Symmetry violation in nuclei

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Motivation (theory)

- Consistency for Parity Violating Effects
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Ann. Phys. (NY) **124**, 449 (1980).
  - S.-L. Zhu, C. M. Maekawa, B. R. Holstein, M. J. Ramsey-Musolf, and U. van Kolck, Nucl. Phys. A **748**, 435 (2005).
  - M. J. Ramsey-Musolf and S. A. Page, Annu. Rev. Nucl. Part.Sci. **56**, 1 (2006).
  - C. P. Liu, Phys. Rev. C **75**, 065501 (2007).

- New physics

Time Reversal Invariance Violation: independent test (for the case of suppression/cancelation)

- V. G., Phys. Rept. 212, 77 (1992)
- Y.-H. Song, R. Lazauskas and V. G., Phys. Rev. C83, 065503; Phys. Rev. C84, 025501 (2011)
- Y.-H. Song, and V. G. , AIP Conf. Proc. 1441, 582 (2012)

- Strong interactions

Short range properties of strong interactions

Y.-H. Song, R. Lazauskas and V. G., arXiv:1207. 7039 (2012)

Motivation (Experiment)

- High Intensity Neutron Facilities

  SNS in Oak Ridge, JSNS at J-PARC, ESS in Lund, NIST, ILL

- Polarized Gamma-Ray sources

  HIGS2 provides unique source of high intensity, highly polarized, controlled resolution photons

What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?

- A comprehensive analysis of Party Violating (PV) and Time Reversal Invariance Violating (TRIV) effects in three body system using DDH and EFT type potentials has been performed. (*All PV and TRIV effects were calculated using the same approach.*)

R. Schiavilla, M. Viviani, L. Girlanda, A. Kievsky, and L. E. Marcucci, Phys. Rev. **C78**, 014002 (2008).
Y.-H. Song, R. Lazauskas, and V.G. , Phys. Rev. C83, 015501 (2011); C83, 065503 (2011); Phys. Rev. C84, 025501 (2011); arXiv:1207. 7039 (2012).
J. Vanasse, Phys. Rev. **C86**, 014001 (2012).
H. W. Griesshammer, M. R. Schindler, R. P. Springer, Eur.Phys.J. A48, 7 (2012).

- As a result:
- (a) the possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach is found;
- (b) one can see a new opportunity to study a short range interactions in nuclei using PV effects;
- (c) For TRIV experiments in neutron-nuclear scattering at high intensity neutron sources a “discovery potential” of about $10^2 - 10^4$ is found for the improvement of the current limits on the TRIV interaction obtained from the EDM experiments.

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach

n	c_n^{DDH}	$f_n^{DDH}(r)$	$c_n^{\not\pi}$	$f_n^{\not\pi}(r)$	c_n^{π}	$f_n^{\pi}(r)$	$O_{ij}^{(n)}$
1	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\pi(r)$	$-\frac{\mu^2 C_6^{\not\pi}}{\Lambda_\chi^3}$	$f_\mu^{\not\pi}(r)$	$+\frac{g_\pi}{2\sqrt{2}m_N}h_\pi^1$	$f_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(1)}$
2	$-\frac{g_\rho}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i \cdot \tau_j)(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(2)}$
3	$-\frac{g_\rho(1+\kappa_\rho)}{m_N}h_\rho^0$	$f_\rho(r)$	0	0	0	0	$(\tau_i \cdot \tau_j)(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(3)}$
4	$-\frac{g_\rho}{2m_N}h_\rho^1$	$f_\rho(r)$	$\frac{\mu^2}{\Lambda_\chi^3}(C_2^{\not\pi}+C_4^{\not\pi})$	$f_\mu^{\not\pi}(r)$	$\frac{\Lambda^2}{\Lambda_\chi^3}(C_2^{\pi}+C_4^{\pi})$	$f_\Lambda(r)$	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(4)}$
5	$-\frac{g_\rho(1+\kappa_\rho)}{2m_N}h_\rho^1$	$f_\rho(r)$	0	0	$\frac{2\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(5)}$
6	$-\frac{g_\rho}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	$-\frac{2\mu^2}{\Lambda_\chi^3}C_5^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$-\frac{2\Lambda^2}{\Lambda_\chi^3}C_5^{\pi}$	$f_\Lambda(r)$	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(6)}$
7	$-\frac{g_\rho(1+\kappa_\rho)}{2\sqrt{6}m_N}h_\rho^2$	$f_\rho(r)$	0	0	0	0	$\mathcal{T}_{ij}(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(7)}$
8	$-\frac{g_\omega}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}C_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_1^{\pi}$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(8)}$
9	$-\frac{g_\omega(1+\kappa_\omega)}{m_N}h_\omega^0$	$f_\omega(r)$	$\frac{2\mu^2}{\Lambda_\chi^3}\tilde{C}_1^{\not\pi}$	$f_\mu^{\not\pi}(r)$	$\frac{2\Lambda^2}{\Lambda_\chi^3}\tilde{C}_1^{\pi}$	$f_\Lambda(r)$	$(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(9)}$
10	$-\frac{g_\omega}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(10)}$
11	$-\frac{g_\omega(1+\kappa_\omega)}{2m_N}h_\omega^1$	$f_\omega(r)$	0	0	0	0	$(\tau_i + \tau_j)^z(\boldsymbol{\sigma}_i \times \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(11)}$
12	$-\frac{g_\omega h_\omega^1 - g_\rho h_\rho^1}{2m_N}$	$f_\rho(r)$	0	0	0	0	$(\tau_i - \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,+}^{(12)}$
13	$-\frac{g_\rho}{2m_N}h_\rho^{\prime 1}$	$f_\rho(r)$	0	0	$-\frac{\sqrt{2}\pi g_A\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$L_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(13)}$
14	0	0	0	0	$\frac{2\Lambda^2}{\Lambda_\chi^3}C_6^{\pi}$	$f_\Lambda(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(14)}$
15	0	0	0	0	$\frac{\sqrt{2}\pi g_A^3\Lambda^2}{\Lambda_\chi^3}h_\pi^1$	$\tilde{L}_\Lambda^\pi(r)$	$(\tau_i \times \tau_j)^z(\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j)\cdot \boldsymbol{X}_{ij,-}^{(15)}$

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (2)

$$\frac{1}{N}\frac{d\phi^{\not p}}{dz} = (59\ \mathrm{rad}\cdot\mathrm{fm}^2)\left[h_\pi^1 + h_\rho^0(0.10) + h_\omega^0(0.14) + h_\rho^1(-0.042) + h_\omega^1(-0.12) + h_\rho^{\prime 1}(0.014)\right]$$

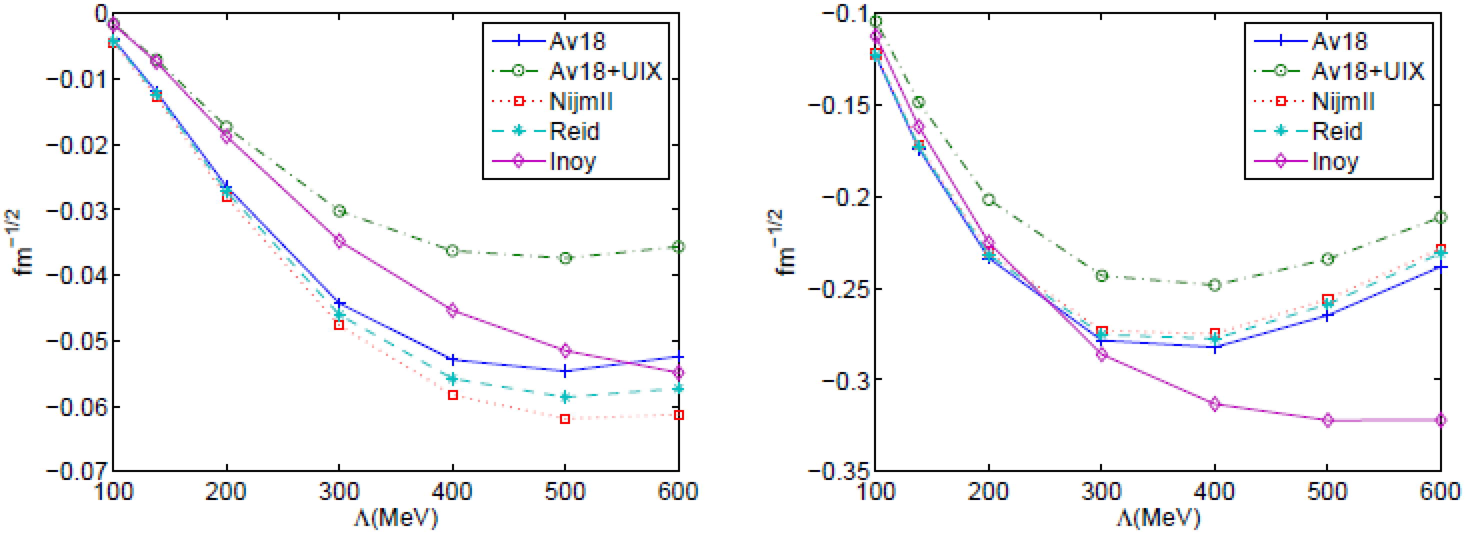
$$P^{\not p} = \frac{\Delta\sigma^{\not p}}{2\sigma_{tot}} = \frac{(0.140\ \mathrm{b})}{2\sigma_{tot}}\left[h_\pi^1 + h_\rho^0(0.021) + h_\omega^0(0.022) + h_\rho^1(0.002) + h_\omega^1(-0.044) + h_\rho^{\prime 1}(-0.012)\right]$$

$$\begin{aligned}
a_n &= 0.42h_\pi^1 - 0.17h_\rho^0 + 0.085h_\rho^1 + 0.008h_\rho^2 \\
&\quad -0.238h_\omega^0 + 0.086h_\omega^1 - 0.010h_\rho^{\prime 1} = 4.11\times 10^{-7} \\
P_\gamma &= -1.05h_\pi^1 + 0.19h_\rho^0 - 0.096h_\rho^1 - 0.018h_\rho^2 + 0.28h_\omega^0 \\
&\quad -0.046h_\omega^1 + 0.023h_\rho^{\prime 1} = -7.31\times 10^{-7} \\
A_d^\gamma &= -1.51h_\pi^1 + 0.17h_\rho^0 - 0.083h_\rho^1 - 0.024h_\rho^2 + 0.024h_\omega^0 \\
&\quad +0.013h_\omega^1 + 0.032h_\rho^{\prime 1} = -9.05\times 10^{-7}.
\end{aligned}$$

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (3)

models	DDH-best values a_n	P_γ	A_d	4-parameter fits a_n	P_γ	A_d
AV18+UIX/DDH-I	3.30	−6.38	−8.23	1.97	−2.16	−1.81
AV18/DDH-II	4.61	−8.30	−10.3	4.60	−5.18	−4.46
AV18+UIX/DDH-II	4.11	−7.30	−9.04	4.14	−4.71	−4.09
Reid/DDH-II	4.74	−8.45	−10.4	4.70	−5.25	−4.46
NijmII/DDH-II	4.71	−8.45	−10.5	4.76	−5.26	−4.41
INOY/DDH-II	9.24	−12.9	−13.8	17.5	−17.9	−13.5

(a) The possible reason for the existing discrepancy in PV nuclear data analysis using the DDH approach (4)



(a)$\mu^2\widetilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 1 (b)$\mu^2\widetilde{\mathcal{E}}_{\frac{3}{2}(+)}$ for operator 9

(c) Discovery potential for TRIV in neutron-nuclear scattering

- **“Weak” structure**

$$\frac{\Delta\sigma^{T\not{P}}}{\Delta\sigma^{\not{P}}} \sim \left(\frac{\bar{g}_{\pi}^{(0)}}{h_{\pi}^{1}} + (0.26)\frac{\bar{g}_{\pi}^{(1)}}{h_{\pi}^{1}} \right)$$

$h_{\pi}^{1} \sim 4.6 \cdot 10^{-7}$ "best" DDH

or 10 - 100 Enhancement!!!

- **“Strong” structure**

P-violation:

$$(\vec{\sigma}_n \cdot \vec{k}) \sim 10^{-1} (not\ \ 10^{-7})$$

Enhanced of about $\sim 10^6$

O. P. Sushkov and V. V. Flambaum, JETP Pisma 32 (1980) 377

V. E. Bunakov and V.G., Z. Phys. A303 (1981) 285

(c) Discovery potential for TRIV in neutron-nuclear scattering (2)

From n EDM [1]

$$\bar{g}_{\pi}^{(0)} < 2.5 \cdot 10^{-10}$$

$$d_n = \frac{e}{4\pi m_N} \bar{g}_{\pi}^{(0)} g_{\pi} \ln \frac{\Lambda}{m_{\pi}}$$

From ^{199}Hg EDM [2]

$$\bar{g}_{\pi}^{(1)} < 0.5 \cdot 10^{-10}$$

$$\Rightarrow \quad \frac{\not{T}\not{P}}{\not{P}} \sim 10^{-3}$$ from the current EDMs

$\equiv$ "discovery potential" 10^2 (nucl) -- 10^4 (nucl & "weak")

- M. Pospelov and A. Ritz (2005)
- V. Dmitriev and I. Khriplovich (2004)

What compelling and unique science is to be done in the next 5 years?

- Developing theory to describe PV and TRIV in light (A=4-10) nuclei
- Applying developed theory for a study of strong short range interactions in light nuclei
- To test theory using most sensitive experiments
- Developing theory and experimental approaches to search for TRIV in nuclei as a complementary to the EDM and independent approach to search for new physics beyond the standard model.

What science would you expect to pursue in the program in 2020 and beyond?

- To develop precise many-body approaches for study the possible manifestations of new physics in low energy (nuclear and atomic) physics: *TRIV, exotic interactions, neutrino-nuclear interactions, etc.*

What is the international context, and how does it affect your vision?

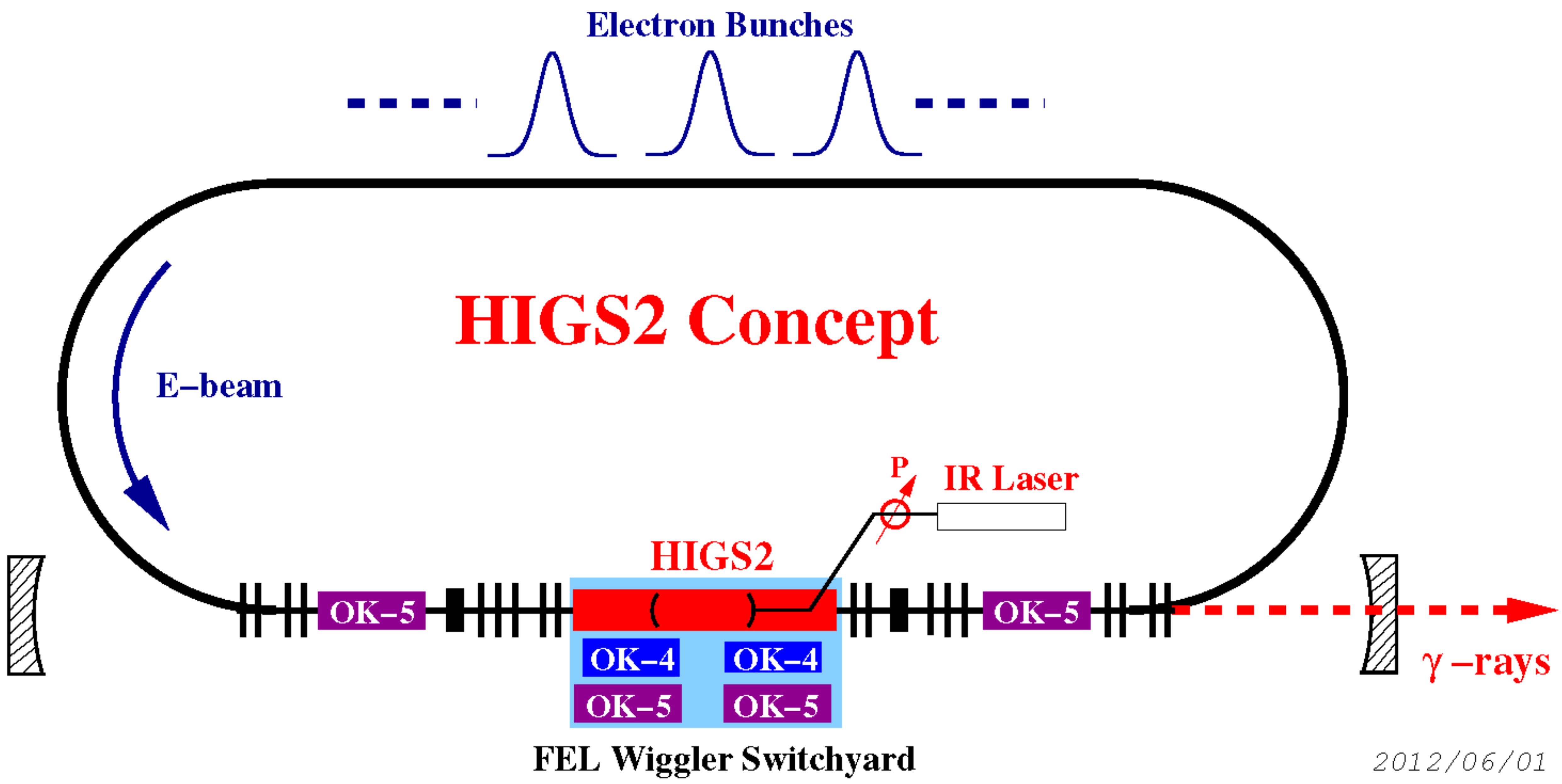
- There are a number of proposals for high intensity neutron sources and low energy neutrino sources to test the Standard model and to search for new physics. They require new theory approaches which are capable to unambiguously calculate a background related to the Standard model and to predict possible manifestations of new physics. Therefore, this program will be very beneficial for national and international collaborations working at the SNS (ORNL), J-PARC (Japan), European Spallation Neutron Source (Lund), Institute Laue-Langevin (France), High Intensity Gamma Source at TUNL/DFELL (HIGS2) etc.

Conclusions

- We know how to resolve the “consistency problem” for PV in nuclear
  - Primary, there is a lot of work for theory
  - It will require new precise experiments
- The expected important outcome:
  - The opportunity to search for new physics (nuclear enhancement)
  - New sensitive method to study short range strong interactions

Parity Violation in Few Nucleon Systems at Low Energy

From a proposed upgrade of the High Intensity Gamma Source at TUNL/DFELL -- HIGS2



- PV in nuclei currently not understood
- Milestone F18 from 2007 LRP ``Perform independent measurements of parity violation in few-body systems to constrain the non-leptonic weak interaction"
- Effective Field Theory of QCD/Weak interactions available to analyze measurements in few nucleon systems
- At low energies five LECs must be determined to establish consistency
- Photon induced PV asymmetries required
- HIGS2 provides unique source of high intensity, highly polarized, controlled resolution photons
- HIGS2 is designed using known accelerator and laser technology

Expected Range of HIGS2 Machine Specifications

Parameters	Value Range
Gamma-ray Beam Energy (With an external laser of wavelength = 2 microns, Subject to change based upon scientific programs)	2 - 12 MeV
Gamma-ray Beam Pulse Rate	89.3 MHz
Polarization (Rapid Switch) (Degree of polarization depends on collimation, laser beam polarization, electron beam energy, etc)	Linear and Circular (90% - 99%)
Total Gamma-ray Flux Collimated flux = 0.015 x (total flux) x (FWHM energy resolution in %)	10^{11} - 10^{12} photons/second
Best Energy Resolution (Tight collimation and at a low flux)	FWHM < 0.5 %
Gamma-ray Beam Angular Spread (full opening) (=D/L, D is the collimator diameter, L=53 m)	Typical D/L = 0.19 - 0.60 mrad Dmin = 10 mm, Dmax = 32 mm
Full Beam "Without" Collimation	D ~ 32 mm (effective collimation)
Gamma-ray beam angular spread	D/L ~ 0.6 mrad
Gamma-ray beam energy spread	7% (2 MeV) to 30% (12 MeV)

$$\vec{\gamma} d \to np$$

$$P_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = -2\sqrt{\frac{r^{(^3S_1)}}{\pi}} \frac{M^2}{\kappa_1 \left(1 - \gamma a^{(^1S_0)}\right)} \left[\left(1 - \frac{2}{3}\gamma a^{(^1S_0)}\right) g^{(^3S_1 - ^1P_1)} + \frac{\gamma a^{(^1S_0)}}{3}\sqrt{\frac{r^{(^1S_0)}}{r^{(^3S_1)}}} \left(g^{(^1S_0 - ^3P_0)}_{(\Delta I = 0)} - 2 g^{(^1S_0 - ^3P_0)}_{(\Delta I = 2)}\right)\right]$$