INDIANA UNIVERSITY BLOOMINGTON

ANNRI Data Analysis and PV Measurements at J-PARC

Clayton Auton

NOPTREX China Meeting 2023

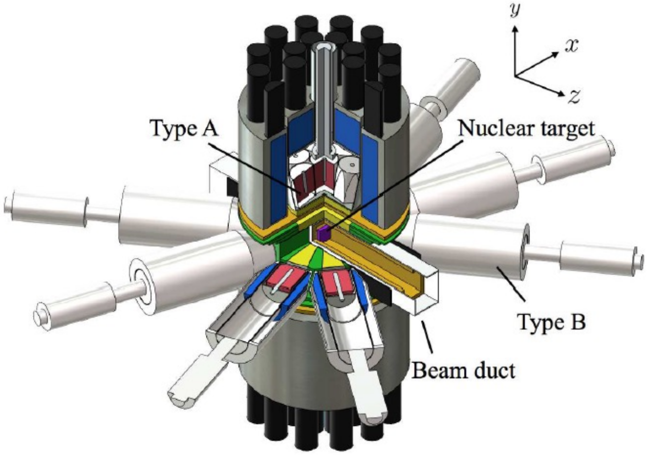
supported by NSF PHY-1913789

Enhancement of T-odd effects

$$\Delta\sigma_{PT} = \frac{4\pi}{k}\mathrm{Im}(f_\uparrow - f_\downarrow)$$

$$\Delta\sigma_P = \frac{4\pi}{k}\mathrm{Im}(f_- - f_+)$$

- Measure κ(J) using (n,γ) resonance spectroscopy
- Almost no data on κ(J) before NOPTREX
- Ongoing measurements using ANNRI Ge detector array at J-PARC



$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} = \kappa(J)\frac{w}{v}$$

$$\langle\phi_s|V_P + W_{PT}|\phi_p\rangle = v + iw$$

Gudkov, Phys. Rep. **212** 77 (1992)

$\kappa(J)$ Spin Factor

total angular momenta — orbit — n spin — nuclear spin

$$J = \underbrace{\ell + \overbrace{s}^{}}_{j}\;\; + I$$

$$J = \ell + s + I, \quad j = \ell + s, \quad S = s + I$$

n entrance spin j — S channel spin

$\Downarrow$ $\qquad\qquad$ $\Downarrow$

$$J = j + I \qquad\qquad J = \ell + S$$

$$P : |\ell s I\rangle \to (-1)^{\ell} |\ell s I\rangle$$

$$\ell = 0{,}1$$

$$\Downarrow$$

P-odd ⇒ s-wave and p-wave interference

$$T : |\ell s I\rangle \to (-1)^{i\pi S} K |\ell s I\rangle$$

$$S = I \pm 1/2$$

$$\Downarrow$$

T-odd ⇒ channel spin S interference

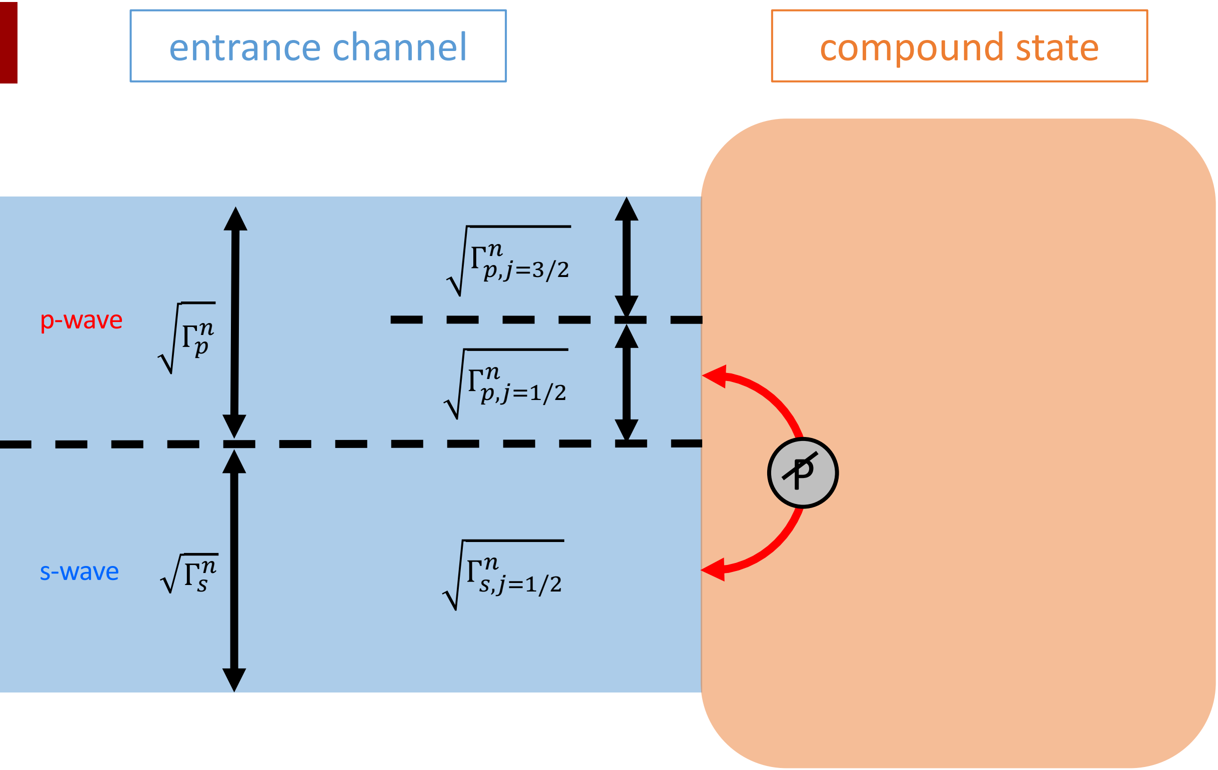
V. Gudkov and H. Shimizu, Phys. Rev. C **97**, 065502 (2018)

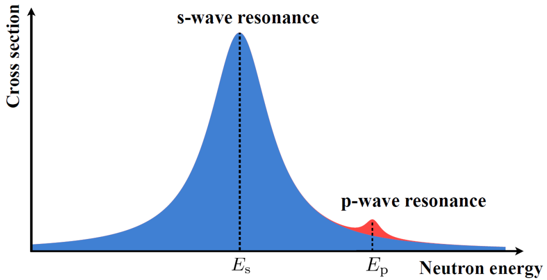
P-odd ⇒ s-wave and p-wave interference

total angular momenta, orbit, n spin, nuclear spin

$$J = \underbrace{\ell + s}_{j} + I, \qquad \underbrace{s + I}_{S}$$

n entrance spin j, S channel spin





states with different ℓ

but same $J = I + \frac{1}{2}$, $j = 1/2$

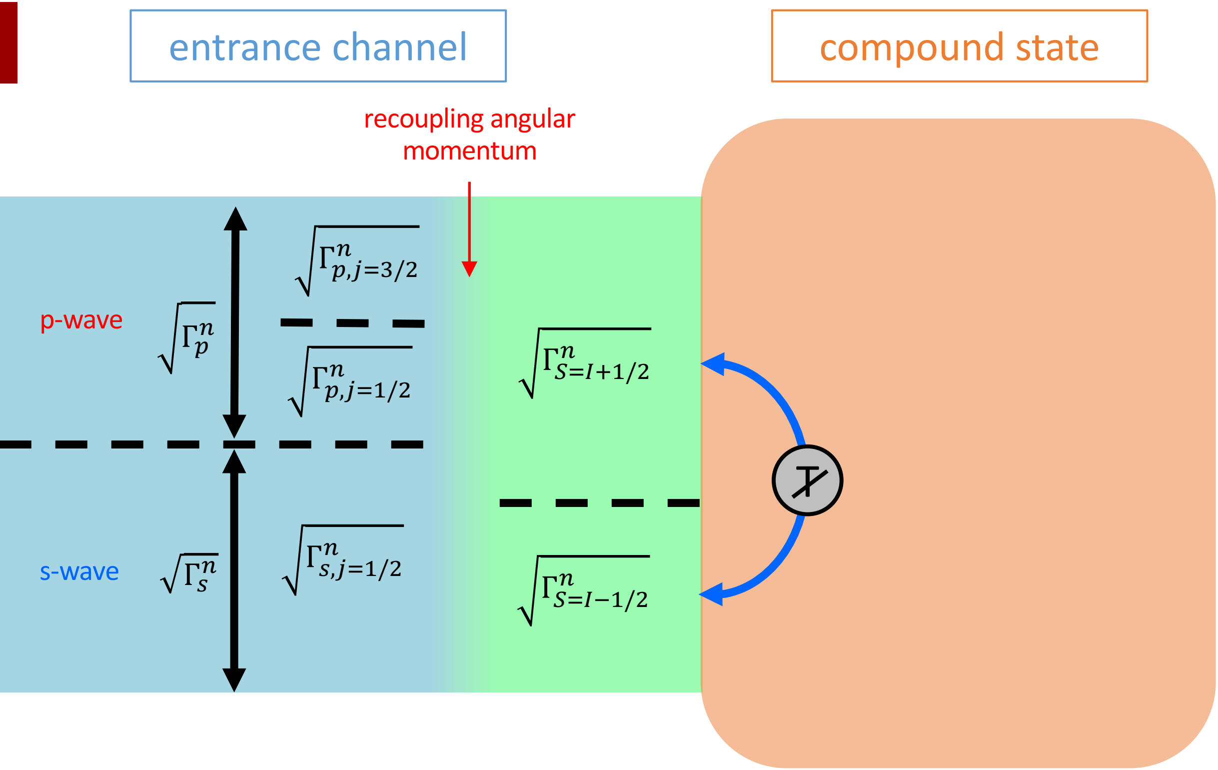
V. Gudkov and H. Shimizu, Phys. Rev. C **97**, 065502 (2018)

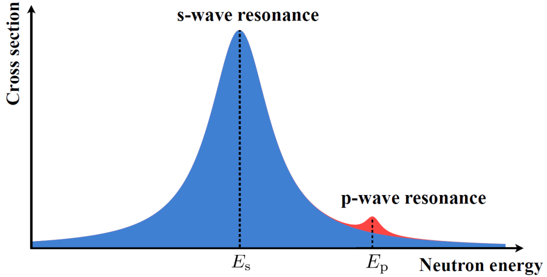
T-odd ⇒ channel spin S interference

total angular momenta | orbit | n spin | nuclear spin

$$J = \ell + s + I$$

$\ell + s$: n entrance spin j; $s + I$: channel spin S





states with different $S = I \pm 1/2$

but same $J = I + \frac{1}{2}$

V. Gudkov and H. Shimizu, Phys. Rev. C **97**, 065502 (2018)

$$\Delta\sigma_P = \frac{4\pi}{k}\mathrm{Im}(f_- - f_+) \qquad \Delta\sigma_{PT} = \frac{4\pi}{k}\mathrm{Im}(f_\uparrow - f_\downarrow)$$

ratio of differences in total neutron cross section

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} = \kappa(J)\frac{w}{v}$$

with

$$\langle\phi_s|V_P + W_{PT}|\phi_p\rangle = v + iw$$

$$\begin{cases} \kappa(J = I + 1/2) = \left[\frac{\sqrt{I}}{2(I+1)}\right]\left(-2\sqrt{I} + \sqrt{2I+3}\frac{y}{x}\right) \\ \kappa(J = I - 1/2) = \left[\frac{1}{2\sqrt{I+1}}\right]\left(2\sqrt{I+1} + \sqrt{2I-1}\frac{y}{x}\right) \end{cases}$$

V. Gudkov and H. Shimizu, Phys. Rev. C **97**, 065502 (2018)

$$\begin{cases} \kappa(J=I+1/2) = \left[\frac{\sqrt{I}}{2(I+1)}\right]\left(-2\sqrt{I}+\sqrt{2I+3}\frac{y}{x}\right) \\ \kappa(J=I-1/2) = \left[\frac{1}{2\sqrt{I+1}}\right]\left(2\sqrt{I+1}+\sqrt{2I-1}\frac{y}{x}\right) \end{cases}$$

$J = I + 1/2$ corresponds to the p-wave resonance

$$x \equiv \sqrt{\frac{\Gamma^n_{p,j=1/2}}{\Gamma^n_p}}$$

$$y \equiv \sqrt{\frac{\Gamma^n_{p,j=3/2}}{\Gamma^n_p}}$$

can be measured in (n,γ)

can reparametrize in terms of j=1/2, 3/2 mixing angle

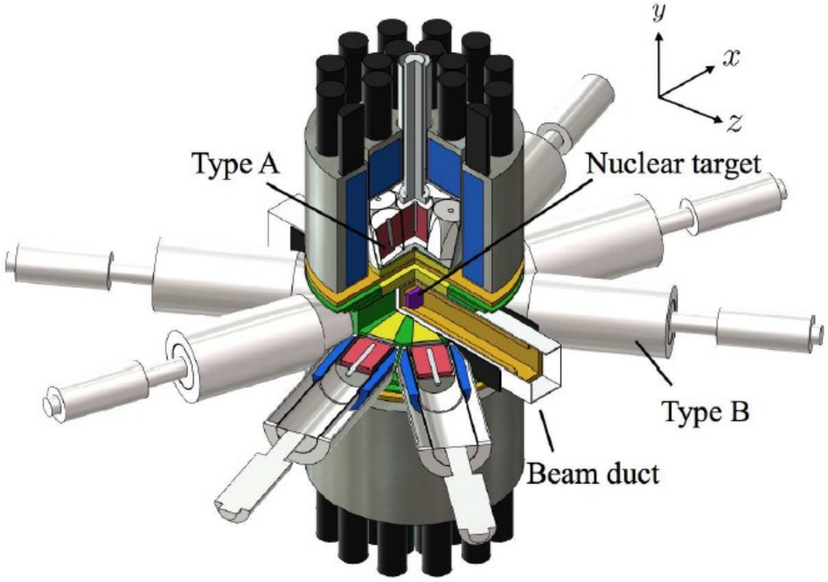
$$x^2 + y^2 = 1 \implies \begin{matrix} x = \cos\phi \\ y = \sin\phi \end{matrix}$$

V. Gudkov and H. Shimizu, Phys. Rev. C **97**, 065502 (2018)

ANNRI Data

ANNRI Detector at JPARC

- High-Purity Germanium Detectors (HPGE)
  - 14 vertical detectors (Type-A)
  - 8 horizontal detectors (Type-B)
- Bismuth Germinate (BGO)
  - 20 crystals surrounding HPGE detectors
  - Summed into 4 channels
- Increased JPARC power to 830 kW



T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

Raw HPGE Data

- CAEN v1724 100-MHz 14-bit ADC
- Gamma ray events are converted from pulse shape to
  - Pulse height
  - Time-of-flight
- Overlapping event are flagged as pile-up events
- Coincidence, timestamp, and trigger number also recorded

```
Column        Type
------        ----
Flags         UInt_t
PulseHeight   UShort_t
Timestamp     ULong64_t
Coin          UInt_t
detector      Int_t
nTrigger      ULong64_t
tof           ULong64_t
```

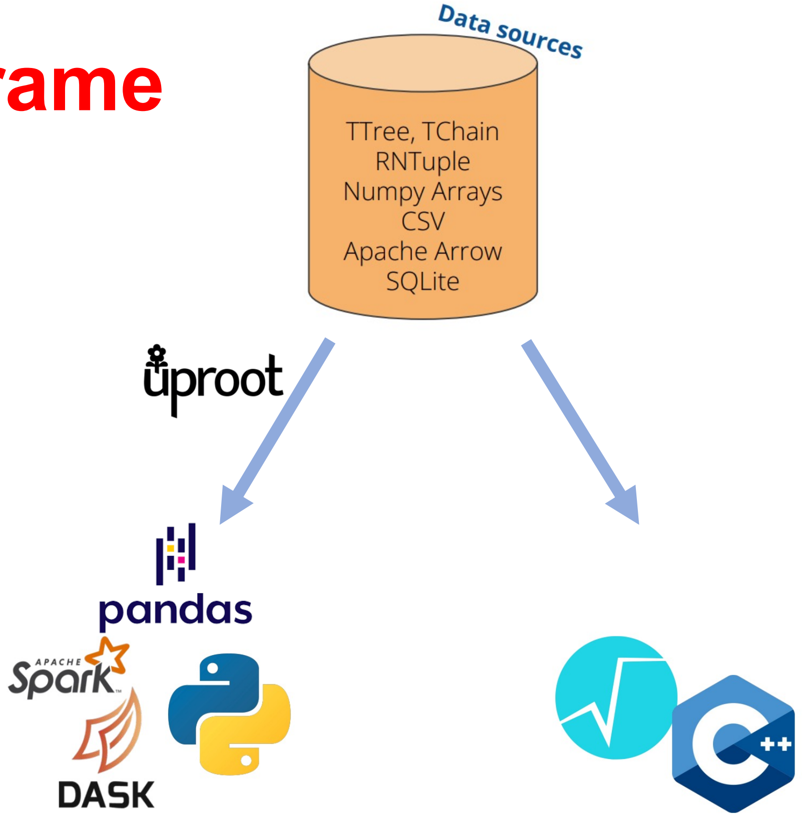
Raw Data Example

- Rows are single detector events

Row	Coin	Flags	PulseHeight	Timestamp	detector	nTrigger	tof
0	0	0	481	3941640000	20	0	394164
1	1	0	435	30796670000	21	0	3079667
2	1	0	435	30796670000	22	0	3079667
3	1	0	435	30796670000	23	0	3079667
4	0	0	1343	4094890000	19	0	409489

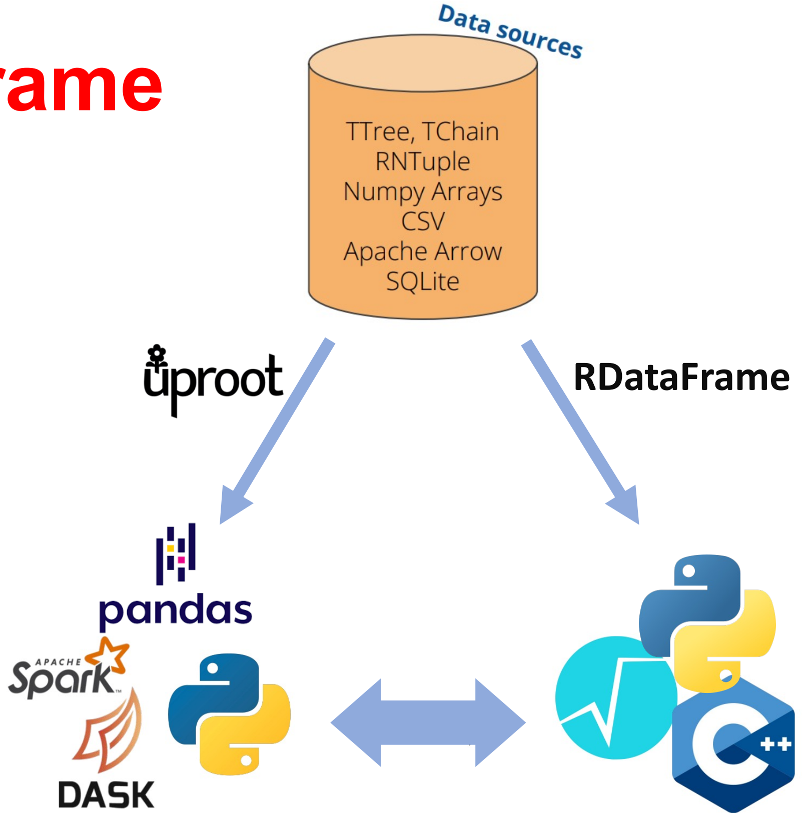
Analysis Using RDataFrame

- Similar to popular frameworks like Pandas/Dask
- Can work with data sets larger than memory
- Allows multi-threading
- Lazy actions reduce number of event loops in computation graph
- JIT compiled C++ in PyROOT



Analysis Using RDataFrame

- Similar to popular frameworks like Pandas/Dask
- Can work with data sets larger than memory
- Allows multi-threading
- Lazy actions reduce number of event loops in computation graph
- JIT compiled C++ in PyROOT



RDataFrame Example

```python
import ROOT

# enable multi-thread event loop
ROOT.EnableImplicitMT()

# read in the TTree
df = ROOT.RDataFrame(tree_name, file_name)

# add a user defined column and filter
df = df.Define("En","pow((72.3*21.5/(tof/100.0)),2)").Filter("detector == 1")

# create a histogram and draw
hist = df.Histo1D(("hEn_d1", "hEn_d1; En [eV]; Counts", 1000, 0, 100),"En")

hist.Draw()
```

RDataFrame Example

using PyROOT

easy parallelism

JIT compiled C++ expression

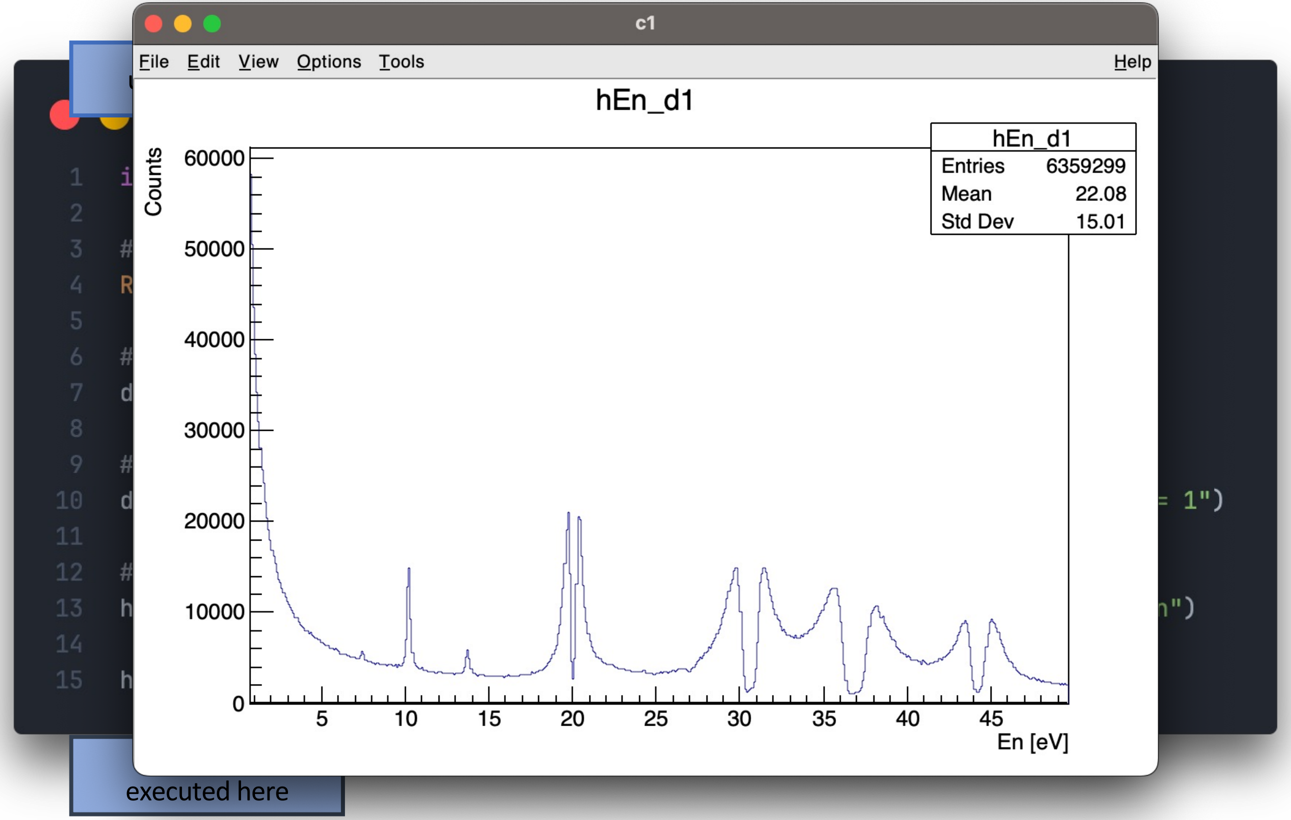
define and Filter are lazy actions

```python
import ROOT

# enable multi-threa vent loop
ROOT.EnableImplicitMT()

# read in the TTree
df = ROOT.RDataFrame(tree_

# add a user defined column and fi er
df = df.Define("En","pow((72.3*21.5/(tof/100.0)),2)").Filter("detector == 1")

# create a histogram and draw
hist = df.Histo1D(("hEn_d1", "hEn_d1; En [eV]; Counts", 1000, 0, 100),"En")

hist.Draw()
```

event loop is executed here

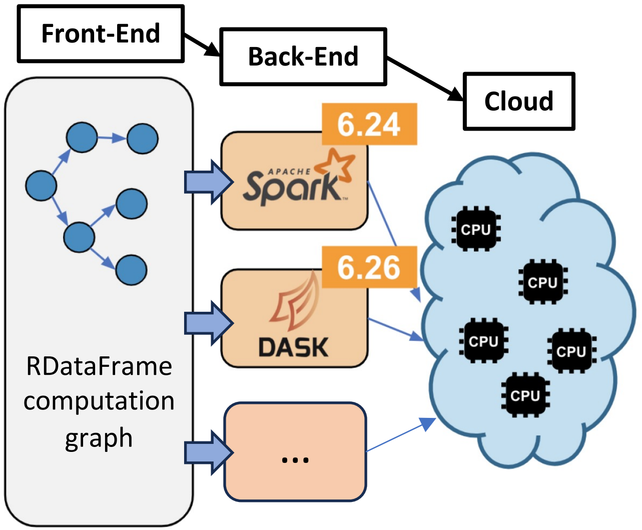
fill histogram with given column (lazy)

RDataFrame Example



Why RDataFrame?

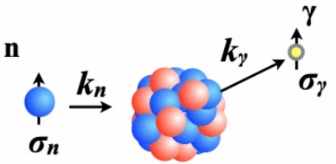
- Enables interactive and idiomatic large-scale distributed data analysis
- Python API (PyROOT) with C++ event loop
- Short learning-curve:
  - No TTreeReader + explicit event loop
  - No TTRee::Draw()
- Native multi-threading
- Scalable with cluster backends such as Spark, Dask, …



$\kappa(J)$ Measurement & Analysis Method

Angular distribution of (n,γ) reactions

V. V. Flambaum et al, Nuclear Physics A, vol. 435, no. 2, pp. 352 – 380, 1985.



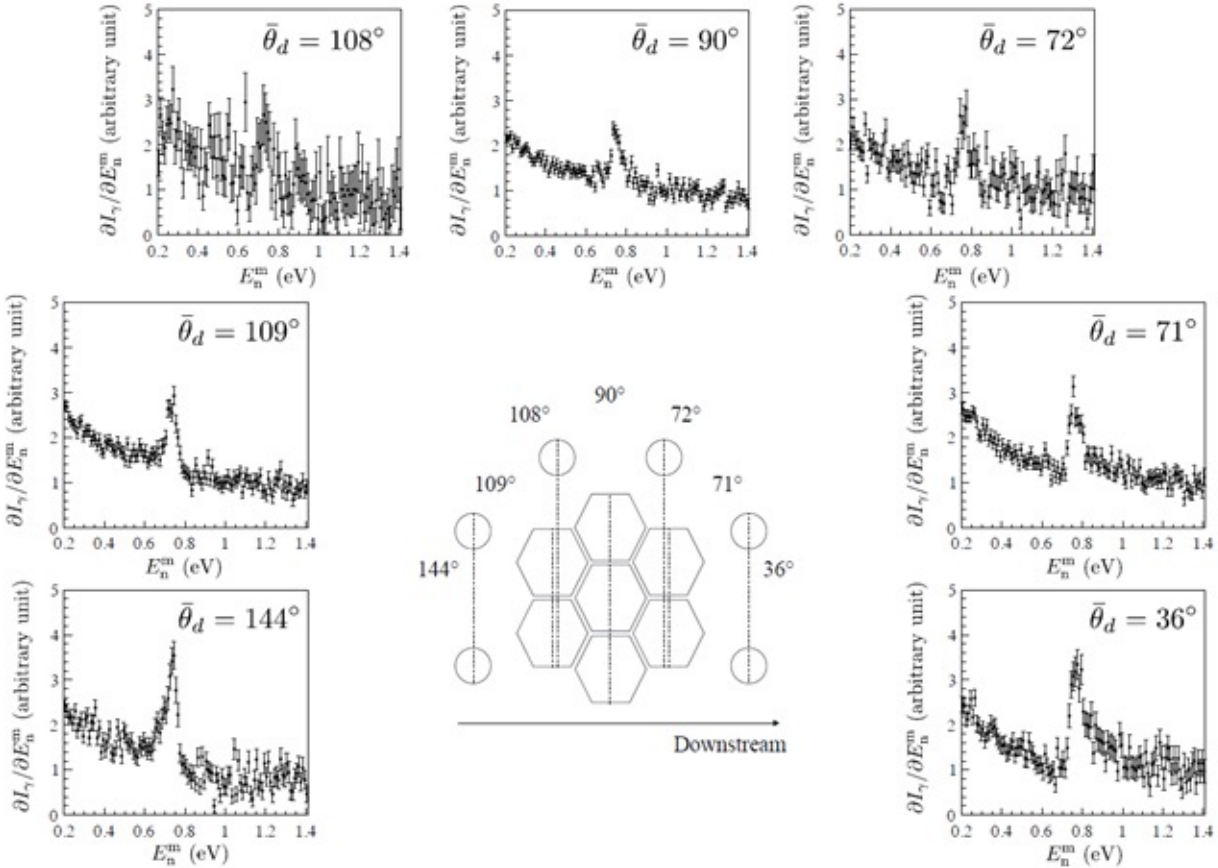
$$
\begin{aligned}
\frac{d\sigma_{n\gamma_f}}{d\Omega_\gamma} = \frac{1}{2}\Big(& a_0 + a_1 \hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma + a_2 \boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma) + a_3 \left((\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_4 (\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma)) + a_5 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_6 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n) + a_7 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_n) - \frac{1}{3} \boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n \right) \\
& + a_8 (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} \boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma \right) \\
& + a_9 \boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma + a_{10} \boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n + a_{11} \left((\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_\gamma \cdot \hat{\boldsymbol{k}}_n) - \frac{1}{3} (\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n) \right) \\
& + a_{12} (\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_n) \left((\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma) - \frac{1}{3} (\boldsymbol{\sigma}_n \cdot \hat{\boldsymbol{k}}_\gamma) \right) \\
& + a_{13} \boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma + a_{14} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma) \\
& + a_{15} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma) + a_{16} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma) \left((\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)^2 - \frac{1}{3} \right) \\
& + a_{17} (\boldsymbol{\sigma}_\gamma \cdot \hat{\boldsymbol{k}}_\gamma)(\hat{\boldsymbol{k}}_n \cdot \hat{\boldsymbol{k}}_\gamma)(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_\gamma)) \Big),
\end{aligned}
$$

- κ(J) related to a_1 via ϕ
- Measured using unpolarized neutrons and target

a term can be written by Φ parameter

10

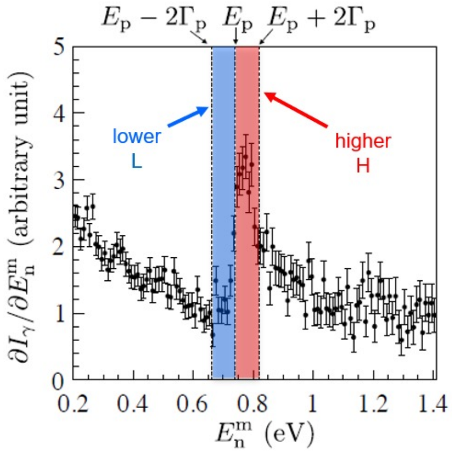
^{139}La(n,γ) data example



T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

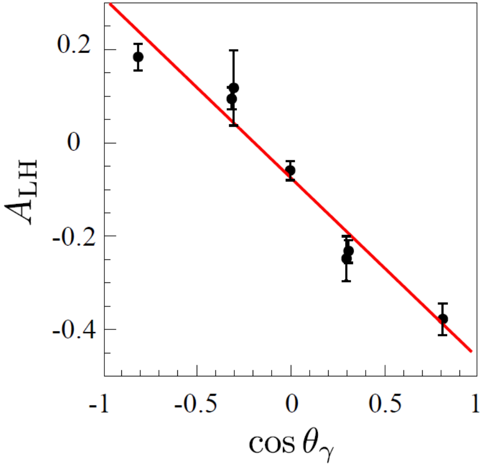
Measure a lower/higher asymmetry on p-wave resonance

$$A_{LH} \equiv \frac{N_L - N_H}{N_L + N_H}$$



A_{LH} has correlation with $\cos\theta_\gamma$

$$A_{LH}(\theta_\gamma) = A\cos\theta_\gamma + B$$



Can extract values for A, B from fit

T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

$$A_{LH}(\theta_\gamma) = A\cos\theta_\gamma + B$$

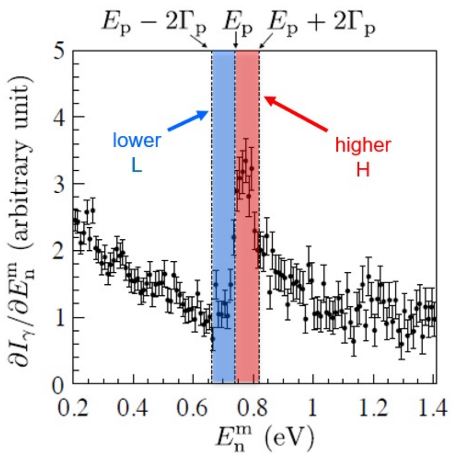
from fit

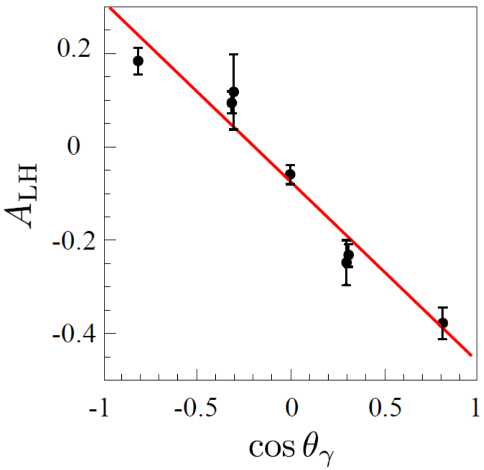
can show $$A = Cx + Dy$$

from resonance parameters

$$x \equiv \sqrt{\frac{\Gamma^n_{p,j=1/2}}{\Gamma^n_p}}$$

$$y \equiv \sqrt{\frac{\Gamma^n_{p,j=3/2}}{\Gamma^n_p}}$$

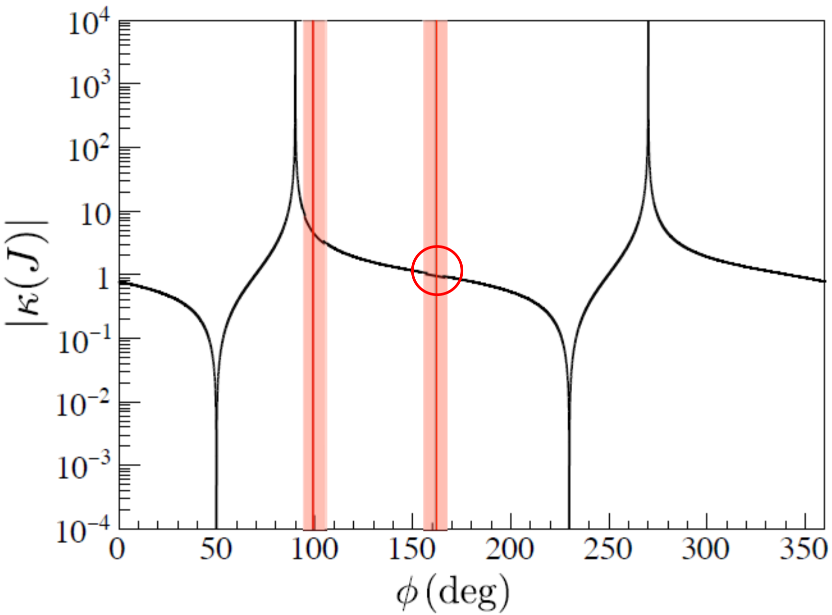




can solve for x and y giving two solutions!

T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

- Measured in ^{139}La 0.73 eV p-wave
  - κ(J) ~0.53
  - The first measurement of κ(J) ever

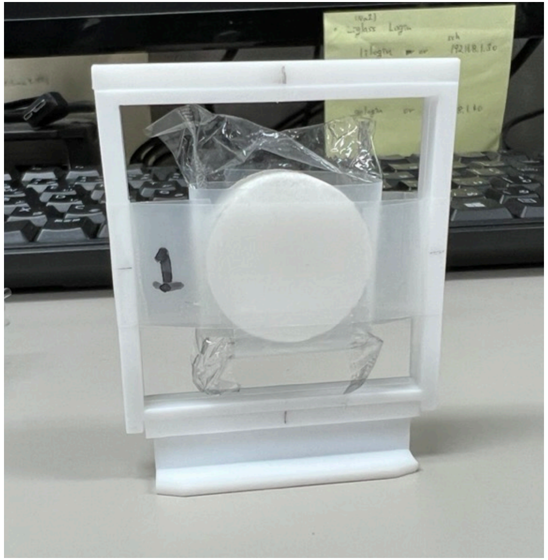


$$x = cos\phi, y = sin\phi$$

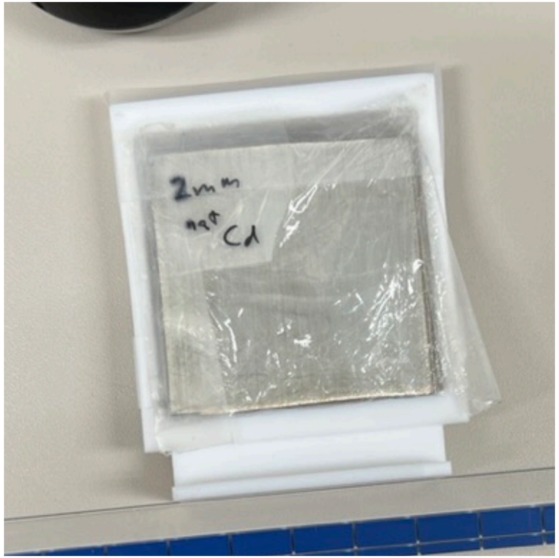
T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

^{127}I and ^{111}Cd a_1 measurements

Targets



- NaI
- 10 mmt, 24 mmϕ
- 20 mmt self-filter



- ^{nat}Cd
- 2 mmt
- 4 mmt self-filter

^{127}I resonances

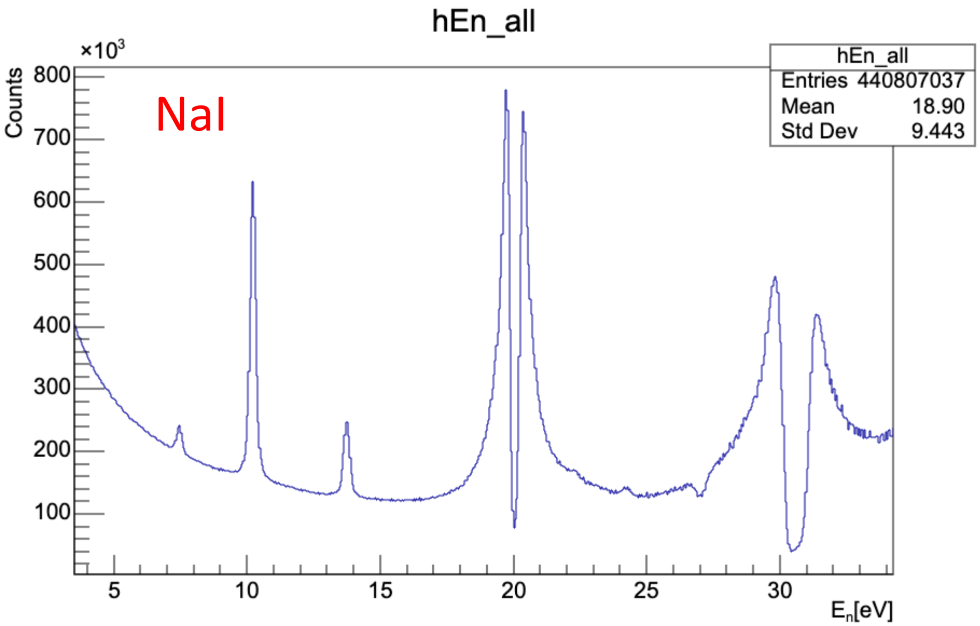
largest PV asymmetry

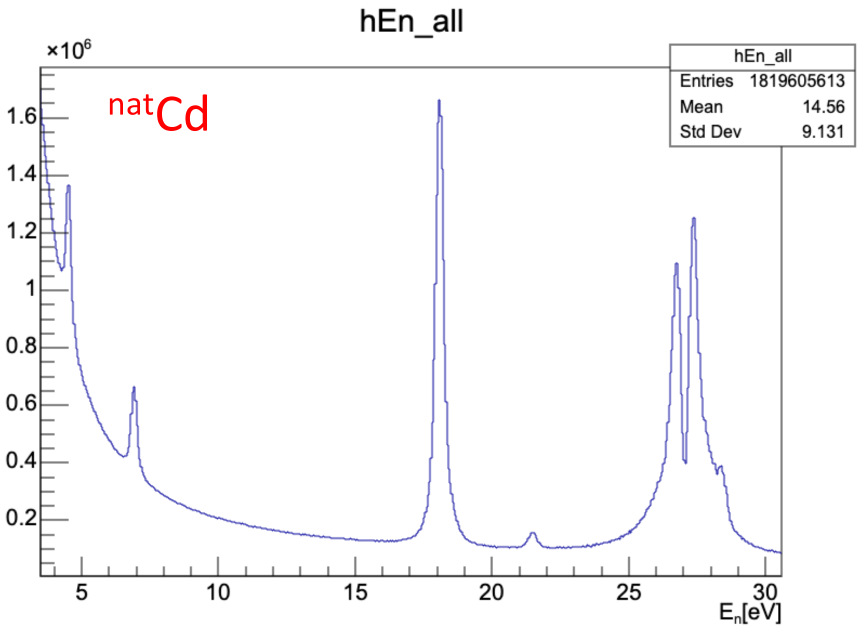
Table 16
Resonance parameters and PNC asymmetries p for ^{127}I. Parameters A_J are in units eV^{-1}

E (eV)	ℓ	J[a]	$g\Gamma_n$ (meV)	A_2[b]	A_3[b]	p (%)	$\lvert p\rvert/\Delta p$
−57.7[a]	0	2					
−52.3[a]	0	3					
7.51[c]	1		0.00012 ± 0.0001	37.6	22.5	0.13 ± 0.14	0.9
10.34[c]	1		0.0028 ± 0.0003	9.0	5.2	−0.005 ± 0.03	0.2
13.93[c]	1		0.0014 ± 0.0001	15.3	9.0	0.01 ± 0.04	0.3
20.43[a]	0	3	0.68 ± 0.05				
24.63[c]	1		0.00064 ± 0.0006	51.7	19.3	1.65 ± 0.16	10.3
31.24[a]	0	2	13.0 ± 1.5				
37.74[a]	0	2	26.0 ± 2.5				
45.39[a]	0	2	11.5 ± 2.0				
52.20[c]	1		0.00085 ± 0.0008	47.8	13.1	0.10 ± 0.18	0.5
53.82	1		0.019 ± 0.002	8.8	2.9	0.24 ± 0.02	12.0
64.04	1		0.008 ± 0.001	13.5	6.8	0.06 ± 0.02	3.0
65.93[a]	0	2	0.80 ± 0.15				
78.53[a]	0		15.5 ± 2.0				
85.84	1		0.0174 ± 0.002	4.7	13.6	0.24 ± 0.02	11.0
90.38[a]	0	3	10.4 ± 1.5				

Self-Filter

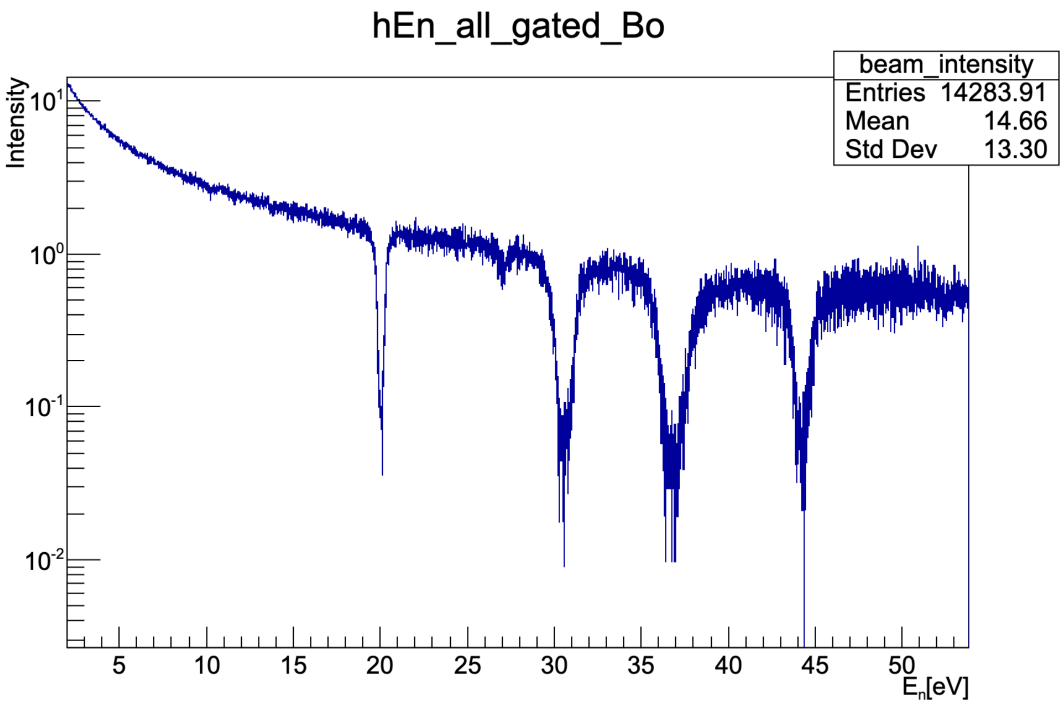
- used upstream self-filters to reduce pileup from nearby s-waves





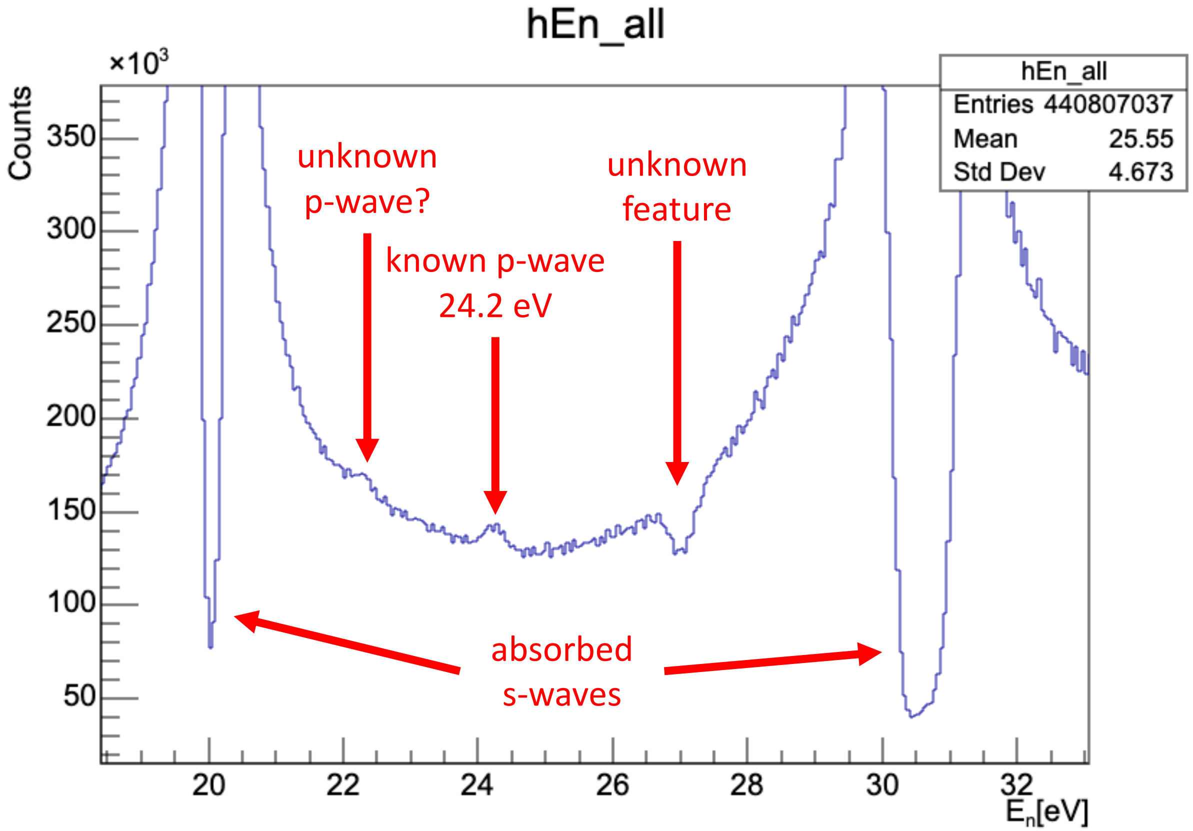
^{127}I Beam Intensity with Self-Filter

- Measure beam intensity using ^{nat}Bo target
- Can clearly see drop in intensity from self-filter



NaI Interesting Features

Discovery still possible!

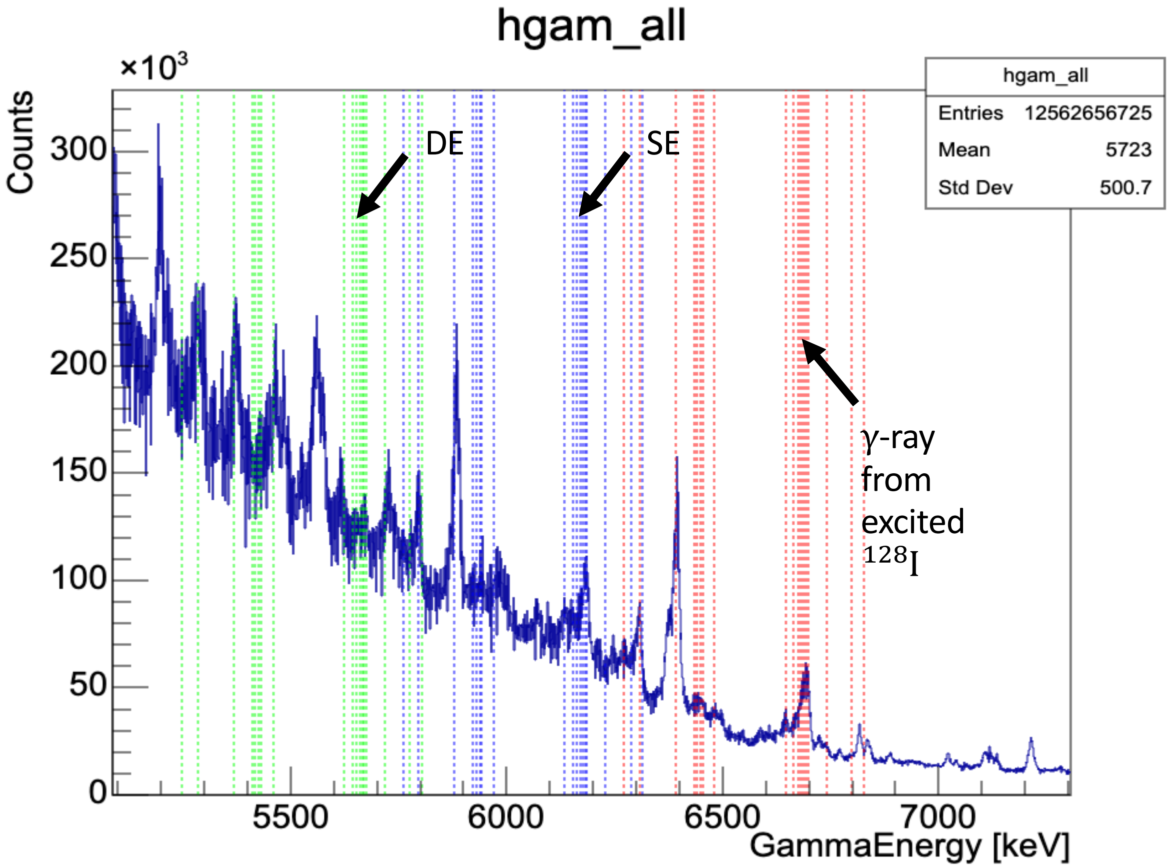


```
S(n)= 6826.13 keV 5
```

highest energy decays with
known final state spins F

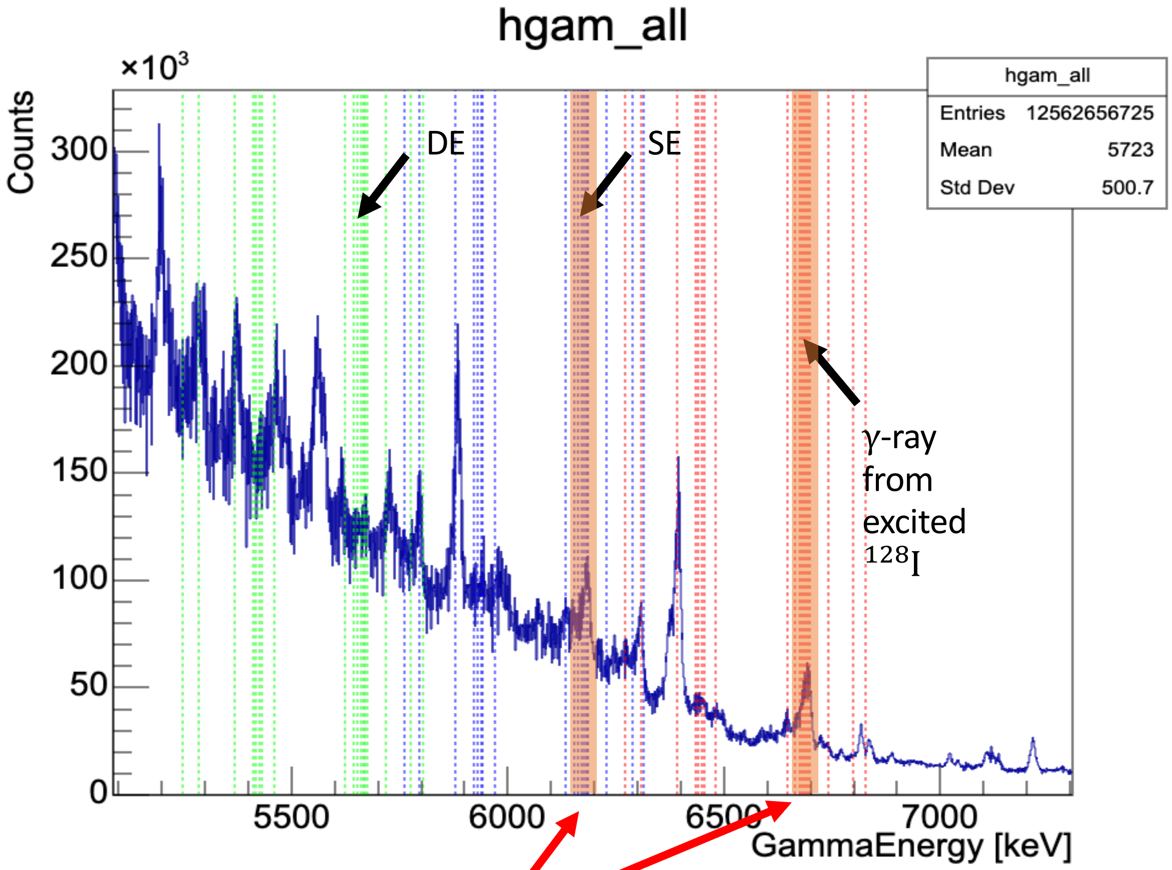
Difficult to isolate decays
from single p-wave resonance

E_γ †	I_γ ‡#	E_i(level)	J_i^π	E_f	J_f^π
6645.61 *2*	185 *8*	(6826.20)	$2^+,3^+$	180.40	$(3)^+$
6665.24 *5*	53 *3*	(6826.20)	$2^+,3^+$	160.77	$1^+,2^+$
6674.53 *9*	25 *1*	(6826.20)	$2^+,3^+$	151.48	$(3)^+$
6681.98 *2*	227 *9*	(6826.20)	$2^+,3^+$	144.03	$(3)^-$
6688.05 *4*	107 *5*	(6826.20)	$2^+,3^+$	137.96	4^-
6692.36 *2*	507 *21*	(6826.20)	$2^+,3^+$	133.65	2^-
6697.73 *4*	126 *5*	(6826.20)	$2^+,3^+$	128.28	$(4)^+$
6740.46 *5*	72 *8*	(6826.20)	$2^+,3^+$	85.54	3^+
6798.68 *6*	38 *2*	(6826.20)	$2^+,3^+$	27.32	2^+
6826.00 *9*	21 *2*	(6826.20)	$2^+,3^+$	0.0	1^+



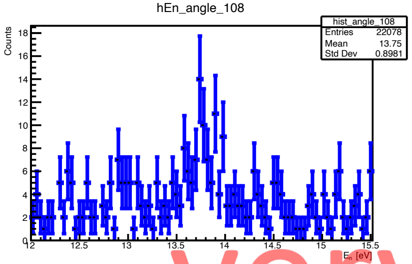
Gate on suspected full absorption and single escape peaks for A_{LH} analysis

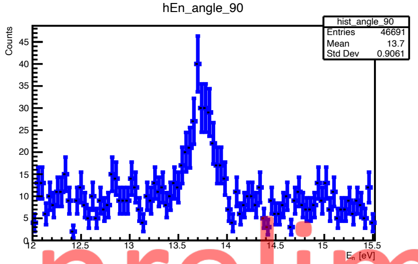
Gate is wide to capture γ-rays responsible

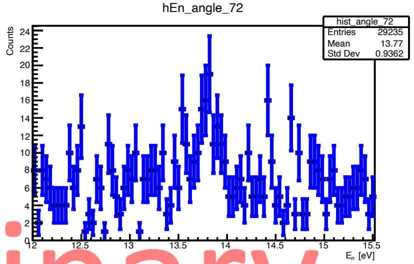


gate on suspected γ-rays from p-wave

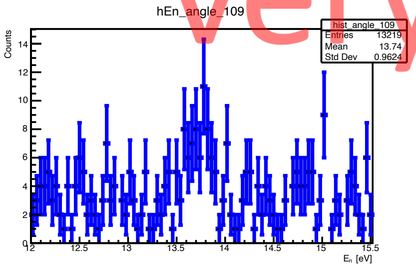
^{127}I 13.6 eV p-wave

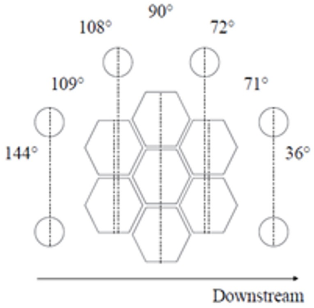


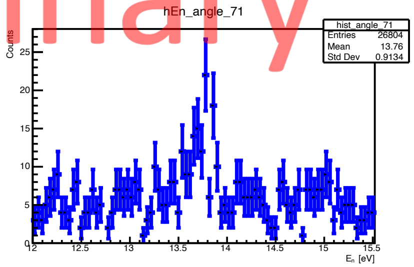


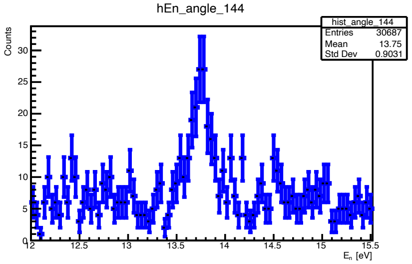


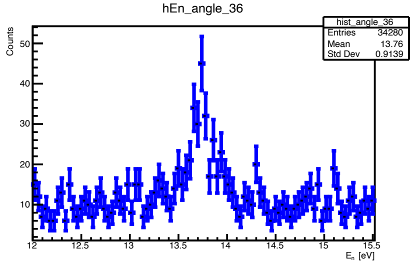
very preliminary

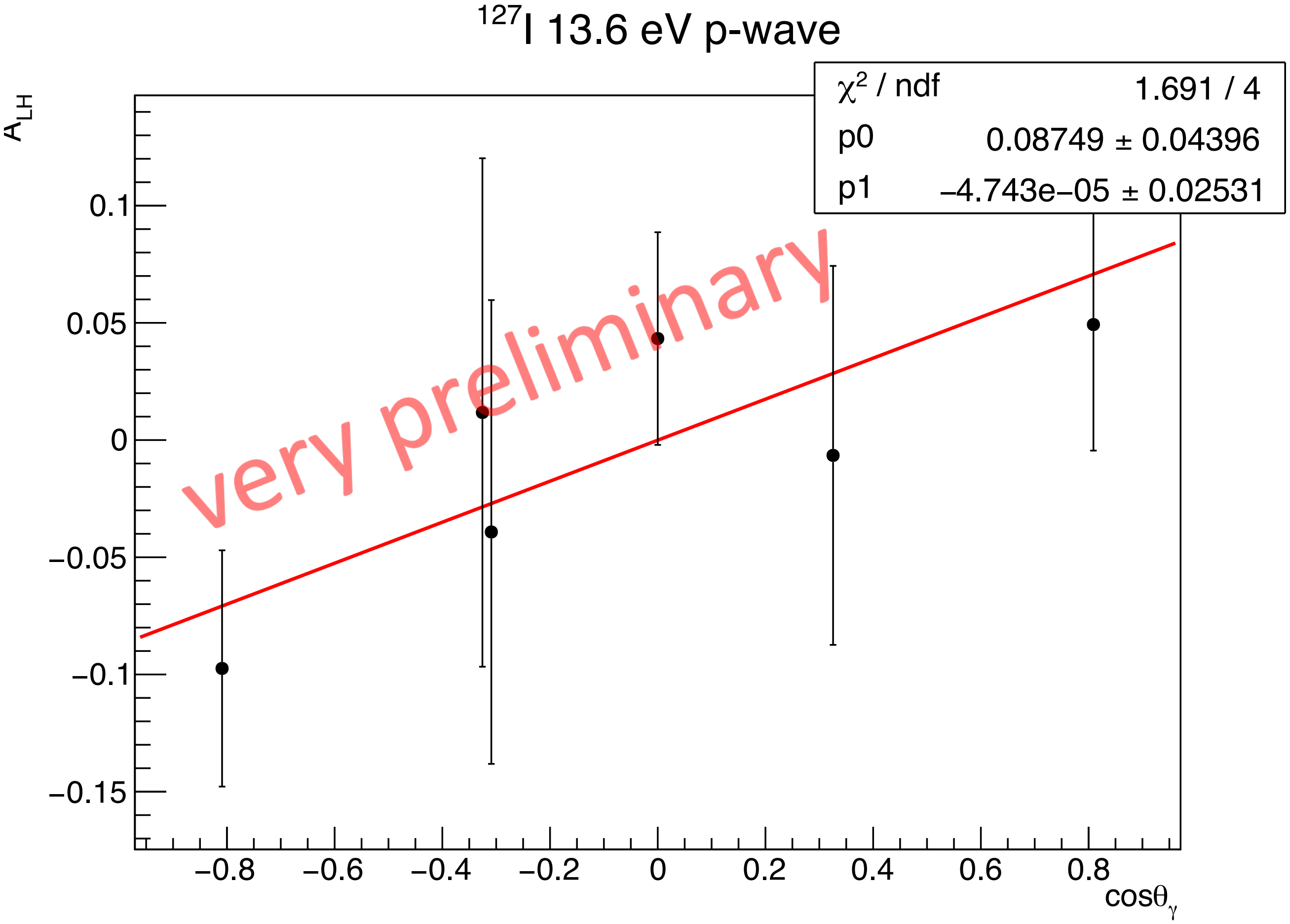












^{127}I 13.6 eV p-wave
χ^2 / ndf 1.691 / 4
p0 0.08749 ± 0.04396
p1 −4.743e−05 ± 0.02531
A_{LH}
0.1
0.05
0
−0.05
−0.1
−0.15
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
$\cos\theta_\gamma$
very preliminary

A_{LH} Summary

nuclei	Resonance energy (eV)	A_{LH} slope	A_L (%)
^{111}Cd	4.5	0.04627 ± 0.07446	1.3 ± 0.4
^{117}I	7.4	0.02724 ± 0.05476	0.13 ± 0.14
^{117}I	10.35	0.02845 ± 0.02671	-0.005 ± 0.0.03
^{117}I	13.6	0.08749 ± 0.04396	0.01 ± 0.04
^{117}I	22.2	0.11350 ± 0.05768	unmeasured
^{117}I	24.2	0.07808 ± 0.05999	1.65 ± 0.16

PV-Search at JPARC

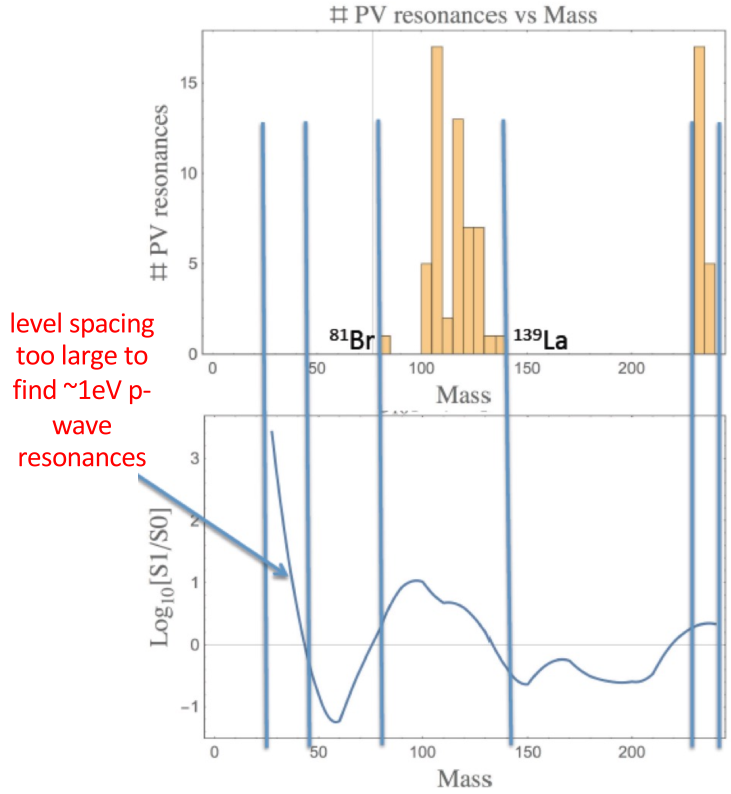
Search for Parity Violation in Unmeasured Heavy Nuclei

- Unmeasured range 140<A<180 with nonzero spin

  - ^{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, and ^{165}Ho polarizable

- Many unmeasured nuclei → just one discovery is meaningful!

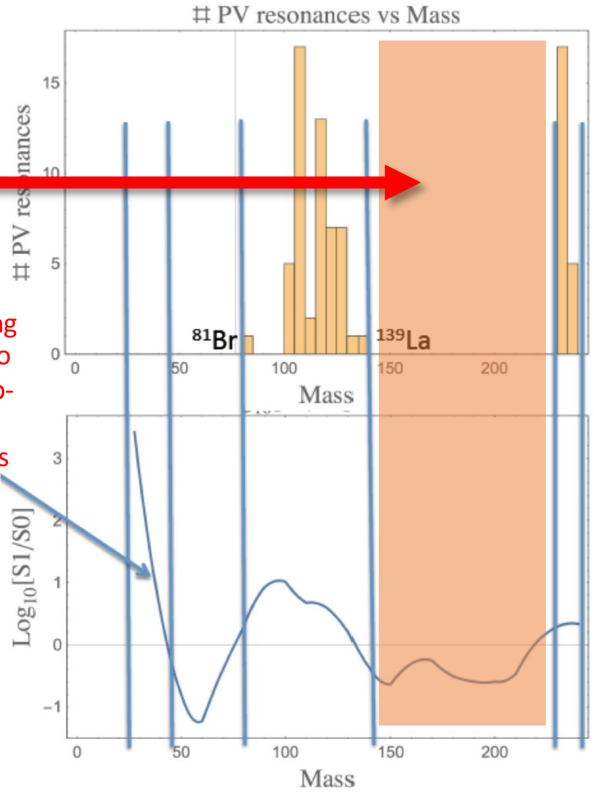
PV resonances found by TRIPLE



Search for Parity Violation in Unmeasured Heavy Nuclei

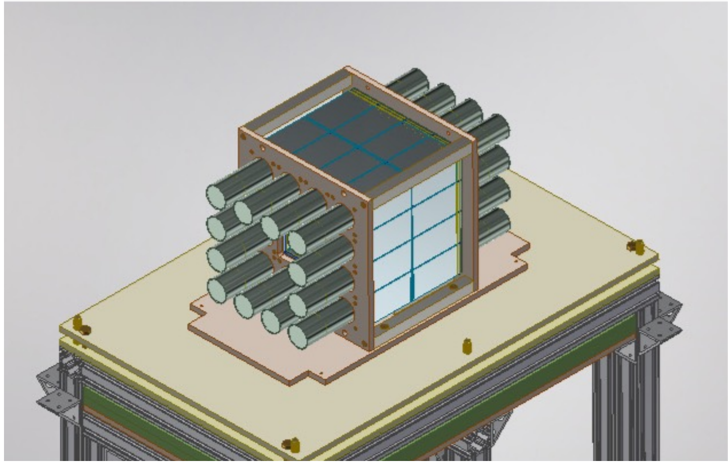
- Unmeasured range 140<A<180 with nonzero spin
  - ^{169}Tm, I=1/2 (100%), DNP possible in a diamagnetic salt
  - ^{171}Yb, I=1/2 (14.1%), has been hyperpolarized
  - ^{149}Sm, ^{151}Eu, ^{167}Er, and ^{165}Ho polarizable
- Many unmeasured nuclei → just one discovery is meaningful!

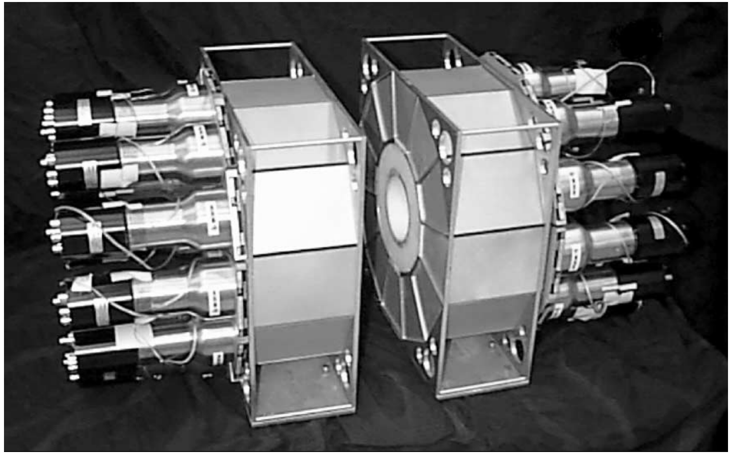
PV resonances found by TRIPLE



Original Plan

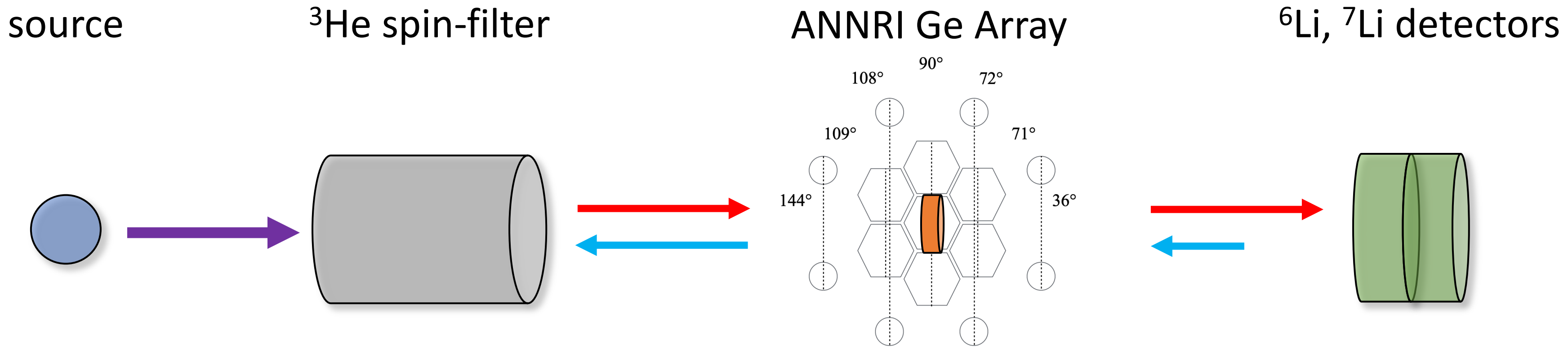
- Original plan was to use NaI array or pure CsI in current mode on BL04
- Could not use to to space constrains and necessity for large spin-transport coils
- Decided to use existing HPGe array instead

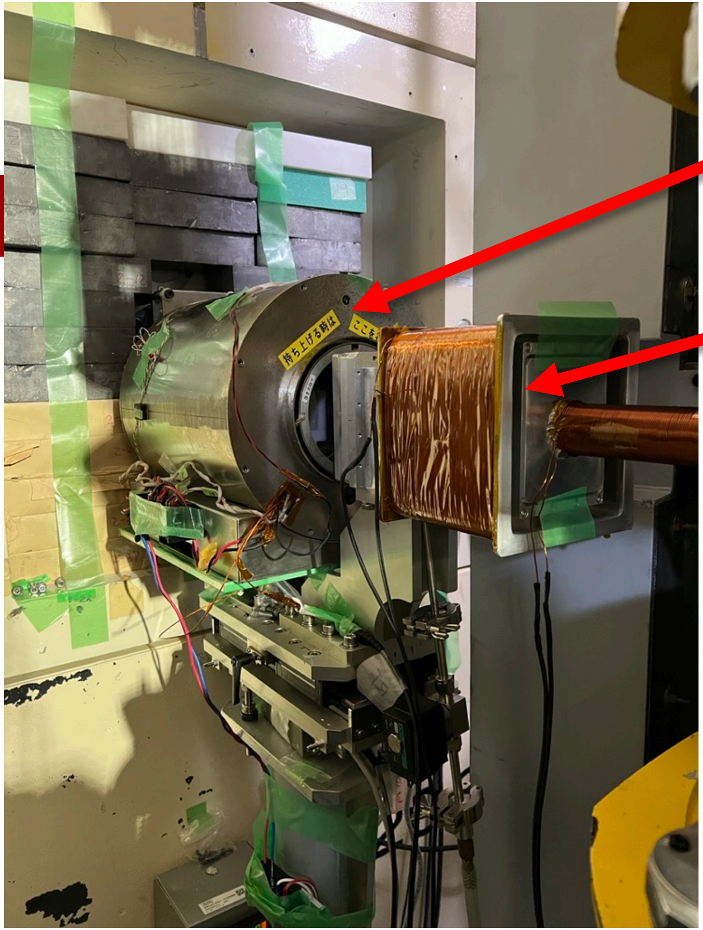




PV Search Experiential Setup

- ^{3}He spin-filter gives net longitudinal polarization of neutrons
- Measure gammas and transmission through target
- Can also easily measure a_1



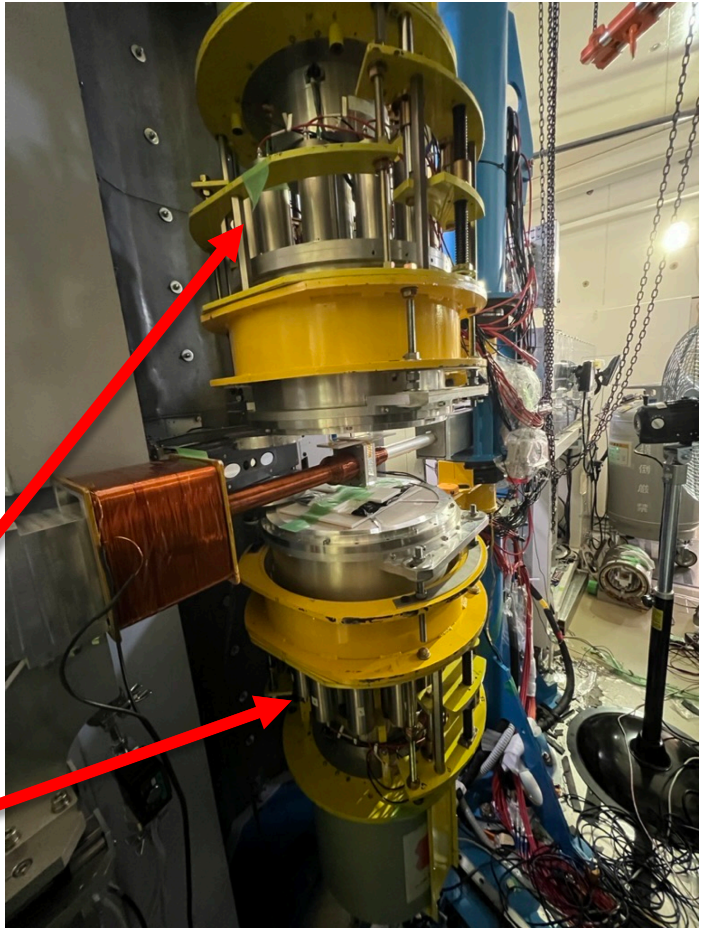


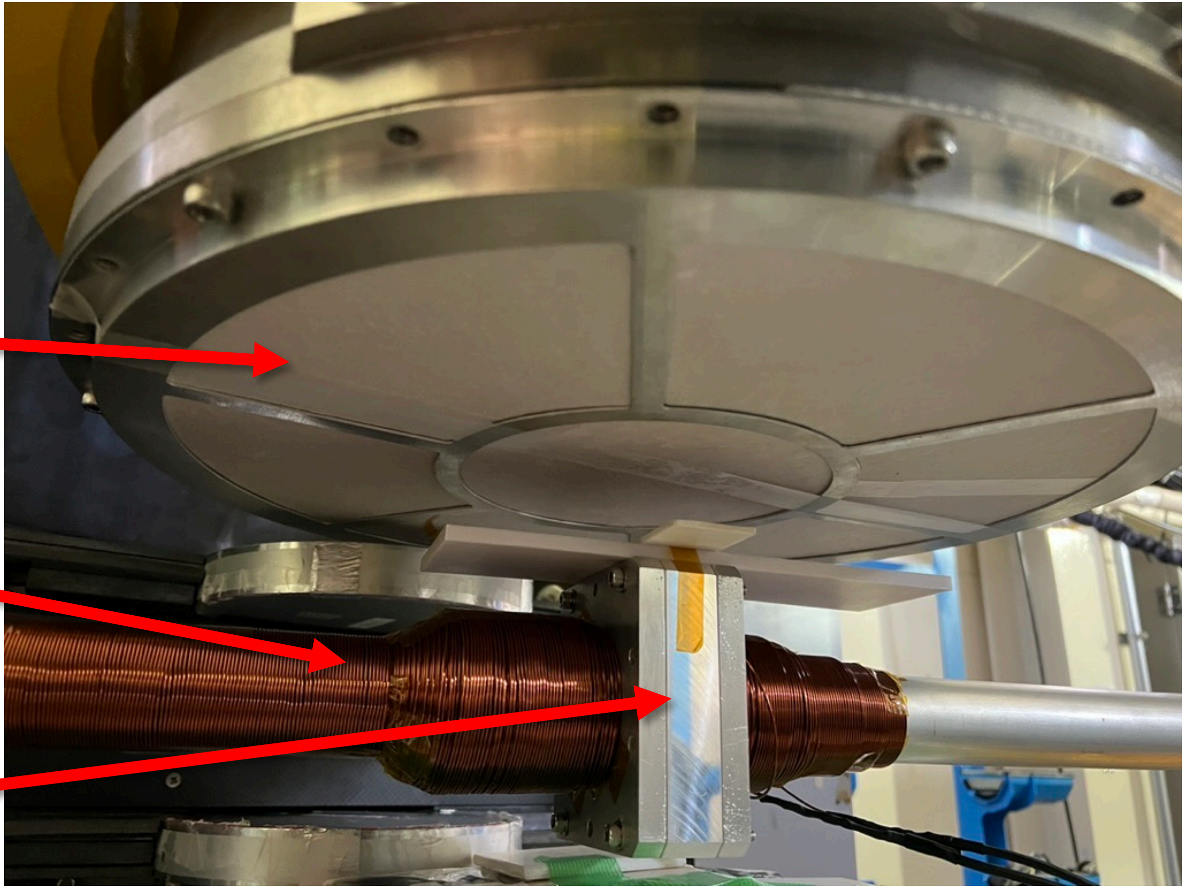
^{3}He spin-filter

spin-transport

upper cluster

lower cluster



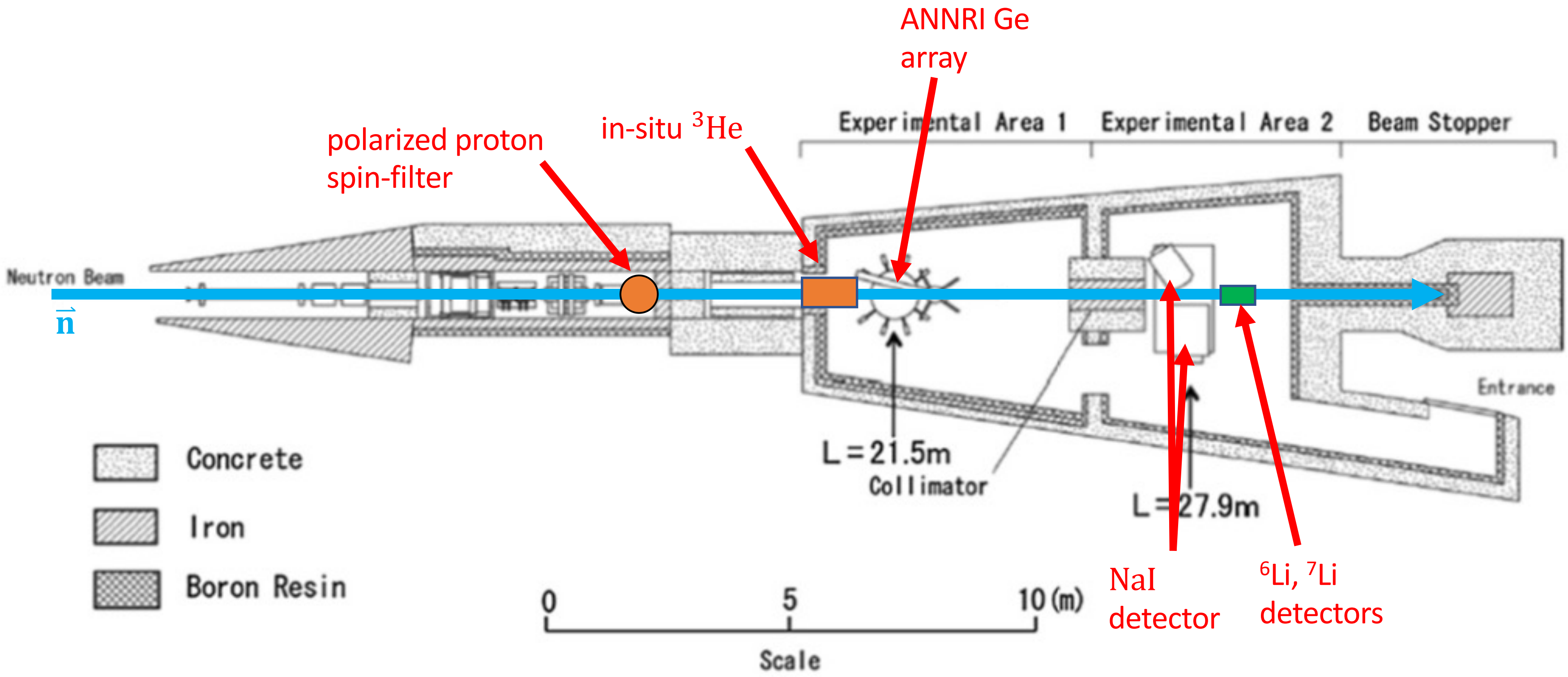

neutron shielding
Spin-transport
target location

Thank you!

BL04 Long-Term Plans

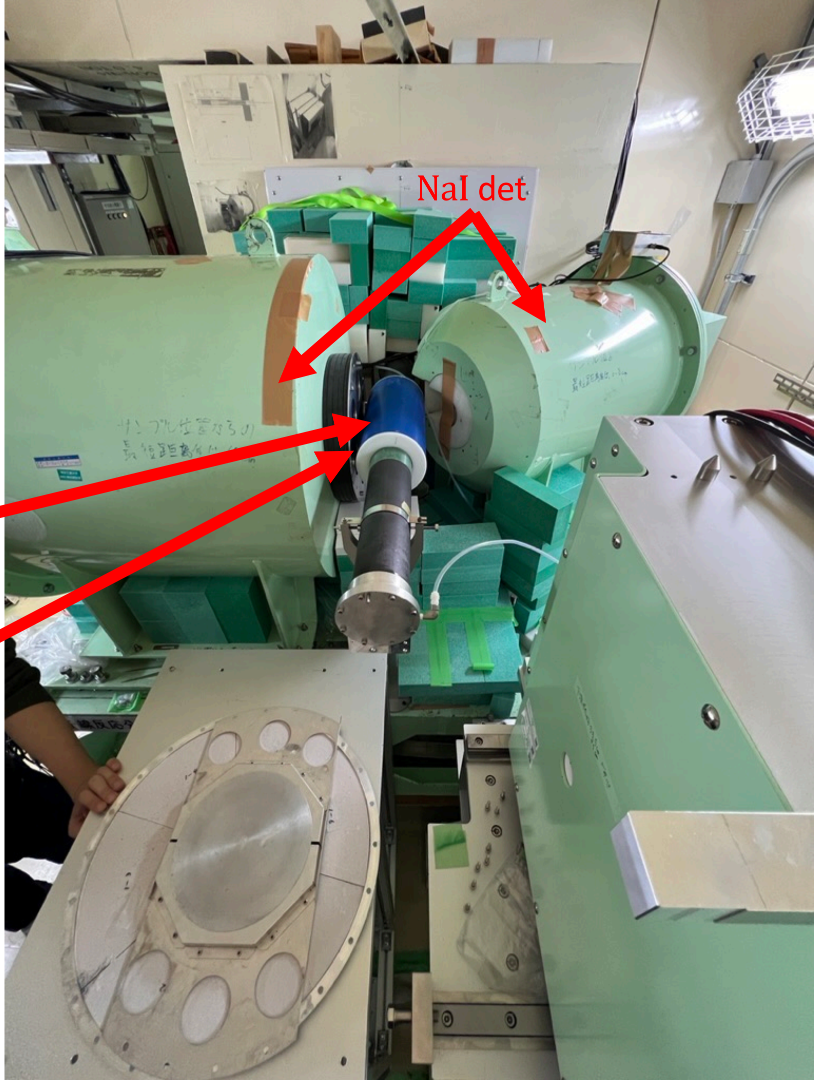
BL04 Layout

Hope to install various upstream spin-filters to cover large energy range



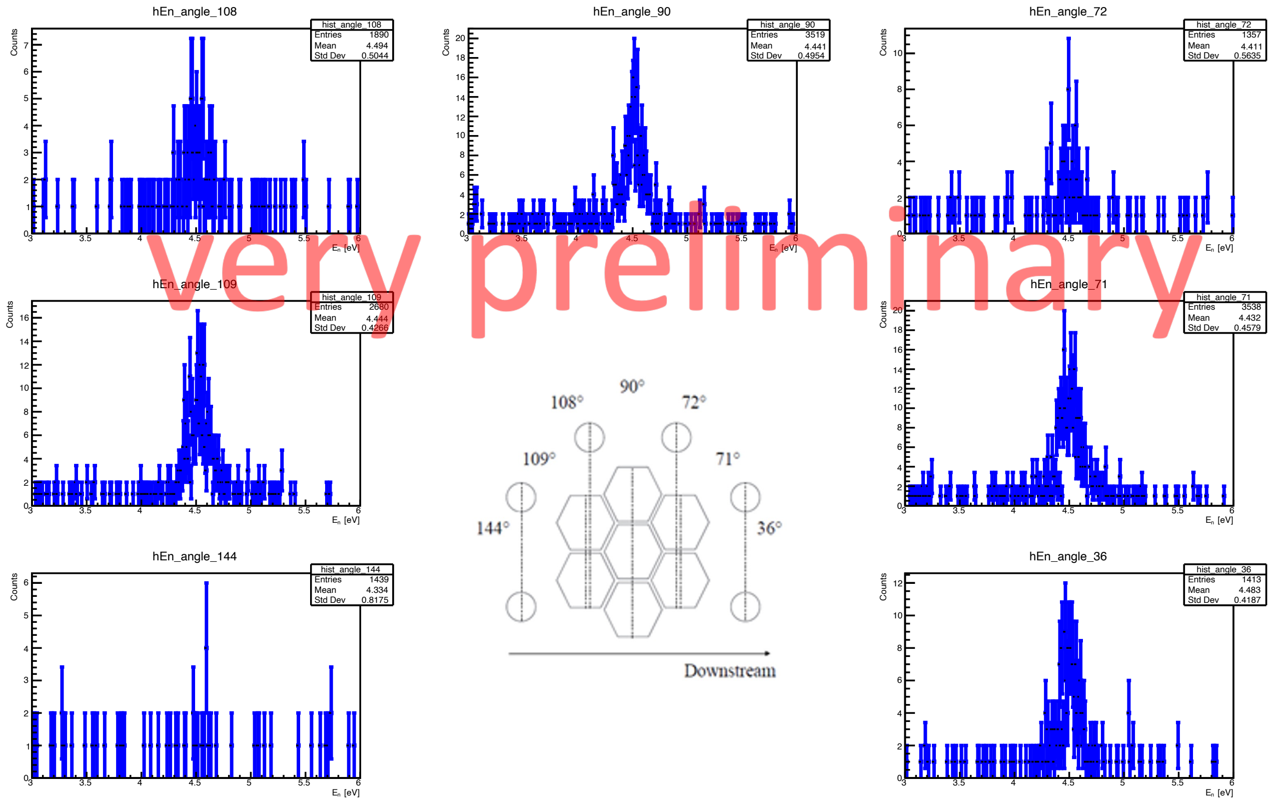
BL04 Experimental Area 2 (downstream)

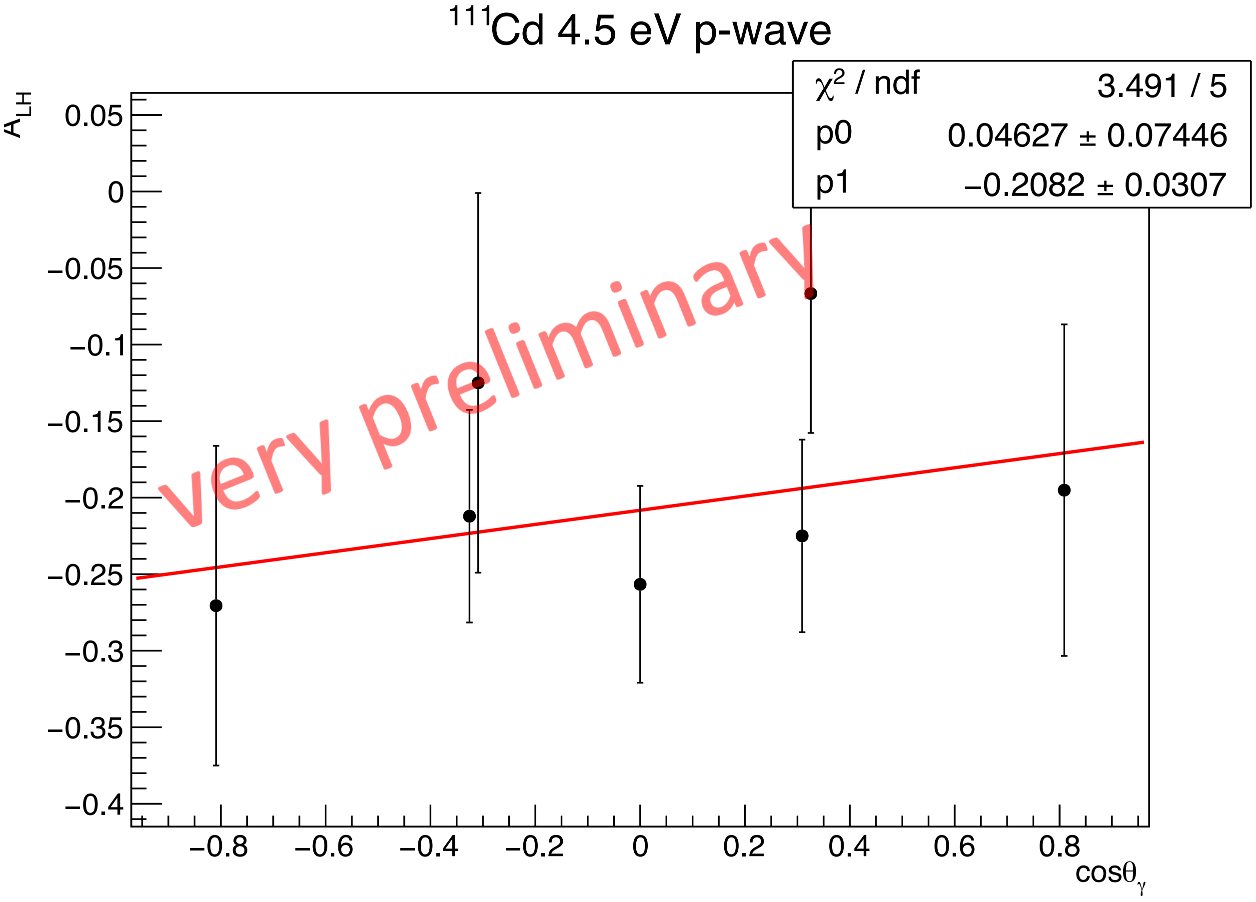
Large sized NaI detectors for higher energy cross-section measurements



Backup Slides

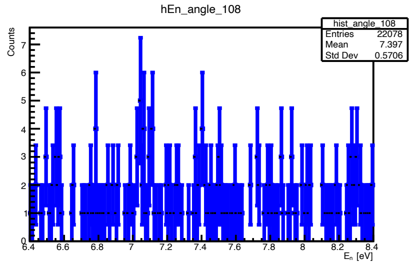
^{111}Cd 4.5 eV p-wave

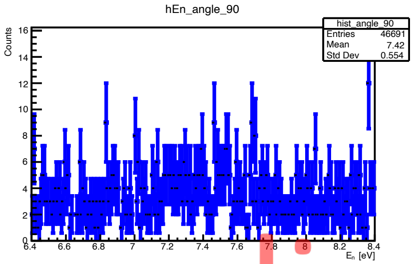


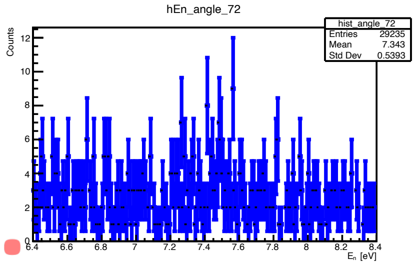


^{111}Cd 4.5 eV p-wave
χ^2 / ndf 3.491 / 5
p0 0.04627 ± 0.07446
p1 −0.2082 ± 0.0307
A_{LH}
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.25
−0.3
−0.35
−0.4
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
$\cos\theta_\gamma$
very preliminary

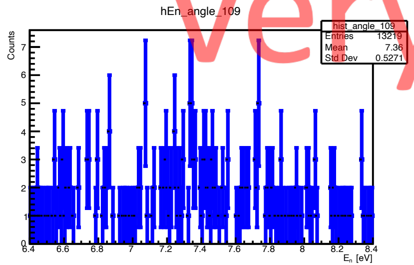
^{127}I 7.4 eV p-wave

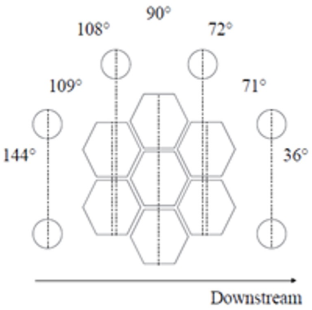


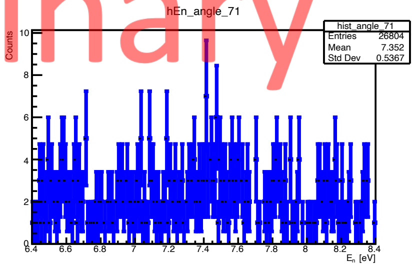


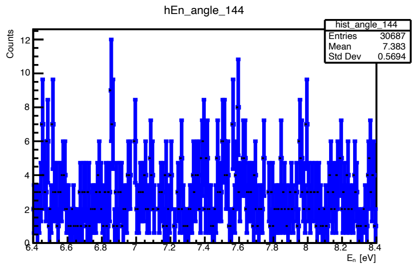


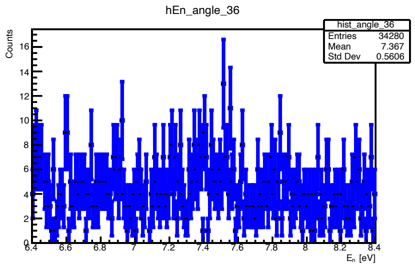
very preliminary

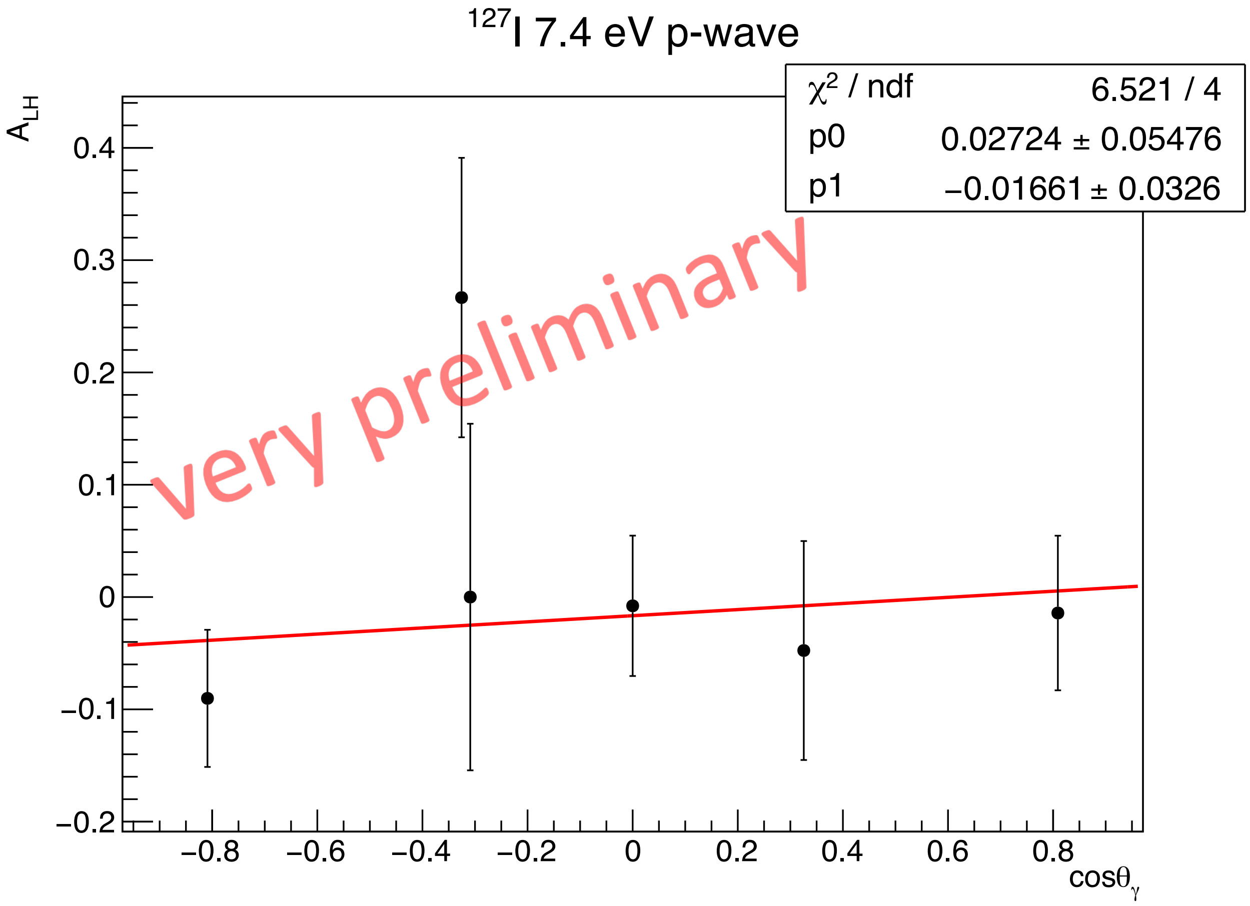






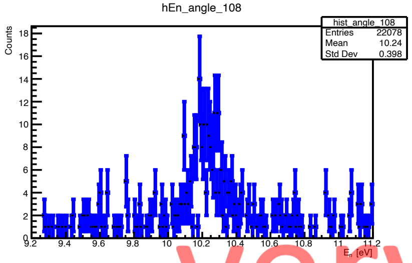


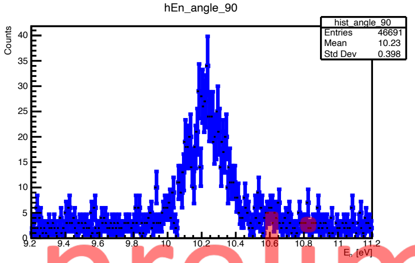


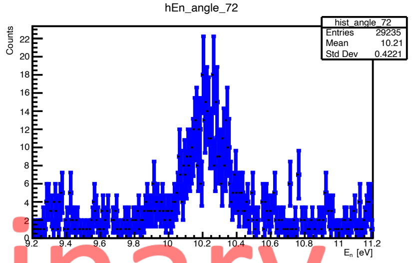


127I 7.4 eV p-wave
χ2 / ndf 6.521 / 4
p0 0.02724 ± 0.05476
p1 −0.01661 ± 0.0326
very preliminary
A_LH
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
cosθγ

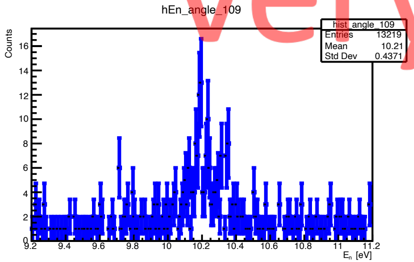
^{127}I 10.35 eV p-wave

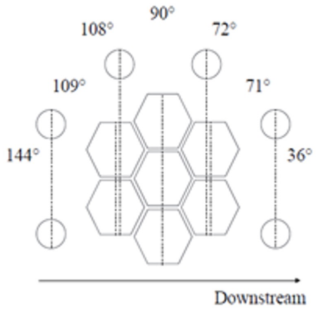


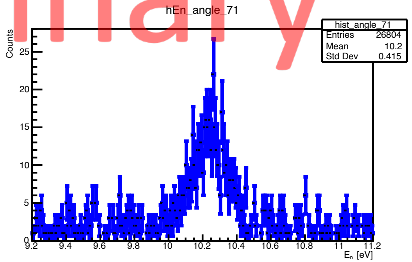


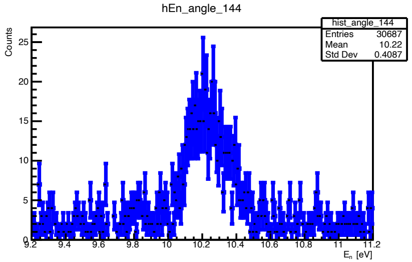


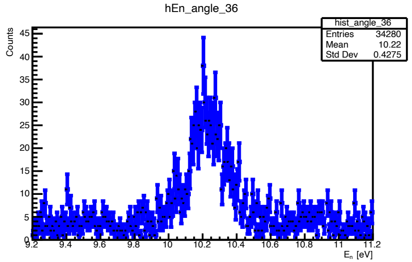
very preliminary

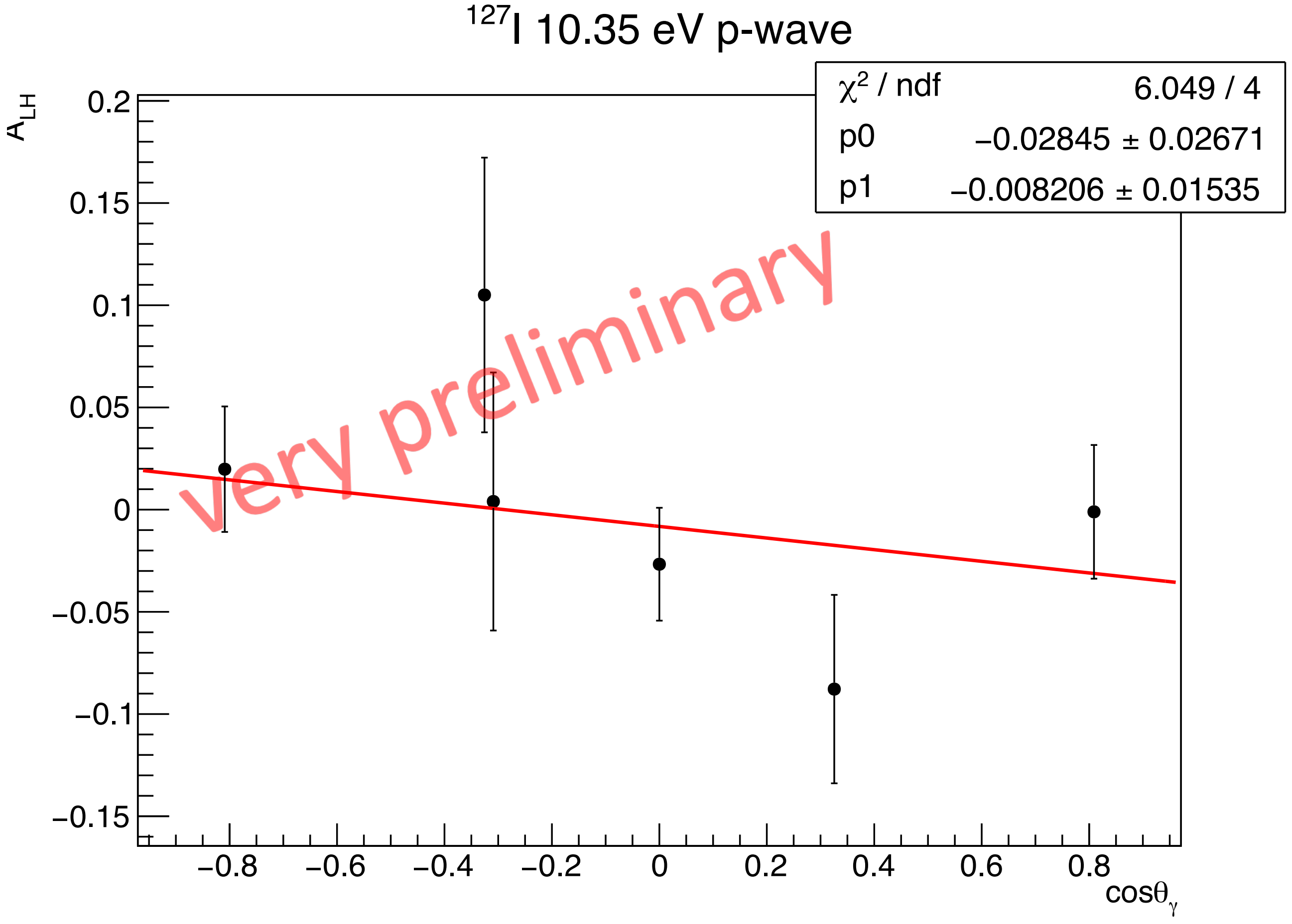






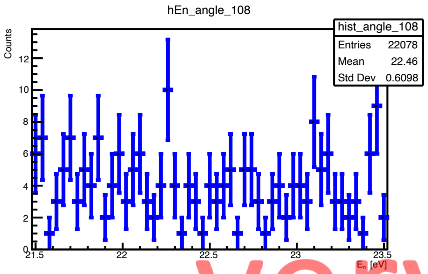


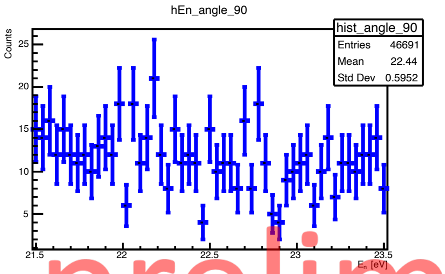


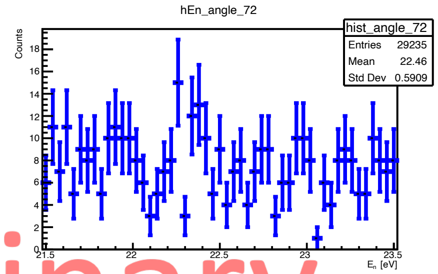


^{127}I 10.35 eV p-wave
χ^2 / ndf 6.049 / 4
p0 −0.02845 ± 0.02671
p1 −0.008206 ± 0.01535
A_{LH}
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
$\cos\theta_\gamma$
very preliminary

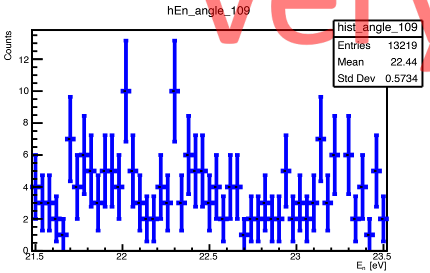
^{127}I 22.2 eV p-wave

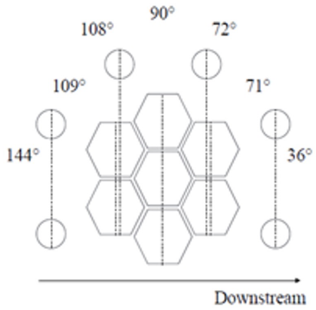


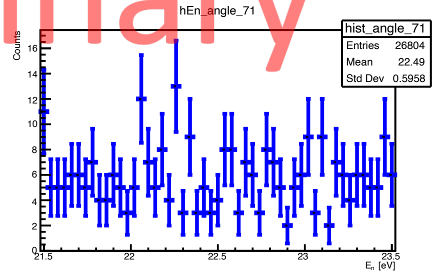


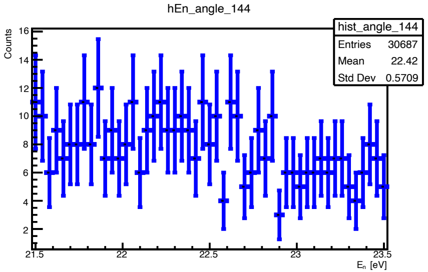


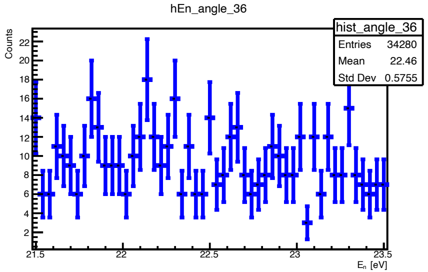
very preliminary

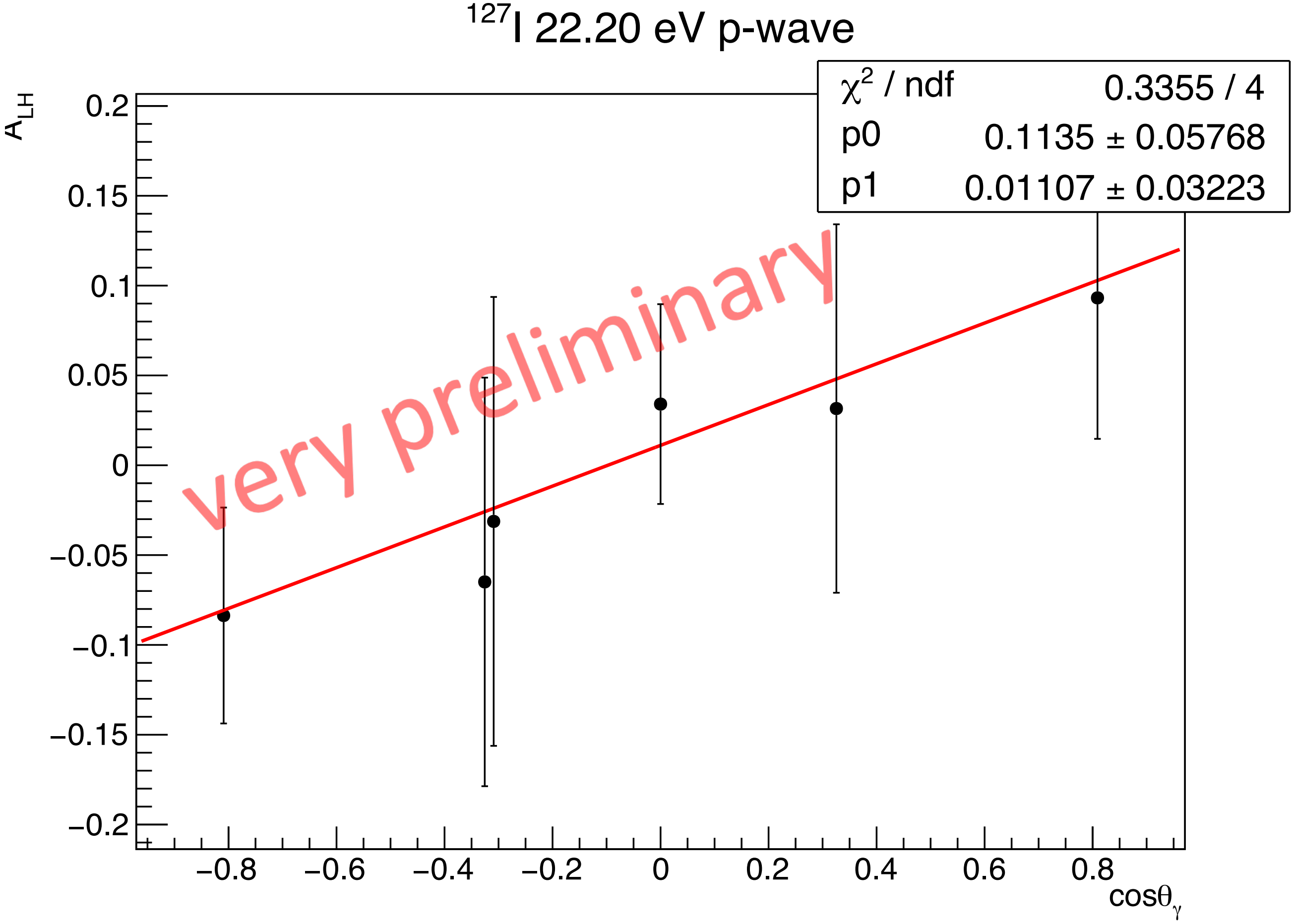






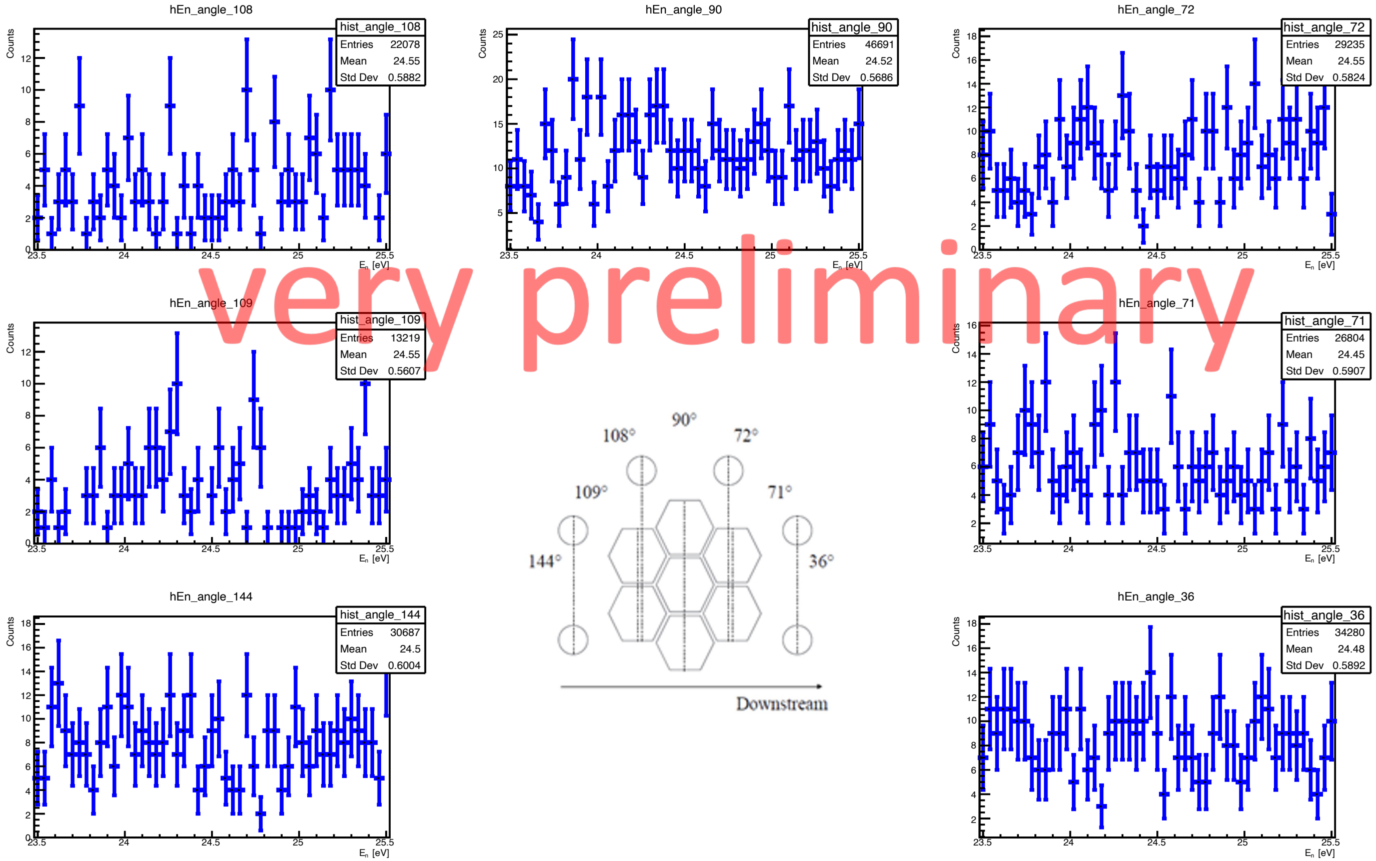


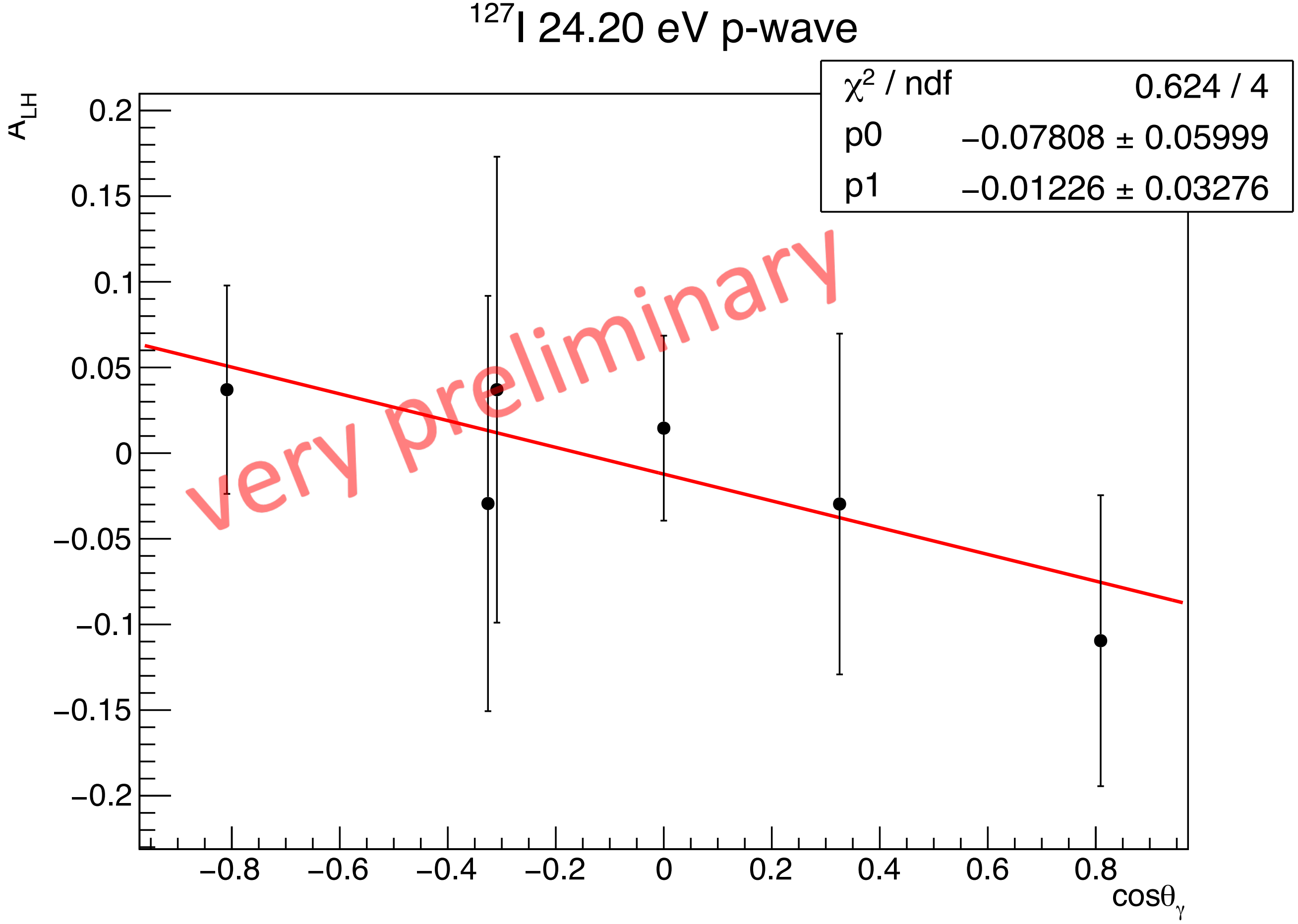




^{127}I 22.20 eV p-wave
χ^2 / ndf 0.3355 / 4
p0 0.1135 ± 0.05768
p1 0.01107 ± 0.03223
A_{LH}
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
$\cos\theta_\gamma$
very preliminary

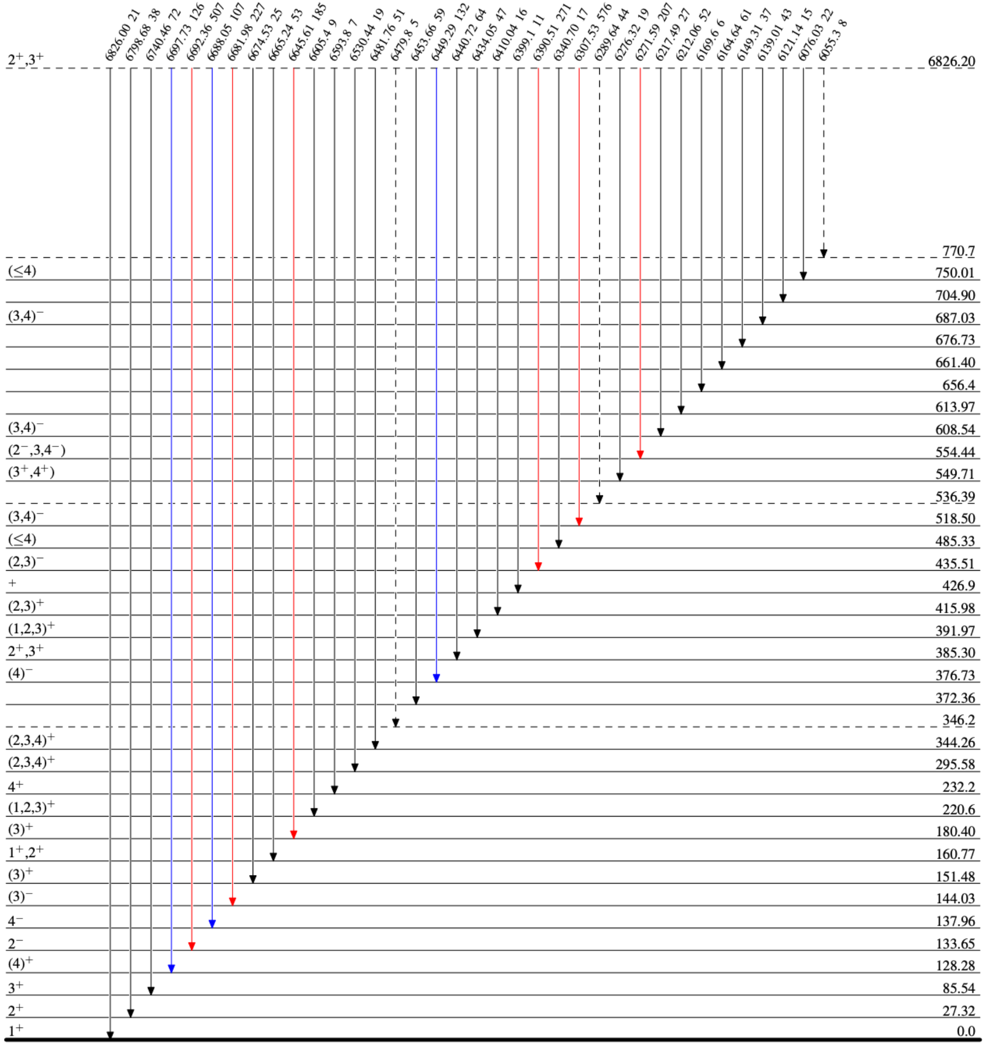
^{127}I 24.2 eV p-wave



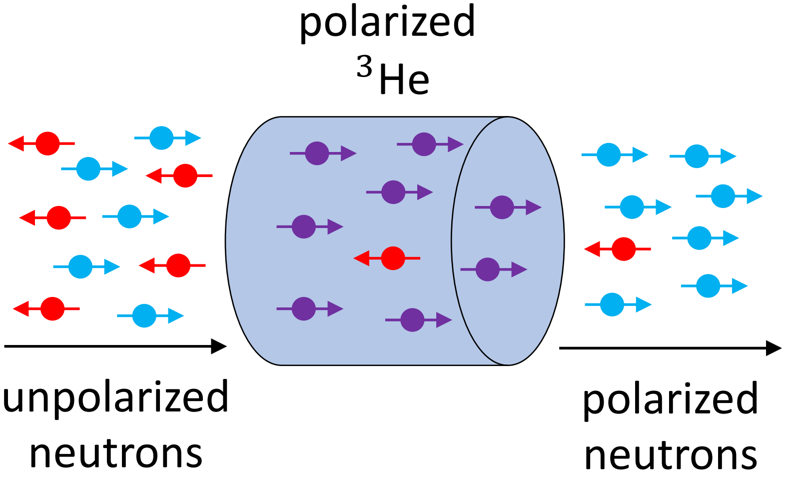


127I 24.20 eV p-wave
χ2 / ndf 0.624 / 4
p0 −0.07808 ± 0.05999
p1 −0.01226 ± 0.03276
A_LH
0.2
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
cosθγ
very preliminary

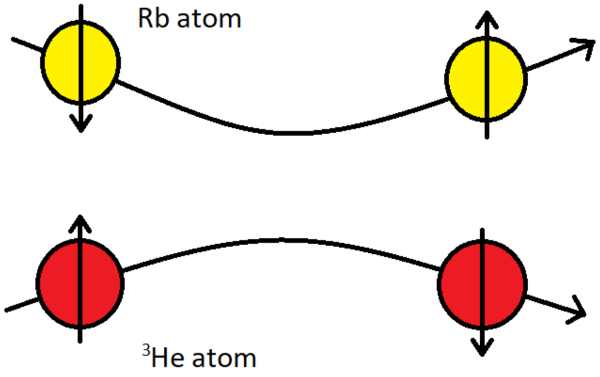
E$_\gamma$†	I$_\gamma$‡#	E$_i$(level)	J$^\pi_i$	E$_f$	J$^\pi_f$
5962.15@ 10	31 2	(6826.20)	$2^+,3^+$	863.90?	
5976.71 5	73 4	(6826.20)	$2^+,3^+$	849.34	(≤4)
5982.53 8	59 3	(6826.20)	$2^+,3^+$	843.52	
5986.00 4	128 5	(6826.20)	$2^+,3^+$	840.04	$(1^-,2,3^+)$
5997.70 4	105 5	(6826.20)	$2^+,3^+$	828.34	
6004.60@ 6	58 3	(6826.20)	$2^+,3^+$	821.44?	
6030.42 19	13 1	(6826.20)	$2^+,3^+$	795.62	
6034.1@ 5	4 1	(6826.20)	$2^+,3^+$	791.9?	
6038.05 17	13 2	(6826.20)	$2^+,3^+$	787.99	
6055.3@ 4	8 1	(6826.20)	$2^+,3^+$	770.7?	
6076.03 13	22 1	(6826.20)	$2^+,3^+$	750.01	(≤4)
6121.14 17	15 1	(6826.20)	$2^+,3^+$	704.90	
6139.01 8	43 3	(6826.20)	$2^+,3^+$	687.03	$(3,4)^-$
6149.31 9	37 2	(6826.20)	$2^+,3^+$	676.73	
6164.64 6	61 3	(6826.20)	$2^+,3^+$	661.40	
6169.6 4	6 1	(6826.20)	$2^+,3^+$	656.4	
6212.06 6	52 3	(6826.20)	$2^+,3^+$	613.97	
6217.49 12	27 2	(6826.20)	$2^+,3^+$	608.54	$(3,4)^-$
6271.59 2	207 9	(6826.20)	$2^+,3^+$	554.44	$(2^-,3,4^-)$
6276.32 19	19 2	(6826.20)	$2^+,3^+$	549.71	$(3^+,4^+)$
6289.64@ 8	44 2	(6826.20)	$2^+,3^+$	536.39?	
6307.53 2	576 23	(6826.20)	$2^+,3^+$	518.50	$(3,4)^-$
6340.70 17	17 1	(6826.20)	$2^+,3^+$	485.33	(≤4)
6390.51 2	271 11	(6826.20)	$2^+,3^+$	435.51	$(2,3)^-$
6399.1 3	11 1	(6826.20)	$2^+,3^+$	426.9	+
6410.04 16	16 1	(6826.20)	$2^+,3^+$	415.98	$(2,3)^+$
6434.05 6	47 2	(6826.20)	$2^+,3^+$	391.97	$(1,2,3)^+$
6440.72 6	64 3	(6826.20)	$2^+,3^+$	385.30	$2^+,3^+$
6449.29 3	132 6	(6826.20)	$2^+,3^+$	376.73	$(4)^-$
6453.66 6	59 3	(6826.20)	$2^+,3^+$	372.36	
6479.8@ 8	5 1	(6826.20)	$2^+,3^+$	346.2?	
6481.76 19	51 4	(6826.20)	$2^+,3^+$	344.26	$(2,3,4)^+$
6530.44 14	19 1	(6826.20)	$2^+,3^+$	295.58	$(2,3,4)^+$
6593.8 4	7 1	(6826.20)	$2^+,3^+$	232.2	4^+
6605.4 4	9 1	(6826.20)	$2^+,3^+$	220.6	$(1,2,3)^+$
6645.61 2	185 8	(6826.20)	$2^+,3^+$	180.40	$(3)^+$
6665.24 5	53 3	(6826.20)	$2^+,3^+$	160.77	$1^+,2^+$
6674.53 9	25 1	(6826.20)	$2^+,3^+$	151.48	$(3)^+$
6681.98 2	227 9	(6826.20)	$2^+,3^+$	144.03	$(3)^-$
6688.05 4	107 5	(6826.20)	$2^+,3^+$	137.96	4^-
6692.36 2	507 21	(6826.20)	$2^+,3^+$	133.65	2^-
6697.73 4	126 5	(6826.20)	$2^+,3^+$	128.28	$(4)^+$
6740.46 5	72 8	(6826.20)	$2^+,3^+$	85.54	3^+
6798.68 6	38 2	(6826.20)	$2^+,3^+$	27.32	2^+
6826.00 9	21 2	(6826.20)	$2^+,3^+$	0.0	1^+



^{3}He Spin-Filter

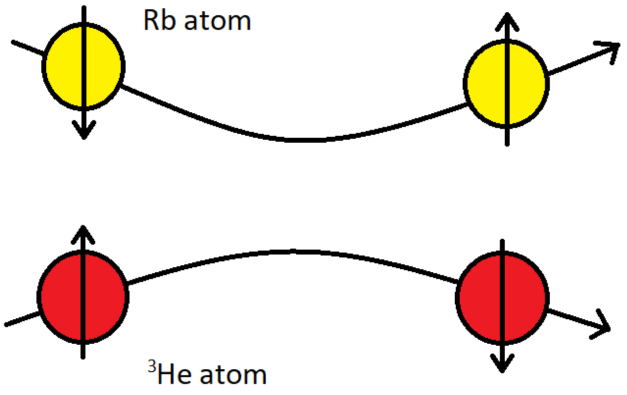


- Polarized ^{3}He has a large spin dependent cross-section
- Effective for meV to eV neutron energies
- Polarize ^{3}He with Spin Exchange Optical Pumping

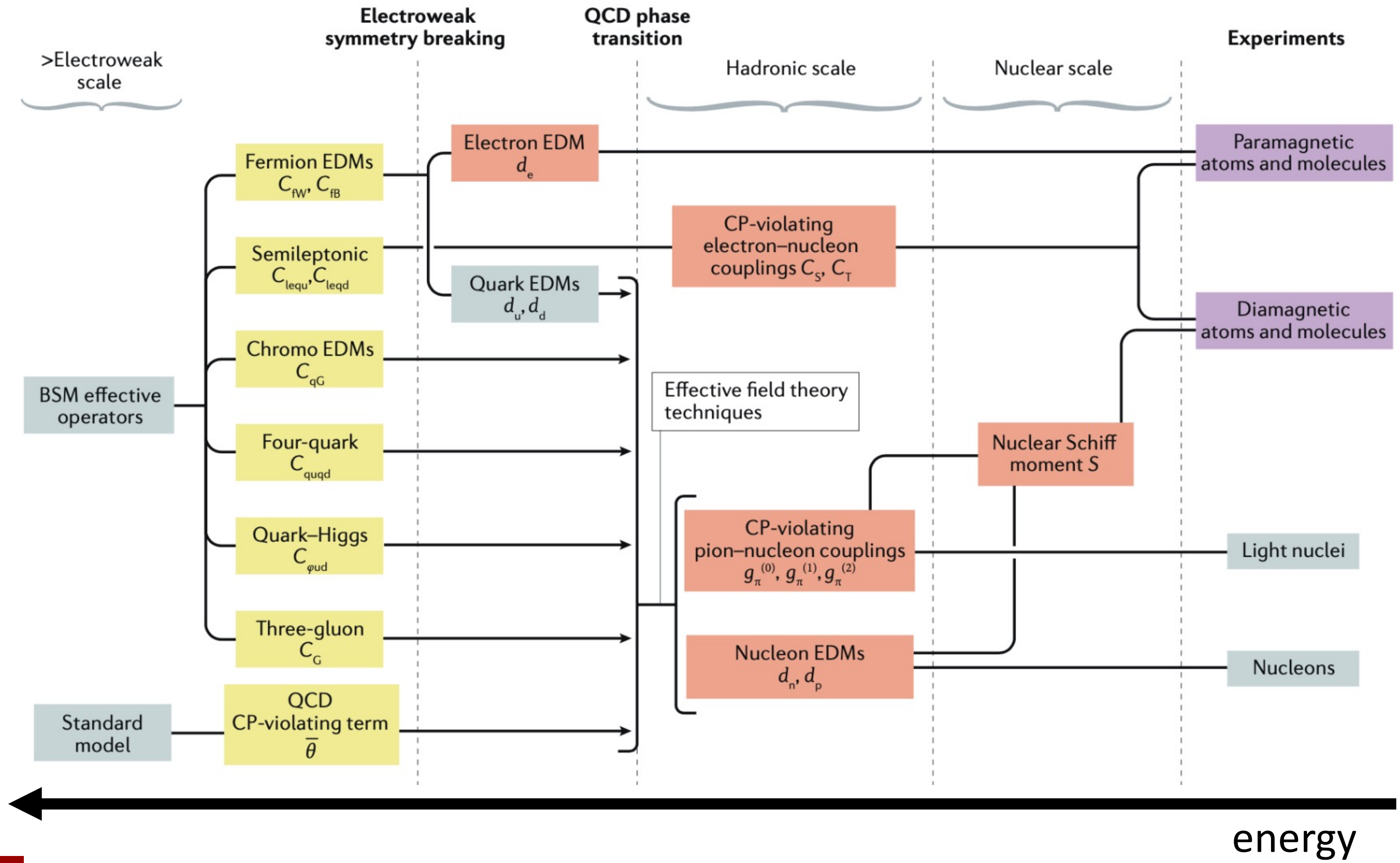


Spin Exchange Optical Pumping

- Use SEOP to polarize $^{3}\mathrm{He}$ gas cell
- Optically pump Rb vapor with 795 nm laser
  - Uniform holding field $\vec{B}_0$
  - Photons with circular polarization transfer spin angular momentum to Rb electrons
- Rb electrons exchange spin with $^{3}\mathrm{He}$ atoms upon collision



(T.R. Gentile et al. 2017)



Electroweak symmetry breaking
QCD phase transition
Experiments
>Electroweak scale
Hadronic scale
Nuclear scale
Fermion EDMs C_{fW}, C_{fB}
Electron EDM d_e
Paramagnetic atoms and molecules
CP-violating electron–nucleon couplings C_S, C_T
Semileptonic C_{lequ}, C_{leqd}
Quark EDMs d_u, d_d
Diamagnetic atoms and molecules
Chromo EDMs C_{qG}
Effective field theory techniques
BSM effective operators
Four-quark C_{quqd}
Nuclear Schiff moment S
Quark–Higgs $C_{\varphi ud}$
CP-violating pion–nucleon couplings $g_\pi^{(0)}$, $g_\pi^{(1)}$, $g_\pi^{(2)}$
Light nuclei
Three-gluon C_G
Nucleon EDMs d_n, d_p
Nucleons
Standard model
QCD CP-violating term $\bar{\theta}$
energy

$\kappa(J)$ Measurement & Analysis cont.

rotationally invariant and independent terms in (n,γ) differential cross section for unpolarized neutrons

$$\frac{d\sigma_{n\gamma_f}}{d\Omega_\gamma} = \frac{1}{2}\left(a_0 + a_1\cos\theta_\gamma + a_3\left(\cos^2\theta_\gamma - \frac{1}{3}\right)\right)$$

a_1, a_3 can be decomposed into functions of x and y with $a_{0,1} \gg a_3$

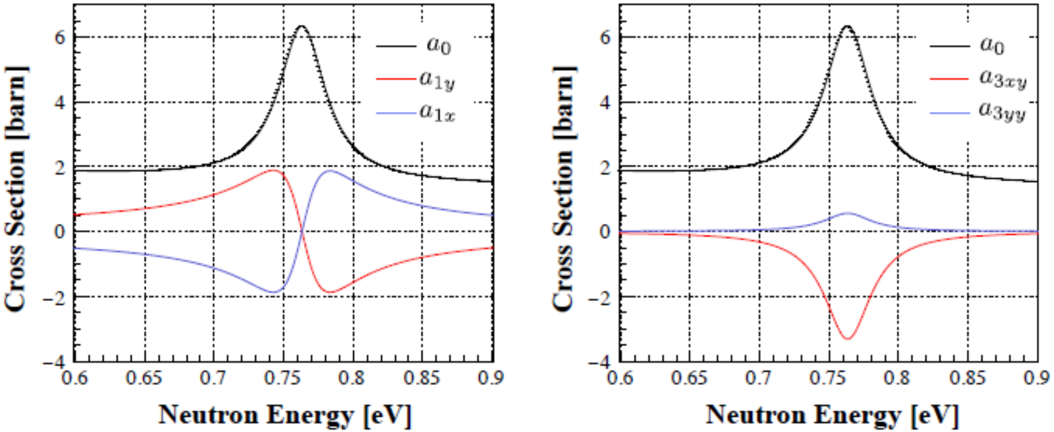
$$a_1 = a_{1x}x + a_{1y}y$$
$$a_3 = a_{3xy}xy + a_{3yy}y^2$$

$$x \equiv \sqrt{\frac{\Gamma^n_{p,j=1/2}}{\Gamma^n_p}}$$
$$y \equiv \sqrt{\frac{\Gamma^n_{p,j=3/2}}{\Gamma^n_p}}$$

Okudaira Takuyu. PhD. thesis, 2018.
T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

$$a_1 = a_{1x}x + a_{1y}y$$
$$a_3 = a_{3xy}xy + a_{3yy}y^2$$

dispersive shape as a function of neutron energy near the p-wave resonance



define $(\bar{a}_{0,1,3})_{L,H}$ the weighted average for lower and higher sides of the resonance

$$(\bar{a}_{0,1,3})_L = \int_{E_p-2\Gamma_p}^{E_p} dE' \int d^3p_A a_{0,1,3}(E')\Phi(t^m, E', p_A)$$
$$(\bar{a}_{0,1,3})_H = \int_{E_p}^{E_p+2\Gamma_p} dE' \int d^3p_A a_{0,1,3}(E')\Phi(t^m, E', p_A)$$

Okudaira Takuyu. PhD. thesis, 2018.
T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).

$$(I_{\gamma,d})_{L,H} = \frac{I_0}{2}[(\bar{a}_0)_{L,H}\bar{P}_{d0} + (\bar{a}_1)_{L,H}\bar{P}_{d1}]$$

Lower and higher γ-ray count in d^{th} detector

$$(A_{LH})_d = \frac{(I_{\gamma,d})_L - (I_{\gamma,d})_H}{(I_{\gamma,d})_L + (I_{\gamma,d})_H}$$

$$= \frac{[(\bar{a}_0)_L - (\bar{a}_0)_H] + [(\bar{a}_1)_L - (\bar{a}_1)_H]\frac{\bar{P}_{d1}}{\bar{P}_{d0}}}{[(\bar{a}_0)_L + (\bar{a}_0)_H] + [(\bar{a}_1)_L + (\bar{a}_1)_H]\frac{\bar{P}_{d1}}{\bar{P}_{d0}}}$$

$$= \frac{[(\bar{a}_1)_L - (\bar{a}_1)_H]}{[(\bar{a}_0)_L + (\bar{a}_0)_H]}\cos\bar{\theta}_\gamma + \frac{[(\bar{a}_1)_L - (\bar{a}_1)_H]}{[(\bar{a}_1)_L + (\bar{a}_1)_H]}$$

$$P_n(\cos\bar{\theta}_\gamma) = \bar{P}_{dn}/\bar{P}_{d0}$$

ignoring a_3, lower higher asymmetry for the d^{th} detector can be written as

$$(A_{LH})_d = \frac{[(\bar{a}_1)_L - (\bar{a}_1)_H]}{[(\bar{a}_0)_L + (\bar{a}_0)_H]} \cos\bar{\theta}_\gamma + \frac{[(\bar{a}_1)_L - (\bar{a}_1)_H]}{[(\bar{a}_1)_L + (\bar{a}_1)_H]}$$

comparing to measured $\mathrm{A_{LH}}$

$$A_{LH}(\theta_\gamma) = A\cos\theta_\gamma + B$$

from $\mathrm{A_{LH}}$ vs. $\cos(\theta_\gamma)$ fit

$(\bar{a}_1)_{L,H}$ are linear combinations of x and y

$$A = \frac{[(\bar{a}_1)_L - (\bar{a}_1)_H]}{[(\bar{a}_0)_L + (\bar{a}_0)_H]} = Cx + Dy$$

from resonance parameters

Can solve for x and y (or ϕ) giving two solutions!

T. Okudaira *et al.*, Phys, Rev. C **97**, 034622 (2018).