pNAB experimental method

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Outline

- Physics goals of the Nab + pNAB: a coherent program,
- The Nab spectrometer and measurement method,
- Nab control of systematic uncertainties,
- The pNAB measurement method – differences from Nab,
- Control of uncertainties in pNAB,
- Additional instrumental requirements.

We refer to Nab because pNAB shares the apparatus and many key methods.

n-beta decay basics;

Nab and pNAB

physics goals

Recap: Nab and pNAB focus on $\lambda = G_A/G_V \Rightarrow$ [for a cleaner V_{ud}^{CKM}]

General Lorentz invariant differential beta decay rate at leading order is:

$$\frac{\mathrm{d}^5\Gamma}{\mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu} \propto \rho(E_e) \times \left\{ 1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left[A_0 \frac{\vec{p}_e}{E_e} + \left(B_0 + b_\nu \frac{m_e}{E_e} \right) \frac{\vec{p}_\nu}{E_\nu} \right] + \ldots \right\}$$

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The $(V-A)$ SM prescribes $b = b_\nu = 0$, and:

$b, b_\nu \neq 0$ would signal presence of S,T int's.

e-ν correl.

$$a(\lambda) = \frac{1-|\lambda|^2}{1+3|\lambda|^2}$$

β asymm.

$$A_0(\lambda) = -2\frac{|\lambda|^2 + Re(\lambda)}{1+3|\lambda|^2}$$

ν asymm.

$$B_0(\lambda) = 2\frac{|\lambda|^2 - Re(\lambda)}{1+3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ $V_{ud}^{\rm CKM}$) .

Proton asymmetry:

$C = \kappa(A + B)$ [with $\kappa \simeq 0.275$] .

$$\frac{\Delta\lambda}{\lambda} \simeq 0.27\frac{\Delta a}{a} \simeq 0.24\frac{\Delta A}{A}$$

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Nab goals: $\frac{\Delta a}{a} \simeq 10^{-3}$, and $\Delta b \simeq 3 \times 10^{-3}$ [$\sim 10\times$ better than existing results.]

pNAB goal: $\frac{\Delta A}{A} \simeq 10^{-3}$ [competitive with PERC; better than PERKEO III].

Both Nab and pNAB bring about new measurement techniques.

The Nab

method and apparatus

The shared experimental approach of Nab and pNAB

Measure: $\frac{\Delta a}{a} \simeq 10^{-3}$ and $\Delta b \simeq 3 \times 10^{-3}$.

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Basic approach: $(n \rightarrow p + e^- + \bar{\nu}_e)$

- Detect electrons directly, in Si detectors,
- Measure electron energy in Si detectors,
- Detect protons, after acceleration, in Si detectors,
- Determine proton momentum from TOF over a long flightpath (electron provides start pulse).

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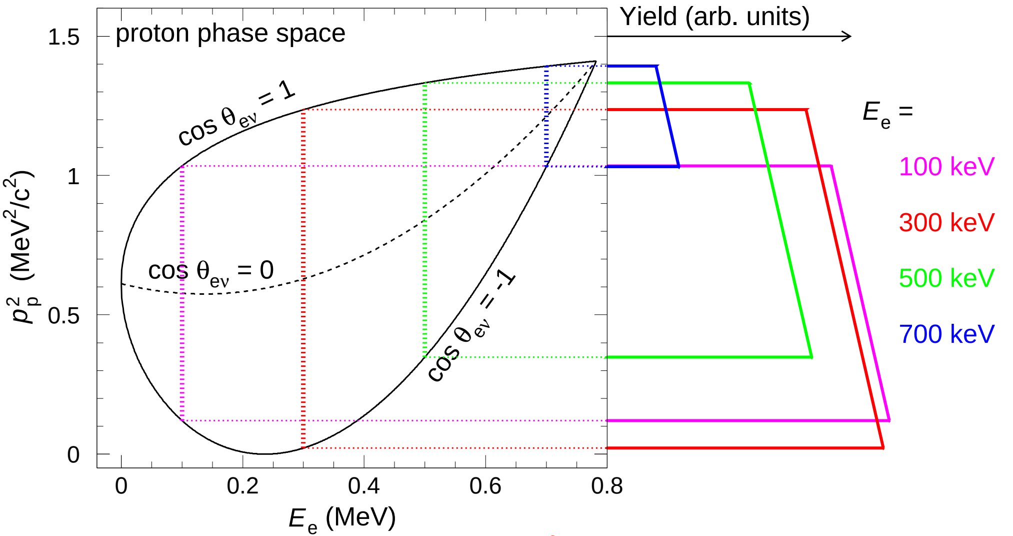
A complex magneto-electrostatic apparatus is required to guide particles (nearly) adiabatically to detectors.

Cold neutrons: FnPB at SNS.

a measurement principles: p phase space as $f(E_e)$



NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

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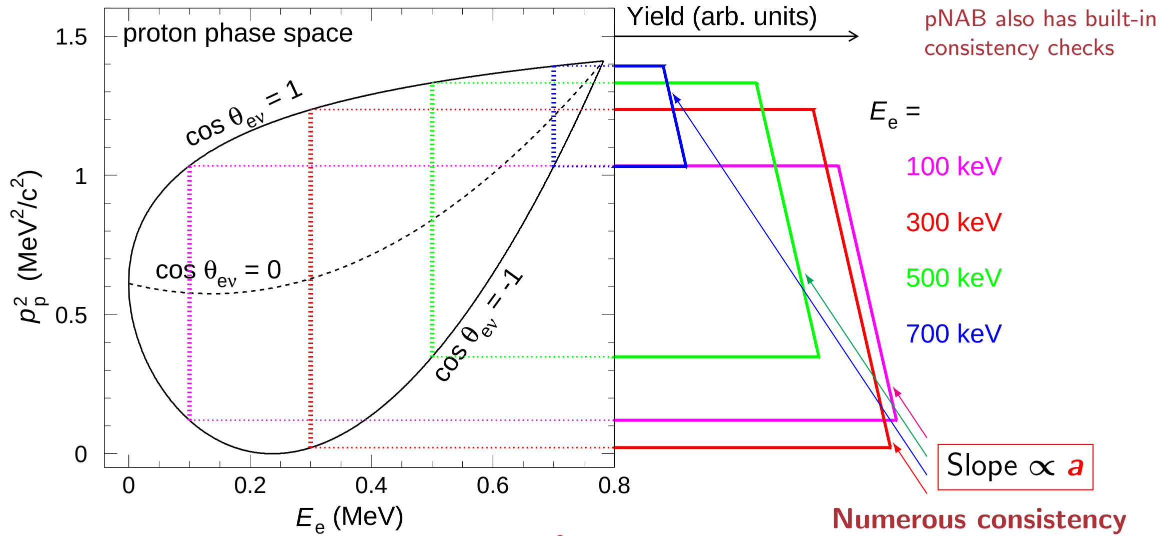

Numerous consistency checks are built-in!

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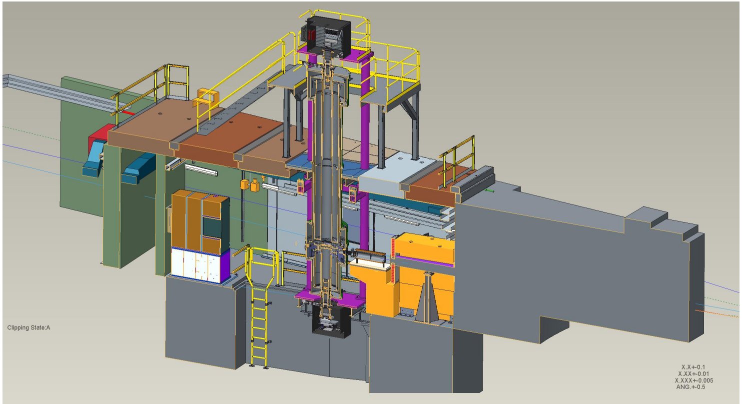
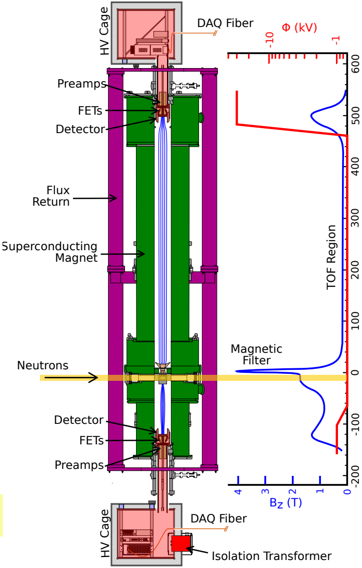
Nab apparatus (overview)

custom magneto-electrostatic asymmetric spectrometer:

Extends: ∼6 m above and ∼2 m below beam height (pit).



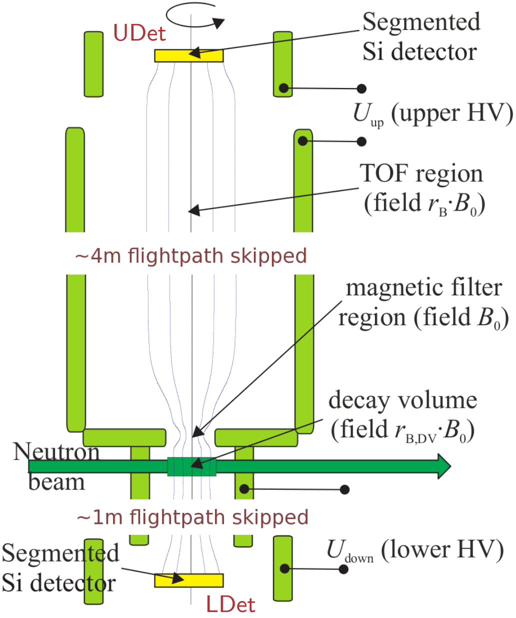


Nab has completed commissioning and is taking physics data

Nab running configurations

Nab $-$ *a*	particle detection
	protons: in UDet
	electrons: in LDet & UDet
	$U_{\mathrm{up}} = -30\,\mathrm{kV}$,
	$U_{\mathrm{down}} = 0\,\mathrm{kV}$ (or $-1\,\mathrm{kV}$);
	b measured parasitically!

Nab $-$ *b*	particle detection
	protons: in LDet
	electrons: in LDet & UDet
	$U_{\mathrm{up}} = 0\,\mathrm{kV}$, (up to $+1\,\mathrm{kV}$)
	$U_{\mathrm{down}} = -30\,\mathrm{kV}$;
pNAB config.	full *e*-*p* coinc. coverage;
	LDet: increased rate;
	$\Delta t(e\text{-}p)$ reduced $\sim \times 1/5$.



Nab systematic uncertainties

Main sources of uncertainties in Nab & relation to pNAB

- Physical properties of the instrument: magnetic and electric fields
  - relative field magnitudes, curvature , etc.,
  - relative geometry of electric and magnetic field distributions,
  - electric field inhomogeneity,
  - relative geometry of the neutron beam
- Physics of particle interactions with the apparatus:
  - electron backscattering (depends on incident angle, E),
  - electron bremsstrahlung,
  - proton detection efficiency, etc.

All of these factors influence details of the detector response functions (for electrons and protons) and, hence, the extraction of a.

Note: regular systematics-motivated measurements during main DAQ adds running time.

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largely not significant in pNAB

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affect pNAB, but less than Nab

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Nab systematic uncertainties: (Method B)

Experimental parameter		Principal specification (comment)	$(\Delta a/a)_{\text{SYST}}$
Magnetic field:	curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (d^2B_z(z)/dz^2)/B_z(0)$	5.3×10^{-4}
	ratio $r_B = B_{TOF}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
	ratio $r_{B,DV} = B_{DV}/B_0$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
L_{TOF}, length of TOF region		(free fit parameter)	—
U inhomogeneity:	in decay / filter region	$\lvert U_F - U_{DV}\rvert < 10\,\text{mV}$	5×10^{-4}
	in TOF region	$\lvert U_F - U_{TOF}\rvert < 200\,\text{mV}$	2.2×10^{-4}
Neutron beam:	position	$\Delta\langle z_{DV}\rangle < 2\,\text{mm}$	1.7×10^{-4}
	profile (incl. edge effect)	slope at edges $< 10\%/\text{cm}$	2.5×10^{-4}
	Doppler effect	(analytical correction)	small
	unwanted beam polarization	$\Delta\langle P_n\rangle < 2 \cdot 10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion			1×10^{-4}
Detector effects:	E_e calibration	$\Delta E_e < 200\,\text{eV}$	$2 \cdot 10^{-4}$
	shape of E_e response	$\Delta N_{tail}/N_{tail} \leq 1\%$	4.4×10^{-4}
	proton trigger efficiency	$\epsilon_p < 100\,\text{ppm/keV}$	3.4×10^{-4}
	TOF shift (det./electronics)	$\Delta t_p < 0.3\,\text{ns}$	3.9×10^{-4}
electron TOF		(analytical correction)	small
TOF in acceleration region		$\Delta r_{\text{GROUND EL.}} < 0.5\,\text{mm}$ (preliminary)	3×10^{-4}
BGDs/accidental coincidences		(will subtract out of time coinc)	small
Residual gas		$P < 2 \cdot 10^{-9}$ torr	3.8×10^{-4}
Overall sum			1.2×10^{-3}

Nab systematic uncertainties: (Method B)

other systematics largely unimportant for pNAB

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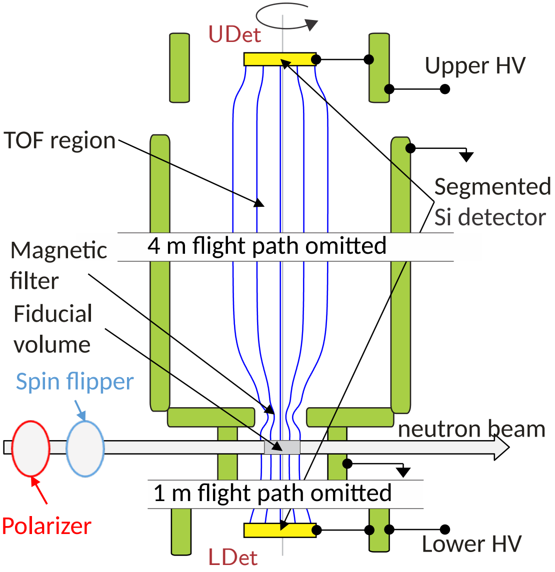
affect pNAB

pNAB apparatus, method and systematics

pNAB running configurations

	particle detection
pNab-*C* (p-asym)	protons: in UDet electrons: in LDet & UDet
	$U_{\text{UDet}} = -30\,\text{kV}$, $U_{\text{LDet}} = 0\,\text{kV}$ (or $-1\,\text{kV}$);

	particle detection
pNAB-*A* (β-asym) main	protons: in LDet electrons: in LDet & UDet
	$U_{\text{UDet}} = 0\,\text{kV}$, (up to $+1\,\text{kV}$) $U_{\text{LDet}} = -30\,\text{kV}$; full e-p coinc. coverage;



Measuring the electron/proton asymmetry

Asymmetry in the count rate of electrons α_e or protons α_p w.r.t. $\vec{\sigma}_n$ (n-spin):

Both e and p count rate asymmetries have the form:

$$\text{differential decay rate} \propto 1 + \alpha_{e/p} P_n \cos\theta_0 \,, \qquad \text{where}$$

P_n ...the degree of polarization of the n beam,
θ_0 ...initial angle of $\vec{p}_e$ or $\vec{p}_p$ w.r.t. $\vec{\sigma}_n$. (i.e., the magnetic field) at time of n decay.

Observables α_e or α_p depend on E_e: to get the asymmetry A, we use

$$\alpha_e = A\frac{v_e}{c} = A\beta_e \,, \qquad \text{or} \qquad A = \frac{\alpha_e}{\beta_e} \,, \qquad \text{where}$$

v_e ...electron velocity, and c ...speed of light.

Key requirement: $\Delta P_n \le 5 \cdot 10^{-4}$ (multiplicative factor in A).

Uncertainty budget in A

$$A_{\rm exp} = \frac{N_e^{\uparrow}(E_{e,{\rm kin}}) - N_e^{\downarrow}(E_{e,{\rm kin}})}{N_e^{\uparrow}(E_{e,{\rm kin}}) + N_e^{\downarrow}(E_{e,{\rm kin}})} = A\, P_n \frac{p_e}{E_e} \langle \cos(\vec{\sigma}_n, \vec{p}_e) \rangle \,.$$

Contribution to uncertainty	$\Delta A/A$
1. Neutron beam polarization, P_n	$5 \cdot 10^{-4}$
2. Electron energy detector response, p_e/E_e	$5 \cdot 10^{-4}$
3. Solid angle coverage of each detector	negligible
4. Statistical uncertainty	$7 \cdot 10^{-4}$
5. Backgrounds: e-p coincidence helps subtract them(*)	small
Total	$< 1 \cdot 10^{-3}$

(*) unlike the competing experiments

Systematic uncertainties shared with Nab

How well do we need to understand the detector response in Nab and pNAB?

Specifications for ↦ / ↲ Parameter ↴	$\Delta a = 3 \cdot 10^{-5}$ (Nab)	$\Delta b = 10^{-3}$ (Nab)	$\Delta A = 3 \times 10^{-5}$ (pNAB)
gain factor ($\Delta g/g$)	fit parameter	fit parameter	0.0018 ✓
offset E_0	0.3 keV	0.06 keV	~~0.2 keV~~ 0.3 keV
nonlinearity ($\lvert\Delta E_{\rm max}\rvert$)	1.5 keV ✓	0.06 keV	0.3 keV
peak width (Δw)	1 keV ✓	–	10 keV ✓
tail to peak ratio (Δt)	0.01%	0.2%	2.4%

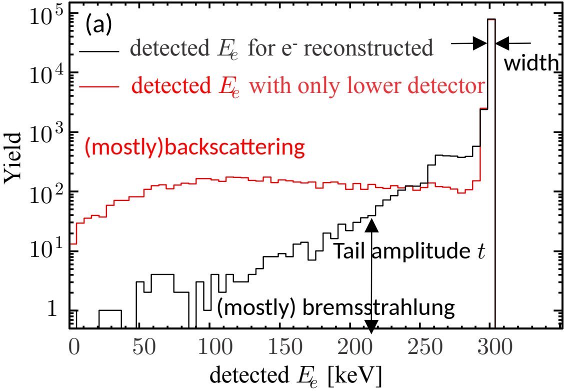
currently 0.37 keV

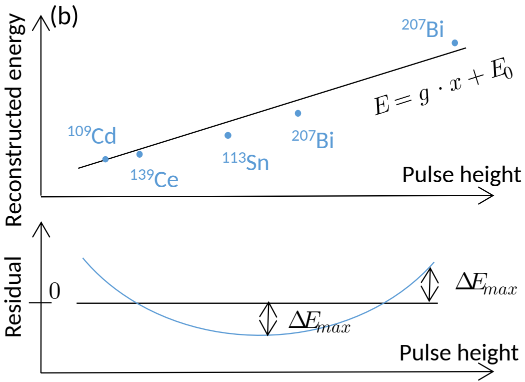
✓ as of Apr. 2025 (Jin Ha Choi, NCSt)

Generally, pNAB requirements on the response parameters are less stringent than those in Nab. Therefore, pNAB will find the apparatus understood more than well enough after Nab.

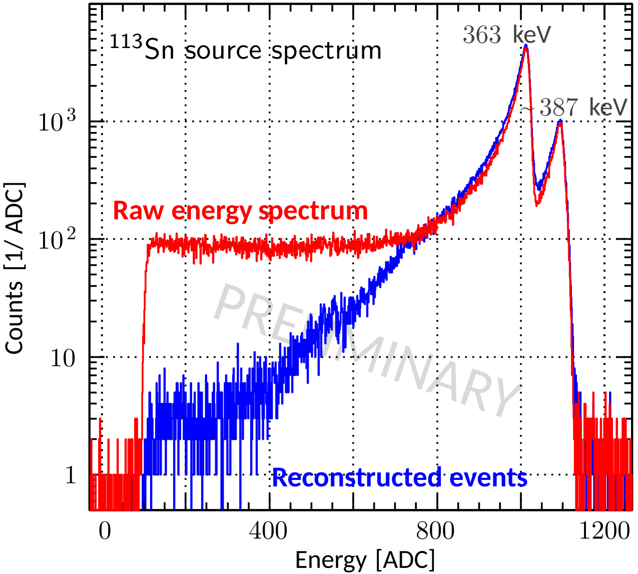
Nab has met, or is close to meeting, the goals for all above parameters except the tail ratio, for which there is a program of study in place.

Electron energy response linearity





Actually observed electron response



Quite effective reconstruction of E_e demonstrated.

Remaining distortion of E_e response: due to Bremsstrahlung.

Nab requires an in depth study of BS, more than sufficient to constrain the electron response tail for pNAB.

Summary

pNAB uses Si detectors with linearity and energy resolution far superior to the plastic scintillation detectors used in previous A measurements.

Unlike competing experiments, pNAB uses coincident detection of e and p in n beta decay. $\Delta\vec{r}$ and Δt correlations allow subtraction of BGDs. Other strong points of pNAB are full coverage and hermeticity.

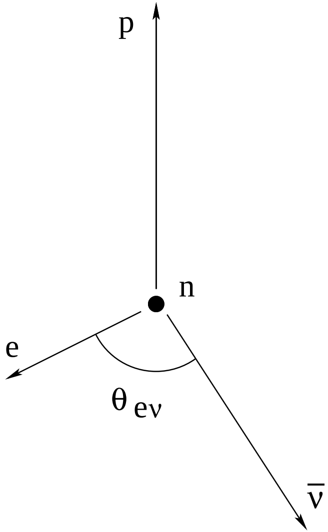
Most sources of systematic uncertainties that are major challenges in Nab, have a low impact in pNAB; many have already been resolved well enough for pNAB.

Producing high (near-100%) P_n, n beam polarization, with acceptable loss of beam rate remains a challenge $\Rightarrow$ addressed in talks that follow.

Ad-hoc review committee for pNAB on 12-Dec-25, endorsed the motivation, goals and method of pNAB, and the preferred SSP option for polarizing neutrons.

Additional slides:

Electron–neutrino angle from E_e and E_p



Conservation of momentum in **n** beta decay,

$$\vec{p}_p + \vec{p}_e + \vec{p}_\nu = 0\,,$$

yields

$$p_p^2 = p_e^2 + 2 p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,.$$

Neglecting the proton recoil energy*, we have $E_e + E_\nu = E_0$,

or, $p_\nu = E_0 - E_e$. Therefore:

$$p_p^2 \simeq {p_e}^2 + 2p_e(E_0 - E_e)\cos\theta_{e\nu} + (E_0 - E_e)^2\,.$$

$\Rightarrow$ $\cos\theta_{e\nu}$ is uniquely determined by measuring E_e and E_p (or $p_p \Leftrightarrow \mathrm{TOF}_p$).

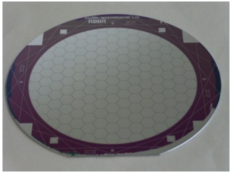
* proton recoil correction is applied a posteriori.

Nab Si detector basics

(LANL-Micron development)

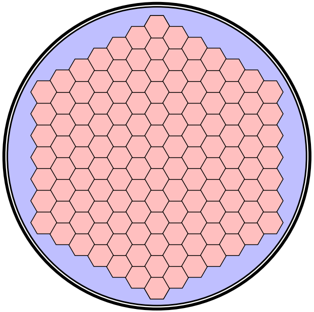
- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels

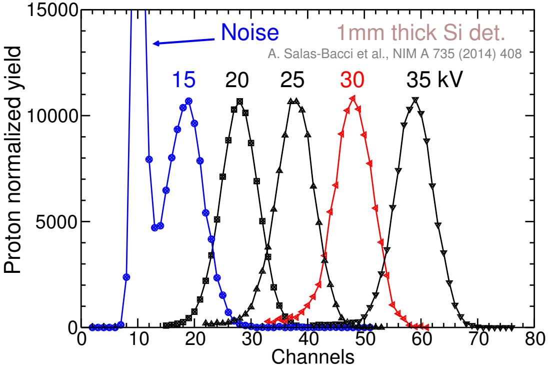
Front



Back

Pixel geometry:





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(LANL-Micron development)

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- dead layer $\leq$100 nm
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easily meet pNAB requirements

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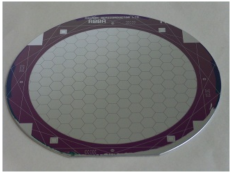
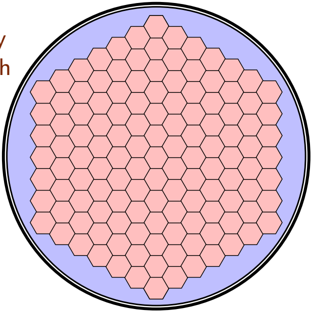


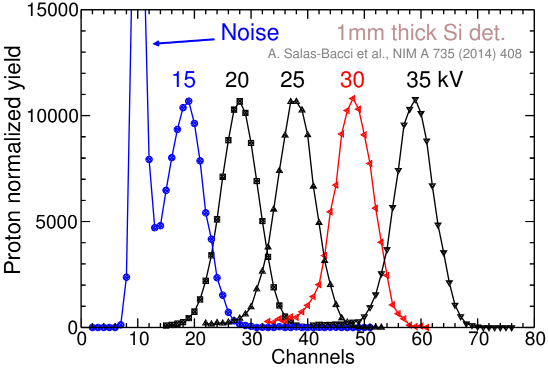
Back

$\vec{B}$ field lines map decay region to pixels on both detectors.

Pixel geometry:



Spatial and temporal correlations of e and p hits enable BGD subtraction.



Run time estimate for $[\Delta A/A]_{\rm stat} \simeq 7 \cdot 10^{-4}$

The run time is based on a count rate estimate of 250 decays/s @2 MW proton power:

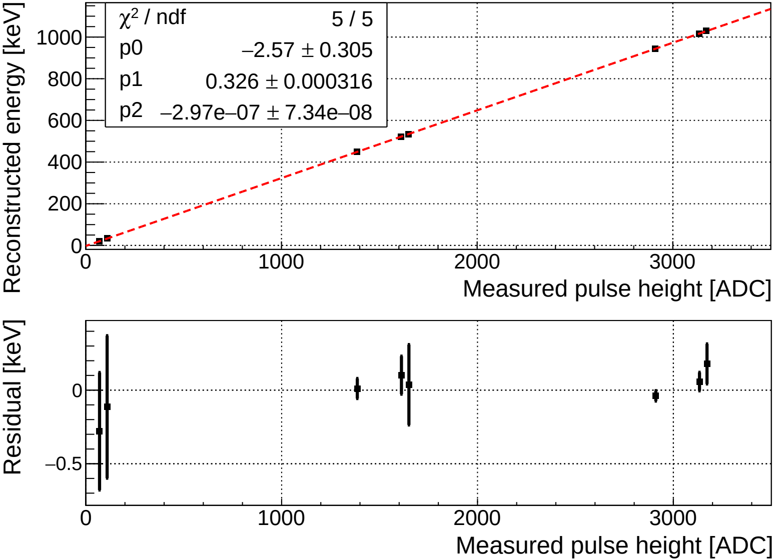
- size of the decay volume: 160 cm^3,
- neutron decay density of 1.6 decays/s/cm^3 @ 2 MW (estimate from Nab),
- Plan A, an SSP polarizer with $P_n \approx 100\%$ and transmission of 15%,
- SNS operating schedule `https://neutrons.ornl.gov/hfir/hfir-sns-5-year-working-schedule`.

Our nominal run time is now 2.5 years and includes the assumption that we spend 35% of the time for data taking, with the remainder for calibrations and downtimes. In addition, we need 1/2 year for the polarization measurements, revised upward from the proposal, when we didn't have a measured count rate estimate. We expect 6% of false coincidences in accidental background, based on:

- We reflect all protons to the lower detector which is on a negative bias voltage of 30 kV.
- The combined background and signal rate is about 10,000 s^{-1} (depending strongly on LDet threshold).
- After an e hit, we wait up to $t_{p,\rm max} = 22\,\mu$s (prelim.) for a p hit, to avoid bias.
- Position coincidence between electron and proton as in Nab.

Accidental background at this level can be measured by requiring coincidence between electron and proton in incorrect times or pixels, and is not making a substantial contribution to the statistical uncertainty.

E_e response linearity: actual fits – pixel 76



(Jin Ha Choi, NCState)