Nab: a precise study of unpolarized neutron beta decay

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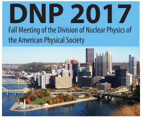

2017 Fall Meeting of the APS
Division of Nuclear Physics
Pittsburgh, PA
25 – 28 October 2017

Neutron beta decay observables (SM)

$$\frac{\mathrm{d}w}{\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu} \simeq p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} \right) + \ldots \right]$$

where in SM:

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

$$B = 2\frac{|\lambda|^2 - Re(\lambda)}{1 + 3|\lambda|^2} \qquad \lambda = \frac{G_A}{G_V} \text{ (with } \tau_n \Rightarrow \text{CKM } V_{ud}\text{)}$$

also proton asymmetry: $C = \kappa(A + B)$ where $\kappa \simeq 0.275$.

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⇒ SM **overconstrains** a, A, B observables in n β decay!
Fierz interf. term b brings add'l. sensitivity to non-SM processes!

Goals of the Nab experiment (at SNS, ORNL)

- Measure the e–ν correlation a in neutron decay with precision

$\Delta a/a \simeq 10^{-3}$ or $\sim 40\times$ better than:

current results:	-0.1090 ± 0.0041	Darius et al 2017 (aCORN)
	-0.1054 ± 0.0055	Byrne et al 2002
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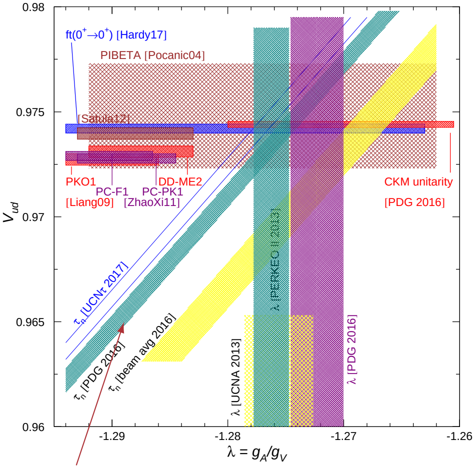
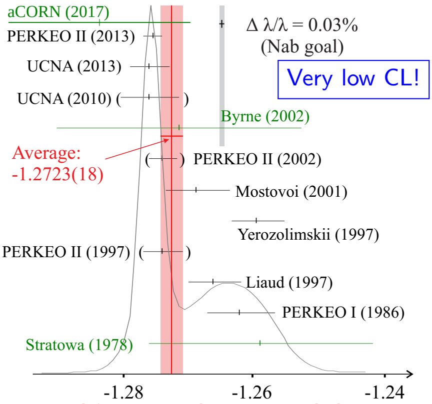
Motivation:

- multiple independent determinations of λ (test of CKM unitarity),
- independent and competitive limits on S, T currents (BSM).

Current status of V_{ud} and λ, from n decay

…remains an unresolved mess:





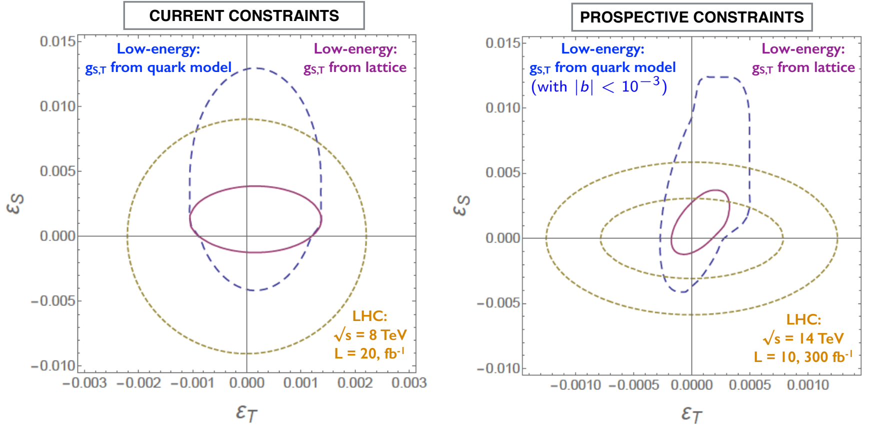
$$\tau_n^{-1} \propto |V_{ud}|^2 |g_V|^2 (1 + 3|\lambda|^2)$$

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

λ sensitivity to a, A is **similar**.

- Nab+abBA ⇒ several independent ~ 0.03% determinations of λ,
- Combined with b ⇒ new limits on non-SM terms, esp. Tensor.

Limits on T, S couplings from beta decay



Measurement of b with $\delta b < 10^{-3} \Rightarrow\ >$ 4-fold improvement on the current limit for ϵ_T from $\pi^+ \to e^+\nu\gamma$ decay [Bychkov et al, PRL **103** (2009) 051802].

Also see: T. Bhattacharya, et al. Phys. Rev. D 94 (2016) 054508,
Martín González-Alonso, arXiv:1209.0689,
G. Konrad, et al., arXiv:1007.3027,
S. Baeßler, et al., J. Phys. G: Nucl. Part. Phys. **41** (2014) 114003.

How to accomplish the goals of Nab?

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

- Detect electrons directly, in Si detectors,
- Measure electron energy in Si detectors,
- Detect protons, after acceleration, in Si detectors,
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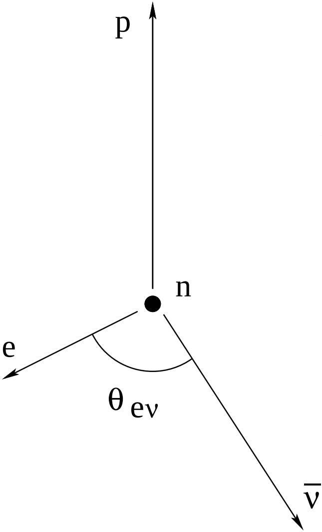
A complex magneto-electrostatic apparatus is required to guide particles (nearly) adiabatically to detectors.

Location: FnPB at SNS

Electron–neutrino angle from E_e and E_p



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

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

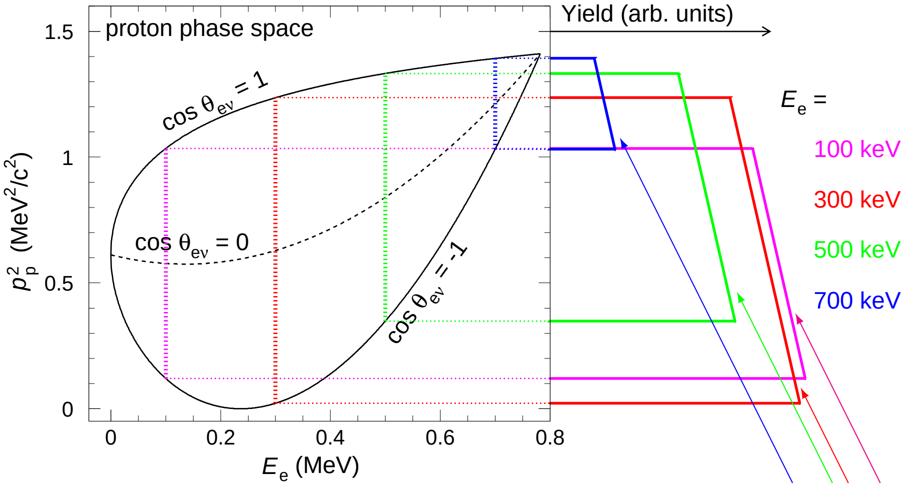
yields

$$\begin{aligned} p_p^2 &= p_e^2 + 2p_e p_\nu \cos\theta_{e\nu} + p_\nu^2\,, \\ &\simeq p_e^2 + 2p_e(E_0 - E_e)\cos\theta_{e\nu} + (E_0 - E_e)^2 \end{aligned}$$

neglecting proton recoil energy: $E_e + E_\nu \simeq E_0$, so that $p_\nu = E_0 - E_e$. Therefore:

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

Nab measurement principles: proton phase space



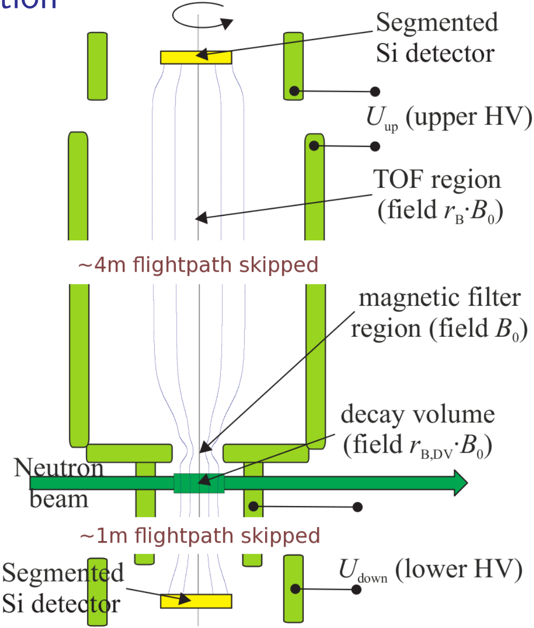
NB: For a given E_e, $\cos\theta_{e\nu}$ is a function of p_p^2 only.

Slope $\propto$ ***a***

Numerous consistency checks are built-in!

Nab principles of operation

- Collect and detect **both** electron and proton from **n decay**.
- Measure E_e and TOF_p and reconstruct decay kinematics



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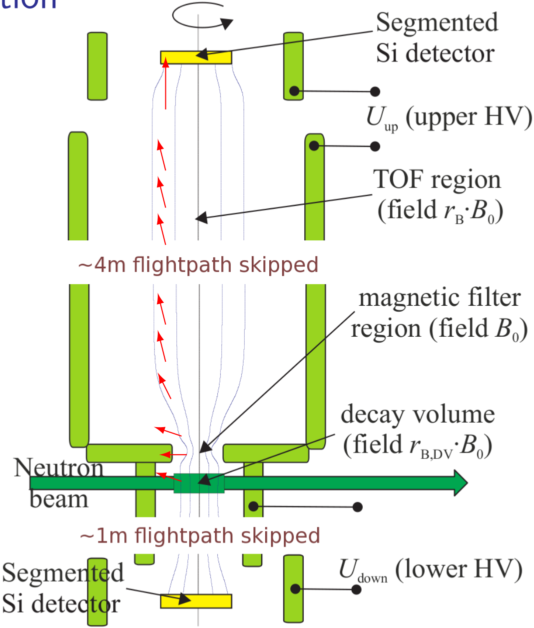

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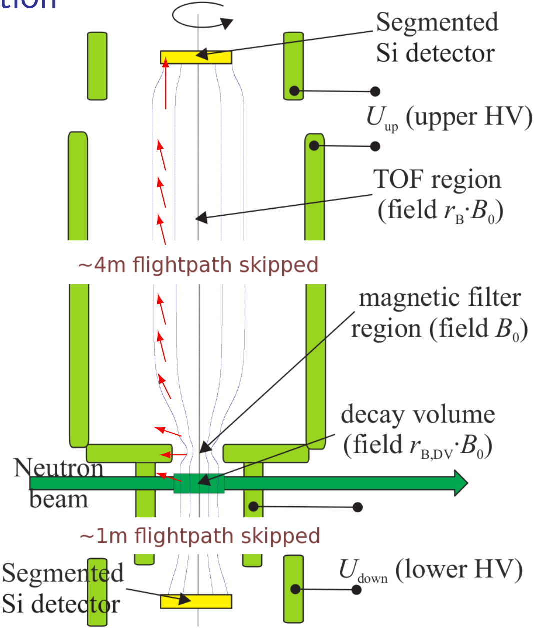
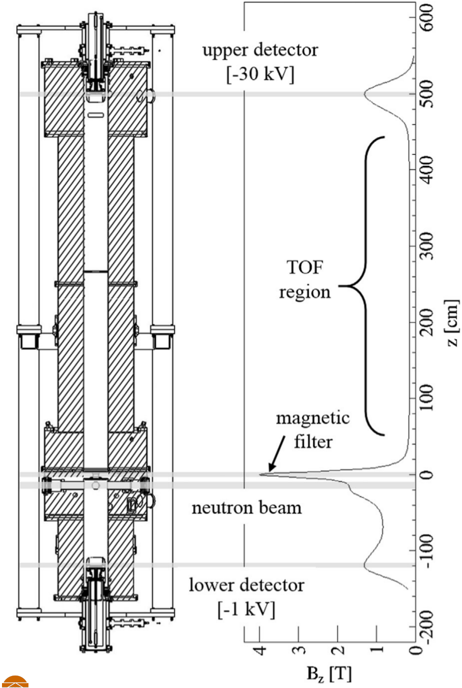
Key requirements:

- Specific magnetic field properties,
- Electrode system,
- Ultra-high vacuum,
- Silicon detectors,
- No particle trapping.



Spectrometer coil design and $\vec{B}$ field profile



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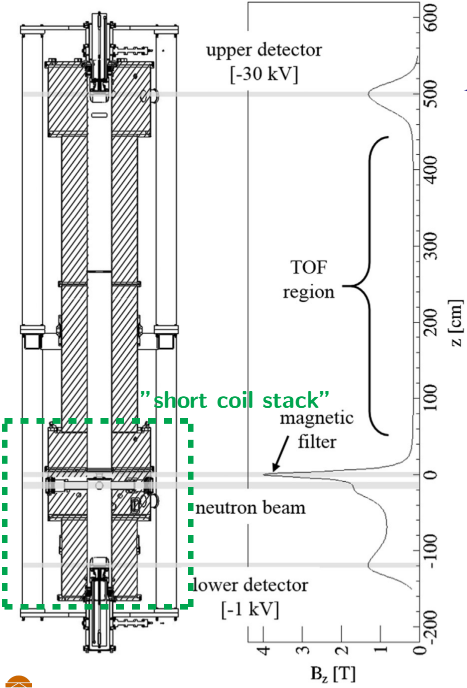
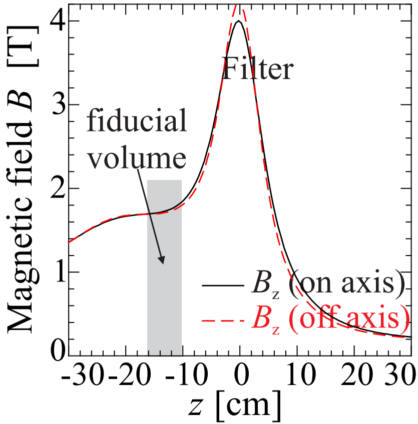
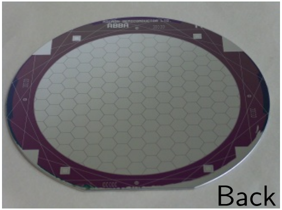


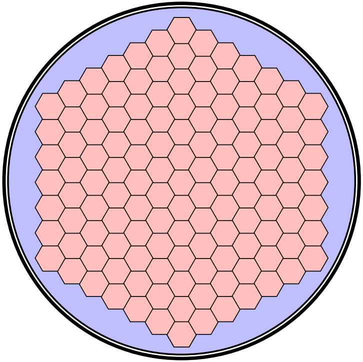
central region details

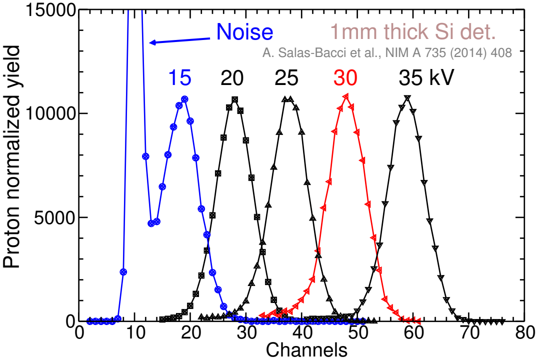


Nab Si detectors (LANL-Micron development)

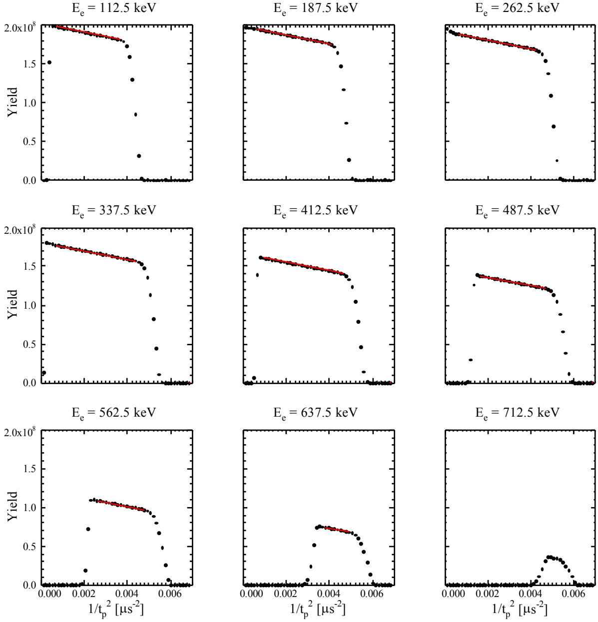
- 15 cm diameter
- full thickness: 2 mm
- dead layer ≤100 nm
- 127 pixels







Analysis strategy



- ∗ Plan to use edges to determine and verify shape of detection function $\Phi(1/t_\mathrm{p}^2, p_\mathrm{p}^2)$;
- ∗ Shown are model generated events, randomly shifted to reflect counting statistics;
- ∗ Central part of $P_t(1/t_p^2)$, $\sim 75\%$, used to extract ***a*** — red fit. Note: events with $E_\mathrm{e} > 650\,\mathrm{keV}$ will not contribute to the fit of parameter ***a***.

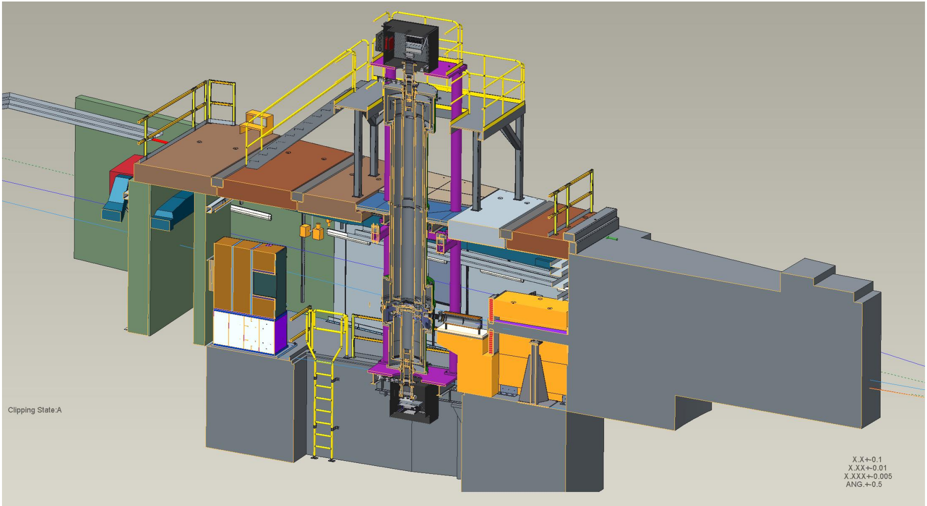
Nab systematic uncertainties: Method B

Experimental parameter	Principal specification (comment)	$(\Delta a/a)_{\mathrm{SYST}}$
Magnetic field:		
curvature at pinch	$\Delta\gamma/\gamma = 2\%$ with $\gamma = (\mathrm{d}^2 B_z(z)/\mathrm{d}z^2)/B_z(0)$	5.3×10^{-4}
ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$	$(\Delta r_B)/r_B = 1\%$	2.2×10^{-4}
ratio $r_{\mathrm{B,DV}} = B_{\mathrm{DV}}/B_0$	$(\Delta r_{\mathrm{B,DV}})/r_{\mathrm{B,DV}} = 1\%$	1.8×10^{-4}
L_{TOF}, length of TOF region		(*)
U inhomogeneity:		
in decay / filter region	$\lvert U_{\mathrm{F}} - U_{\mathrm{DV}}\rvert < 10\,\mathrm{mV}$	5×10^{-4}
in TOF region	$\lvert U_{\mathrm{F}} - U_{\mathrm{TOF}}\rvert < 200\,\mathrm{mV}$	2.2×10^{-4}
Neutron beam:		
position	$\Delta\langle z_{\mathrm{DV}}\rangle < 2\,\mathrm{mm}$	1.7×10^{-4}
profile (incl. edge effect)	slope at edges $< 10\%/\mathrm{cm}$	2.5×10^{-4}
Doppler effect	(analytical correction)	small
unwanted beam polarization	$\Delta\langle P_{\mathrm{n}}\rangle < 2 \cdot 10^{-5}$ (with spin flipper)	1×10^{-4}
Adiabaticity of proton motion		1×10^{-4}
Detector effects:		
E_{e} calibration	$\Delta E_{\mathrm{e}} < 200\,\mathrm{eV}$	$2 \cdot 10^{-4}$
shape of E_{e} response	$\Delta N_{\mathrm{tail}}/N_{\mathrm{tail}} \leq 1\%$	5.7×10^{-4}
proton trigger efficiency	$\epsilon_{\mathrm{p}} < 100\,\mathrm{ppm/keV}$	3.4×10^{-4}
TOF shift (det./electronics)	$\Delta t_{\mathrm{p}} < 0.3\,\mathrm{ns}$	3×10^{-4}
BGD/accid. coinc's	(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}

(*) Free fit parameter

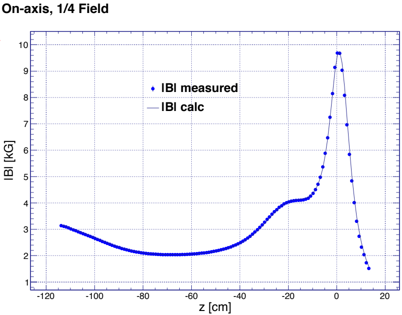
Nab apparatus in FnPB

extends: ∗ ∼6 m above beam height,
∗ ∼2 m below beam height (pit).



Nab plans to collect samples of $1-2\times10^9$ events in several 6–8-week runs; these runs will take most of a year's running cycle at SNS.

⇔



⇑
30 Sep 2016

20 Oct 2017 ⇒

- Delivery at SNS by end of 2017
- Ready for beam in 2018

Active and recent Nab collaborators (as of Oct 2017)

R. Alarcon[a], S. Baeßler[b,c*], S. Balascuta[a§], L. Barrón Palos[e], K. Bass[f§], N. Birge[f§], A. Blose[j§], D. Borissenko[b§], J.D. Bowman[c†], L. Broussard[d,c], A.T. Bryant[b§], J. Byrne[g], J.R. Calarco[f,c], T. Chupp[i], V. Cianciolo[c], J.N. Clement[b§], C. Crawford[j], W. Fan[b§], W. Farrar[b§], N. Fomin[f], E. Frlež[b], J. Fry[b], M.T. Gericke[k], M. Gervais[j§], F. Glück[ℓ], G.L. Greene[c,f], R.K. Grzywacz[f], V. Gudkov[m], J. Hamblen[p], C. Hendrus[i§], T. Ito[d], H. Li[b§], C.C. Lu[b§], M.F. Makela[d], R. Mammei[k], J. Martin[n], M. Martinez[a§], D.G. Matthews[j§] P.L. McGaughey[d], C.D. McLaughlin[b§], P. Mueller[c], D. van Petten[b§], S.I. Penttilä[c‡], D. Počanić[b†], G. Randall[a§], N. Roane[b§], C.A. Royse[o§], K.P. Rykaczewski[c], A. Salas-Bacci[b], E.M. Scott[f§], S.K. Sjue[d], A. Smith[b§], E. Smith[d], A. Sprow[j§], E. Stevens[b§], D. van Petten[b§], J. Wexler[o§], R. Whitehead[f§], W.S. Wilburn[d], A.R. Young[o], B. Zeck[o].

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[§]Nab students, or recent Nab students/collaborators

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