^{\mu\alpha}Z^\nu_\alpha .$$

Some operators considered in previous work

Concentrated on using EDM limits to constrain P-even/T-odd interactions

Considered particular terms: not a general analysis

Later work (Kurylov et al PRD 2001, El Menoufi et al PLB 2017): loopholes in previous constraints



I. B. Khriplovich. What do we know about T odd but P even interaction? *Nucl. Phys.*, B352:385–401, 1991.

R. S. Conti and I. B. Khriplovich. New limits on T odd, P even interactions. *Phys. Rev. Lett.*, 68:3262–3265, 1992.

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M. J. Ramsey-Musolf. Electric dipole moments and the mass scale of new T violating, P conserving interactions. *Phys. Rev. Lett.*, 83:3997–4000, 1999. [Erratum: Phys. Rev. Lett.84,5681(2000)].

P-even/T-odd in SMEFT (flavor conserving)

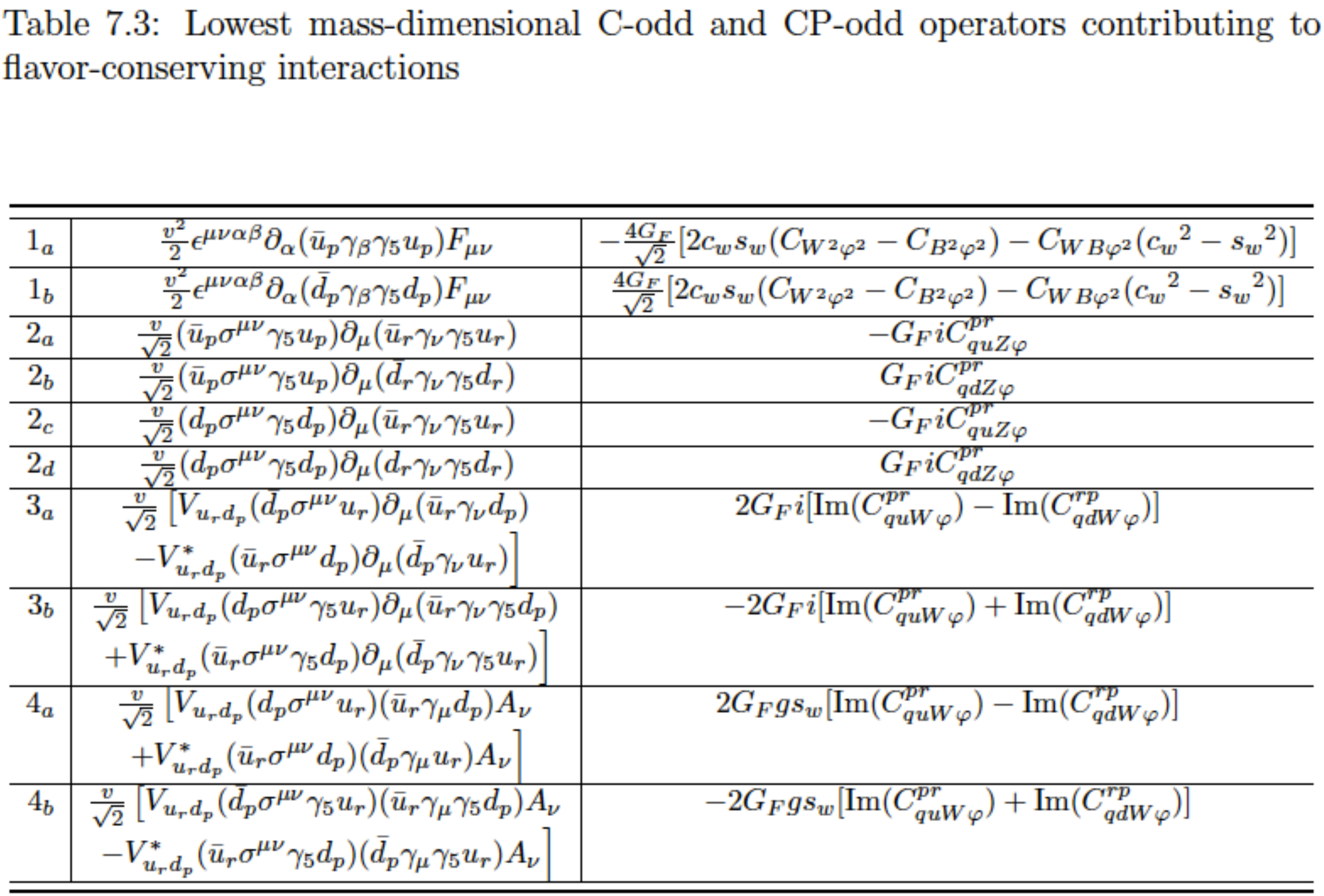


Table 7.3: Lowest mass-dimensional C-odd and CP-odd operators contributing to flavor-conserving interactions

1_a	$\frac{v^2}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\alpha(\bar{u}_p\gamma_\beta\gamma_5 u_p)F_{\mu\nu}$	$-\frac{4G_F}{\sqrt{2}}[2c_w s_w(C_{W^2\varphi^2}-C_{B^2\varphi^2})-C_{WB\varphi^2}({c_w}^2-{s_w}^2)]$
1_b	$\frac{v^2}{2}\epsilon^{\mu\nu\alpha\beta}\partial_\alpha(\bar{d}_p\gamma_\beta\gamma_5 d_p)F_{\mu\nu}$	$\frac{4G_F}{\sqrt{2}}[2c_w s_w(C_{W^2\varphi^2}-C_{B^2\varphi^2})-C_{WB\varphi^2}({c_w}^2-{s_w}^2)]$
2_a	$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F iC^{pr}_{quZ\varphi}$
2_b	$\frac{v}{\sqrt{2}}(\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p)\partial_\mu(\bar{d}_r\gamma_\nu\gamma_5 d_r)$	$G_F iC^{pr}_{qdZ\varphi}$
2_c	$\frac{v}{\sqrt{2}}(d_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 u_r)$	$-G_F iC^{pr}_{quZ\varphi}$
2_d	$\frac{v}{\sqrt{2}}(d_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(d_r\gamma_\nu\gamma_5 d_r)$	$G_F iC^{pr}_{qdZ\varphi}$
3_a	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}u_r)\partial_\mu(\bar{u}_r\gamma_\nu d_p)$ $-V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}d_p)\partial_\mu(\bar{d}_p\gamma_\nu u_r)\big]$	$2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi})-\mathrm{Im}(C^{rp}_{qdW\varphi})]$
3_b	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(d_p\sigma^{\mu\nu}\gamma_5 u_r)\partial_\mu(\bar{u}_r\gamma_\nu\gamma_5 d_p)$ $+V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu(\bar{d}_p\gamma_\nu\gamma_5 u_r)\big]$	$-2G_F i[\mathrm{Im}(C^{pr}_{quW\varphi})+\mathrm{Im}(C^{rp}_{qdW\varphi})]$
4_a	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(d_p\sigma^{\mu\nu}u_r)(\bar{u}_r\gamma_\mu d_p)A_\nu$ $+V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}d_p)(\bar{d}_p\gamma_\mu u_r)A_\nu\big]$	$2G_F g s_w[\mathrm{Im}(C^{pr}_{quW\varphi})-\mathrm{Im}(C^{rp}_{qdW\varphi})]$
4_b	$\frac{v}{\sqrt{2}}\big[V_{u_r d_p}(\bar{d}_p\sigma^{\mu\nu}\gamma_5 u_r)(\bar{u}_r\gamma_\mu\gamma_5 d_p)A_\nu$ $-V^*_{u_r d_p}(\bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p)(\bar{d}_p\gamma_\mu\gamma_5 u_r)A_\nu\big]$	$-2G_F g s_w[\mathrm{Im}(C^{pr}_{quW\varphi})+\mathrm{Im}(C^{rp}_{qdW\varphi})]$

New terms exist which have not been considered in the past

J. Shi. PhD thesis, U Kentucky (2020)
J. Shi and S. Gardner, in preparation

What About P-even/T-odd NN?

$$
\begin{aligned}
f = {} & A' + B'(\vec{\sigma}\cdot\vec{I}) + C'(\vec{\sigma}\cdot\vec{k}) + D'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}]) + H'(\vec{k}\cdot\vec{I}) + K'(\vec{\sigma}\cdot\vec{k})(\vec{k}\cdot\vec{I}) \\
& + E'\left((\vec{k}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{k}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) + F'\left((\vec{\sigma}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{\sigma}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) \\
& \boxed{+ G'(\vec{\sigma}\cdot[\vec{k}\times\vec{I}])(\vec{k}\cdot\vec{I})} + B_3'(\vec{\sigma}\cdot\vec{I})\left((\vec{k}\cdot\vec{I})(\vec{k}\cdot\vec{I}) - \frac{1}{3}(\vec{k}\cdot\vec{k})(\vec{I}\cdot\vec{I})\right) + \ldots,
\end{aligned}
$$

V. Gudkov and H. M. Shimizu,
Phys. Rev. C 102, 015503 (2020).

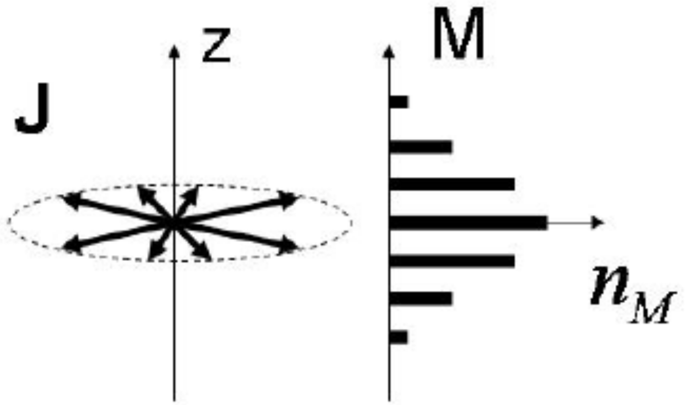
P-even/T-odd term G can be present in forward amplitude resonance amplification of ~1000

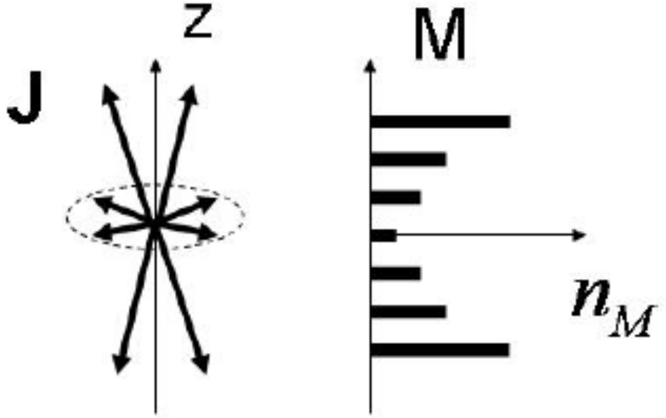
~~(1) Admixture of (large) s-wave amplitude into (small) p-wave ~1/kR~1000~~
(2) Weak amplitude dispersion for 10^6 Fock space components ~sqrt(10^6)=1000

Direct constraints on P-even/T-odd NN interactions are poor

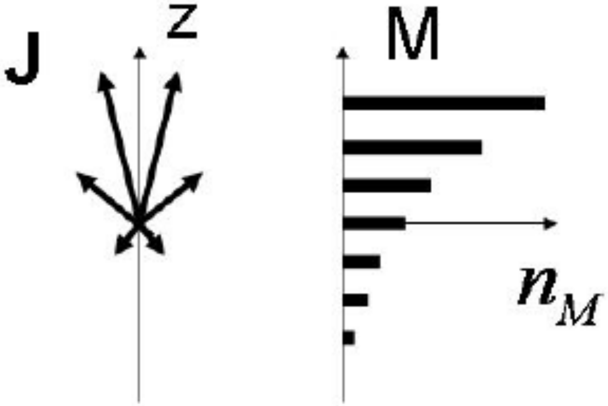
Polarization and Alignment

Alignment: $p_2(J) = \dfrac{3\langle M^2 \rangle - J(J+1)}{J(2J-1)}$





Polarization:



$p_1(J) = \dfrac{\langle M \rangle}{J}$

PHYSICAL REVIEW C VOLUME 55, NUMBER 5 MAY 1997

Test of parity-conserving time-reversal invariance using polarized neutrons and nuclear spin aligned holmium

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and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308

C. R. Gould, D. G. Haase, C. D. Keith,† B. W. Raichle, M. L. Seely,‡ and J. R. Walston
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(Received 28 October 1996)

T (odd): $(\underline{I}\cdot\underline{k})(\underline{I}\,\mathrm{x}\,\underline{k})\cdot\underline{s}$

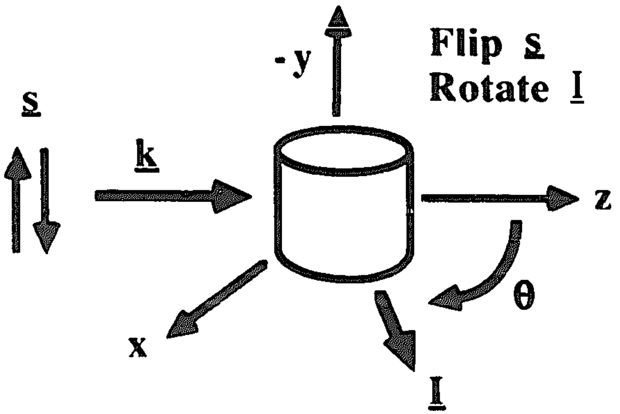


Fig. 1. Geometry for measurement of the $s\cdot(k\times I)(k\cdot I)$ term in neutron transmission through a cylindrical target.

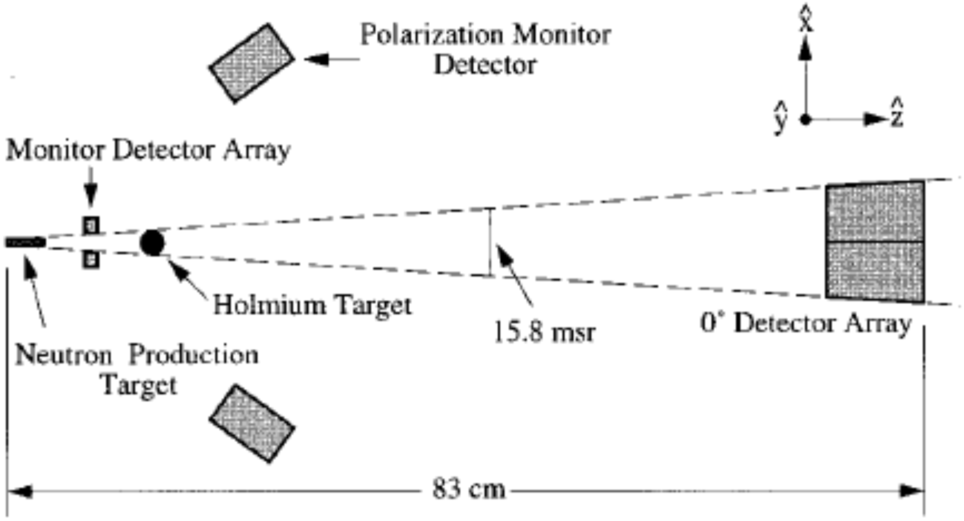
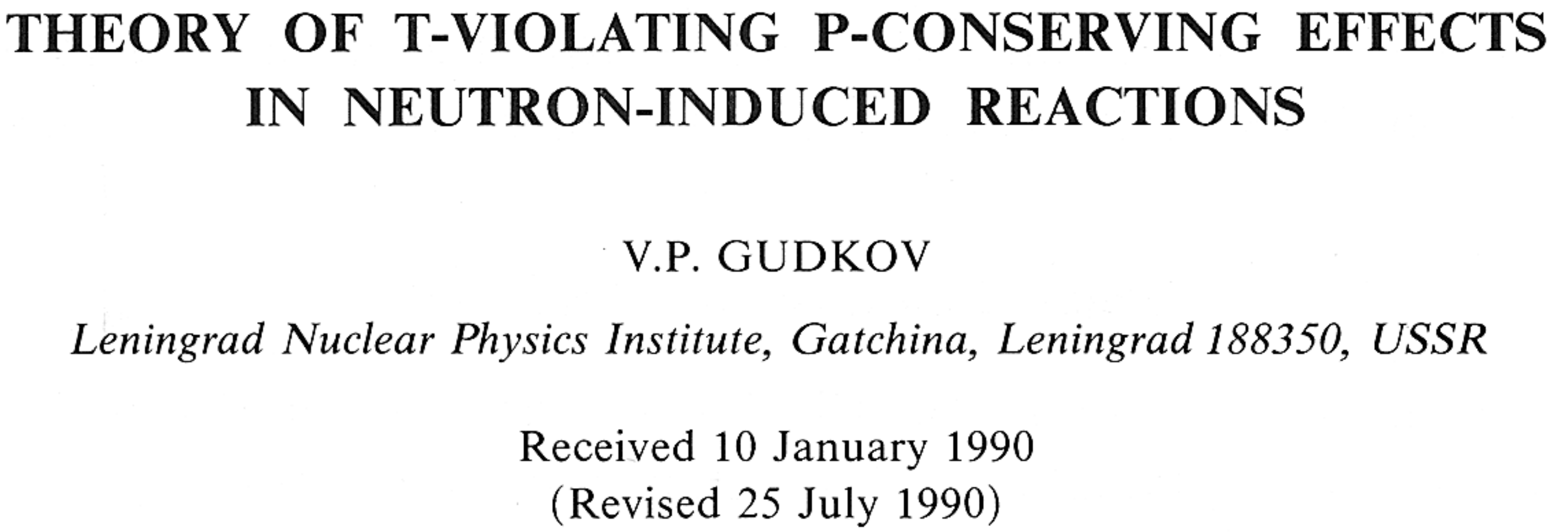


FIG. 1. The experimental setup for the fivefold correlation measurement. Vertically ($\pm\hat{\mathbf{y}}$) polarized neutrons with momentum $\hat{\mathbf{k}}$, directed along $\hat{\mathbf{z}}$, are transmitted through a nuclear-spin aligned holmium target and detected at 0°. The dashed lines depict the solid angle subtended by the neutron detectors. All components and distances are drawn to scale.



THEORY OF T-VIOLATING P-CONSERVING EFFECTS IN NEUTRON-INDUCED REACTIONS

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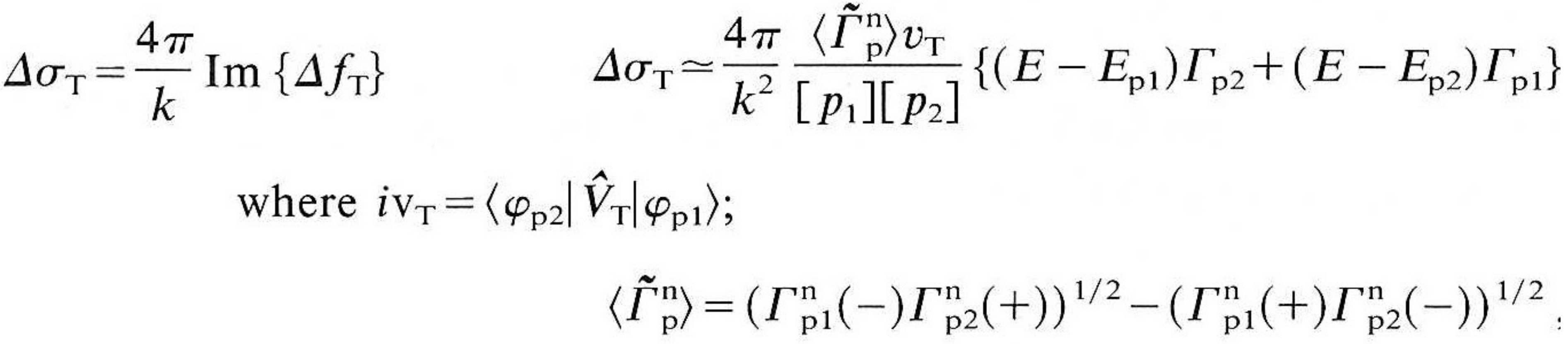
Received 10 January 1990
(Revised 25 July 1990)

Forward transmission ⇒ null test for T violation
Enhancement of asymmetry from high level density~10^3

P even-T-odd NN interactions can mix different p-wave resonances



$$\Delta\sigma_T = \frac{4\pi}{k}\,\mathrm{Im}\,\{\Delta f_T\} \qquad \Delta\sigma_T \simeq \frac{4\pi}{k^2}\frac{\langle\tilde{\Gamma}^{n}_{p}\rangle v_T}{[p_1][p_2]}\{(E-E_{p1})\Gamma_{p2}+(E-E_{p2})\Gamma_{p1}\}$$

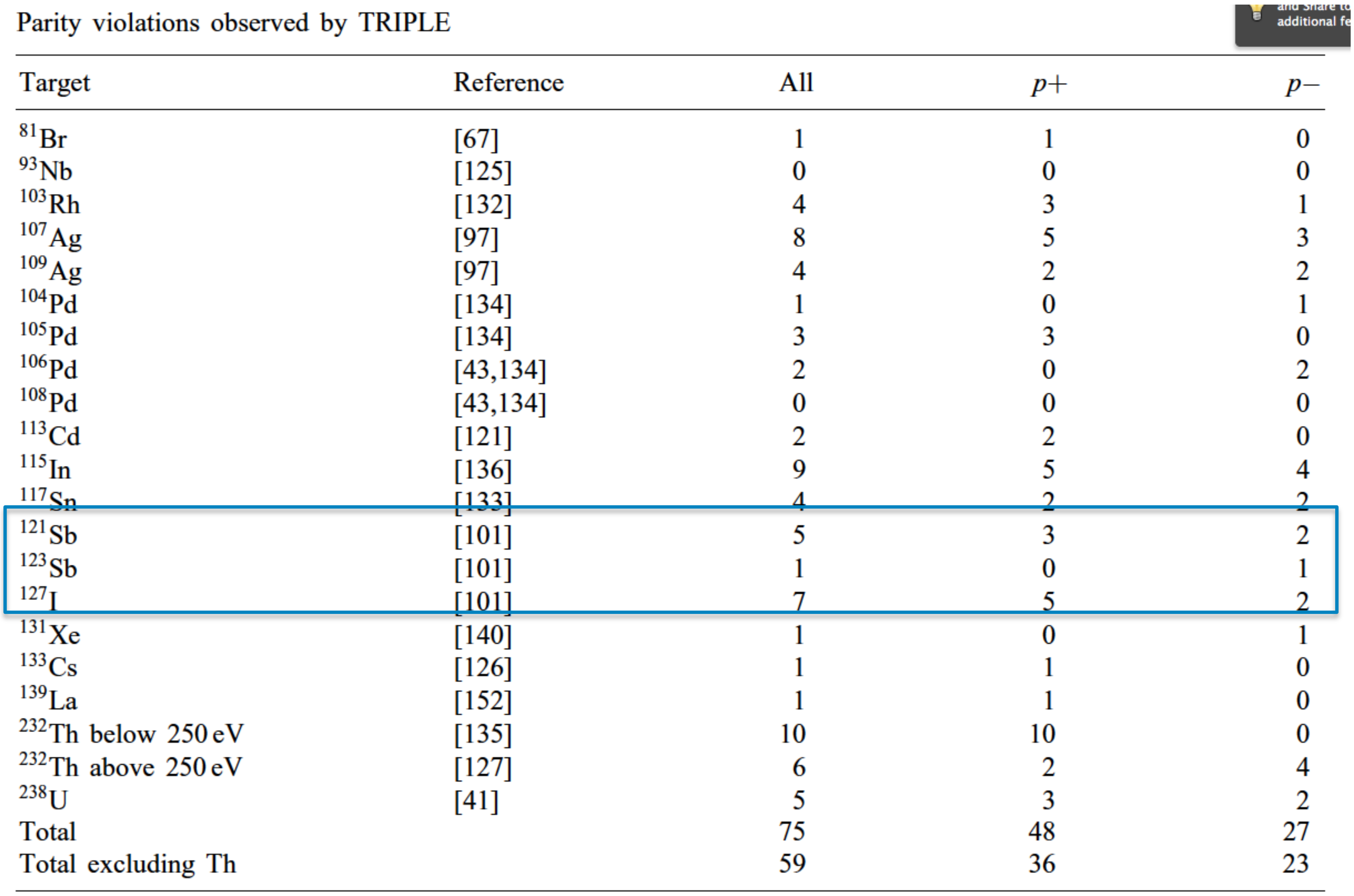
where $iv_T = \langle\varphi_{p2}|\hat{V}_T|\varphi_{p1}\rangle$;

$$\langle\tilde{\Gamma}^{n}_{p}\rangle = (\Gamma^{n}_{p1}(-)\Gamma^{n}_{p2}(+))^{1/2} - (\Gamma^{n}_{p1}(+)\Gamma^{n}_{p2}(-))^{1/2}$$

Γ_p (+) and Γ_p (-) = Γ_p (J=I±½)

P-odd Asymmetries on p-wave Neutron Resonances

G. E. Mitchell, J. D. Bowman, S. I Penttila, E. I. Sharapov, Phys. Rep. **354**, 1 (2001).



Parity violations observed by TRIPLE

Target	Reference	All	$p+$	$p-$
^{81}Br	[67]	1	1	0
^{93}Nb	[125]	0	0	0
^{103}Rh	[132]	4	3	1
^{107}Ag	[97]	8	5	3
^{109}Ag	[97]	4	2	2
^{104}Pd	[134]	1	0	1
^{105}Pd	[134]	3	3	0
^{106}Pd	[43,134]	2	0	2
^{108}Pd	[43,134]	0	0	0
^{113}Cd	[121]	2	2	0
^{115}In	[136]	9	5	4
^{117}Sn	[133]	4	2	2
^{121}Sb	[101]	5	3	2
^{123}Sb	[101]	1	0	1
^{127}I	[101]	7	5	2
^{131}Xe	[140]	1	0	1
^{133}Cs	[126]	1	1	0
^{139}La	[152]	1	1	0
^{232}Th below 250 eV	[135]	10	10	0
^{232}Th above 250 eV	[127]	6	2	4
^{238}U	[41]	5	3	2
Total		75	48	27
Total excluding Th		59	36	23

Current Status of Research on *T* Invariance in Neutron–Nuclear Reactions

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ISSN 1063-7796, Physics of Particles and Nuclei, 2007, Vol. 38, No. 6, pp. 775–794. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © A.G. Beda, V.R. Skoy, 2007, published in Fizika Elementarnykh Chastits i Atomnogo Yadra, 2007, Vol. 38, No. 6.

$$\begin{aligned} f = {} & A + pp_1B(\vec{s}\cdot\vec{I}) + pC(\vec{s}\cdot\vec{k}) + pp_1D(\vec{s}\cdot[\vec{k}\times\vec{I}]) \\ & + p_1E(\vec{k}\cdot\vec{I}) + pp_2F(\vec{k}\cdot\vec{I})(\vec{s}\cdot[\vec{k}\times\vec{I}]) \end{aligned} \qquad (6)$$

F term is P-even/T-odd

$$p = \frac{\langle m_s\rangle}{s} \qquad p_2 = \frac{3\langle m_I\rangle^2 - I(I+1)}{I(2I-1)}$$

Need polarized neutrons (p) and aligned nuclear target (p_2)

^{121}Sb, ^{123}Sb, ^{127}I have large electric quadrupole moments

Can be aligned by electric field gradients in crystals at low T

Need Γ_p ($J=I\pm½$) resonance parameters in ^{121}Sb, ^{123}Sb, ^{127}I , but not measured!

Electric Quadrupole Moment and Alignment

$$p_2(I) = \frac{3\langle m^2\rangle - I(I+1)}{I(2I-1)}$$

“alignment” parameter

Let Q=coupling strength of electric quadrupole moment of nucleus with a local E field gradient.

Then energy levels of m spin sublevels of nucleus are:

$$E_Q(m) = eQq\frac{3m^2 - I(I+1)}{4I(2I-1)}$$

Notice m^2 dependence! This interaction gives ZERO polarization!

Levels of Electric Quadrupole in E gradient

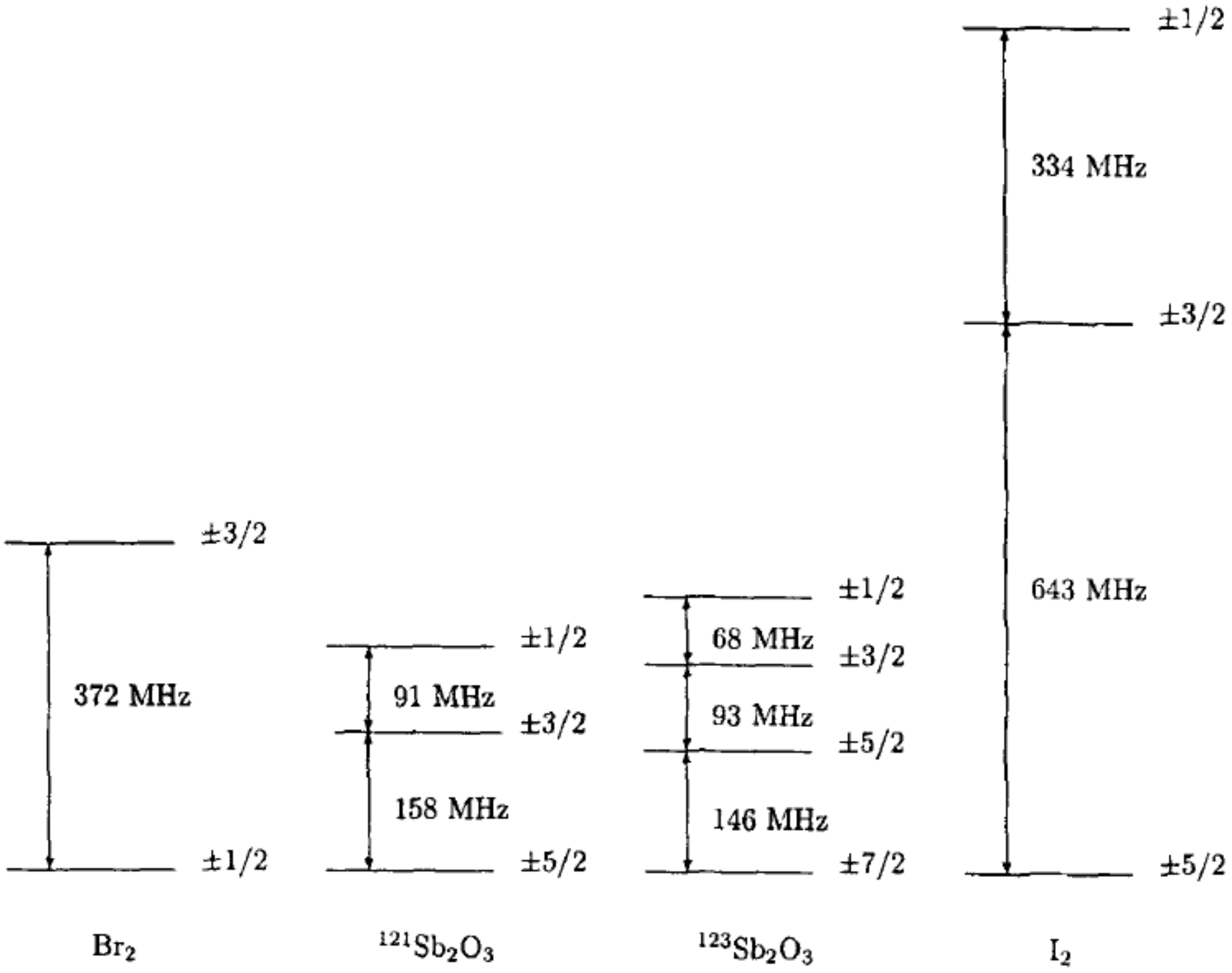


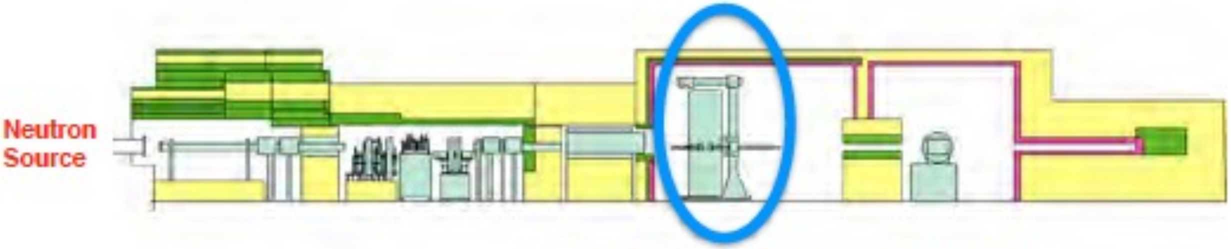
Fig. 1. Splitting of sublevels of the nuclei ^{81}Br, ^{121}Sb, ^{123}Sb and ^{127}I in the compounds Br_2, Sb_2O_3 and I_2 due to quadrupole interaction.

J-PARC MLF BL04 ANNRI

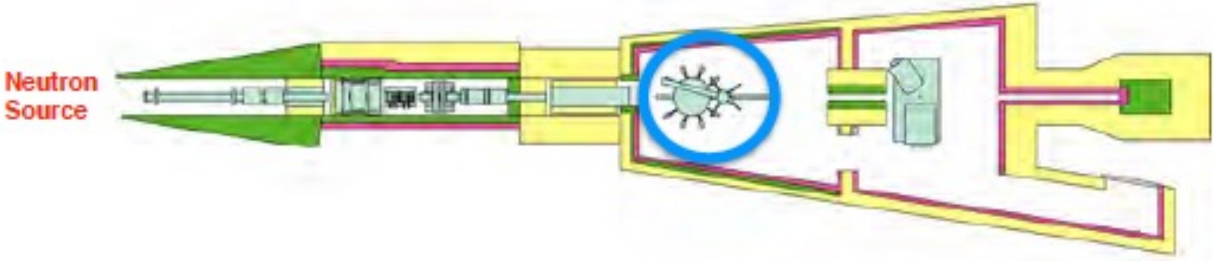
Resonance spectroscopy measurements at JPARC

14 Ge (+BGO) Detectors

θ=70,90,110 deg.



Ge Spectrometer (Flight Length: 21.5m)



Sample Materials : ^{nat}La, La^{nat}Br$_3$, ^{nat}Xe

Intensity : ~3 x 10^5 n/cm^2/s : 0.9 eV < En < 1.1eV @300kW

$\sigma(E_\gamma, E_{n,}, \theta)$ of (n,γ) reaction.

Γ_p (J=I±½) from angular distribution in (n, γ) capture on neutron resonances
see Okudaira et al, Phys. Rev. C **97**, 034622 (2018).

Conclusions

2 ways to violate T (+conserve CPT): P-odd/T-odd , P-even/T-odd

P-odd/T-odd effect can come from:
BSM P-odd/T-odd or [BSM P-even/T-odd][SM P-odd]

Experimental limits on P-even/T-odd NN interactions are quite poor (~10^9 worse than P-odd/T-odd in NN system!)

Polarized neutron transmission through tensor-aligned nuclear target on n-A resonances could improve P-even/T-odd NN limits by ~10^3

Known candidate nuclei exist (^{121}Sb, ^{123}Sb, ^{127}I), but present lack of spectroscopy info. Doable at JPARC, CSNS, LANSCE,…

Need cryo-aligned ^{127}I target, preferably eV-keV polarized neutrons. At IU we have one working “dry” DR and a spin refrigerator cryostat