Precise Measurement of the Neutron Beta Decay Parameters *a* and *b*

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University of Virginia

DoE Review of the FnPB/SNS,
Oak Ridge, 23 April 2009

Outline

Goals of the Experiment

- Measure the electron-neutrino parameter **a** in neutron decay

  with accuracy of $\frac{\Delta a}{a} \simeq 10^{-3}$

	-0.1054 ± 0.0055	Byrne et al '02
current results:	-0.1017 ± 0.0051	Stratowa et al '78
	-0.091 ± 0.039	Grigorev et al '68

- Measure the Fierz interference term **b** in neutron decay

  with accuracy of $\Delta b \simeq 3 \times 10^{-3}$

  current results: **none**

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Neutron Decay Parameters (SM)

$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} \simeq k_e E_e (E_0 - E_e)^2$$

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

with:

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

$$B = 2 \frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1 + 3|\lambda|^2} \qquad D = 2 \frac{\mathrm{Im}(\lambda)}{1 + 3|\lambda|^2}$$

$\lambda = \frac{G_A}{G_V}$ (with $\tau_n \Rightarrow$ CKM V_{ud}) ($D \neq 0 \Leftrightarrow T$ inv. violation)

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n-decay Correlation Parameters Beyond $\mathbf{V_{ud}}$

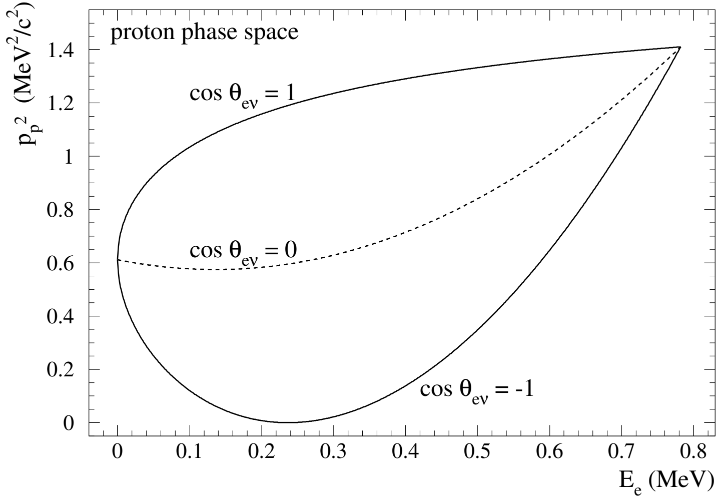
- Beta decay parameters constrain L-R symmetric, SUSY extensions to the SM. [Reviews: Herczeg, Prog. Part. Nucl. Phys. **46**, 413 (2001), N. Severijns, M. Beck, O. Naviliat-Čunčić, Rev. Mod. Phys. **78**, 991 (2006), Ramsey-Musolf, Su, Phys. Rep. **456**, 1 (2008)]

- Fierz interference term, never measured for the neutron, offers a sensitive test of non-$(V - A)$ terms in the weak Lagrangian (S, T). [S. Profumo, M. J. Ramsey-Musolf, S. Tulin, PRD **75**, 075017 (2007)]

- Measurement of the electron-energy dependence of a and A can separately confirm CVC and absence of SCC. [Gardner, Zhang, PRL **86**, 5666 (2001), Gardner, hep-ph/0312124]

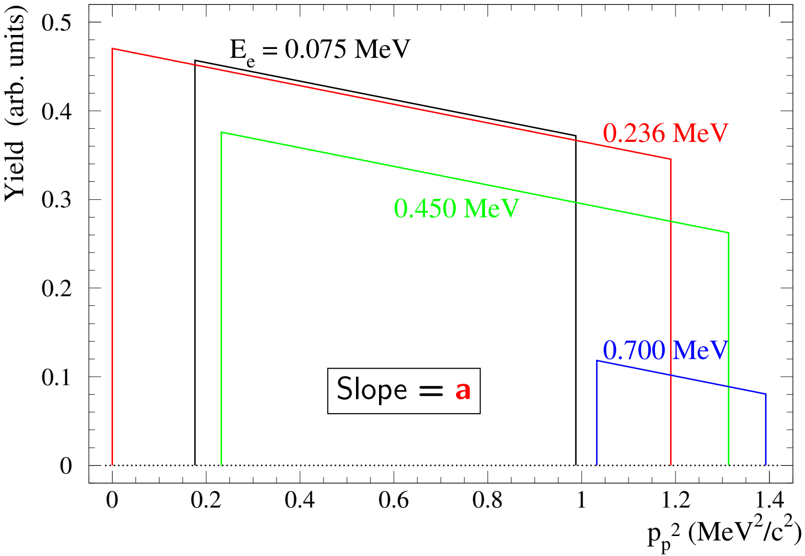
- A general connections exists between non-SM (e.g., S, T) terms in $d \to ue\bar{\nu}$ and limits on ν masses. [Ito + Prézaeu, PRL **94** (2005)]

Nab Measurement principles: Proton phase space

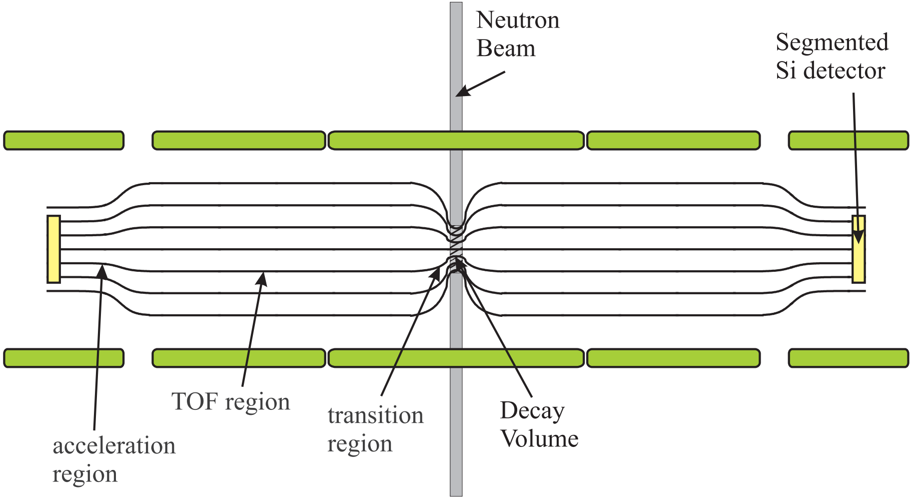


Note: For a given $\mathbf{E_e}$, $\cos\theta_{e\nu}$ is a function of $\mathbf{p_p^2}$ only.

Measurement principles: Proton momentum response

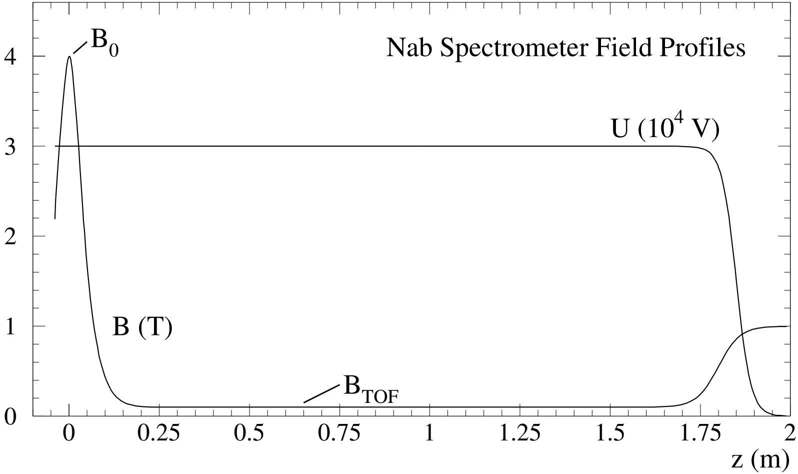


Measurement principles: Symmetric pectrometer



Elements of spectrometer to be shared with other planned n decay experiments, e.g., **abBA**.

Measurement principles: Spectrometer field profiles



$$r_B = \frac{B_{\text{TOF}}}{B_0}$$

Measurement principles: Detection function (I)

Proton time of flight in B field:

$$t_{\rm p} = \frac{f(\cos\theta_{\rm p,0})}{p_{\rm p}} \qquad \text{where} \qquad \cos\theta_{\rm p,0} = \left.\frac{\vec{p}_{\rm p0}\cdot\vec{B}}{p_{\rm p0}B}\right|_{\text{decay pt.}} .$$

For an adiabatically expanding field prior to acceleration,

$$f(\cos\theta_{\rm p,0}) = \int_{z_0}^{l}\frac{m_{\rm p}\,dz}{\cos\theta_{\rm p}(z)} = \int_{z_0}^{l}\frac{m_{\rm p}\,dz}{\sqrt{1-\frac{B(z)}{B_0}\sin^2\theta_{\rm p,0}}} .$$

To this we add effects of magnetic reflections and, later, of electric field acceleration.

Measurement principles: Detection function (II)

The proton momentum distribution within the phase space bounds is given by

$$P_p(p_{\rm p}^2) = 1 + a\beta_e \cos\theta_{e\nu}\,, \qquad [\text{recall: } \cos\theta_{e\nu} = f(p_{\rm p}^2)]$$

while

$$P_t\left(\frac{1}{t_{\rm p}^2}\right) = \int P_p(p_{\rm p}^2)\,\Phi\left(\frac{1}{t_{\rm p}^2}, p_{\rm p}^2\right) dp_{\rm p}^2\,.$$

Detection function Φ relates the proton momentum and time-of-flight distributions! To extract **a** reliably:

- Φ must be as narrow as possible,
- Φ must be understood very precisely.

Two methods ("A" and "B") pursued to specify Φ.

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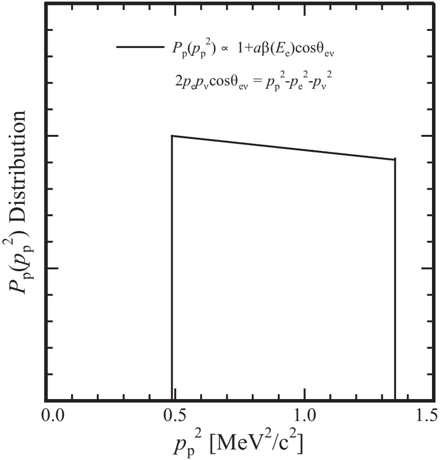
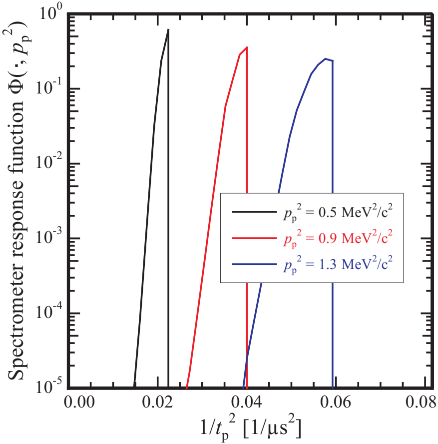
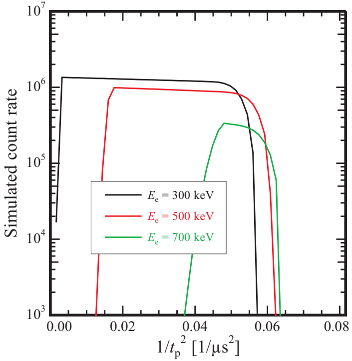
Measurement principles: Detection function (III)



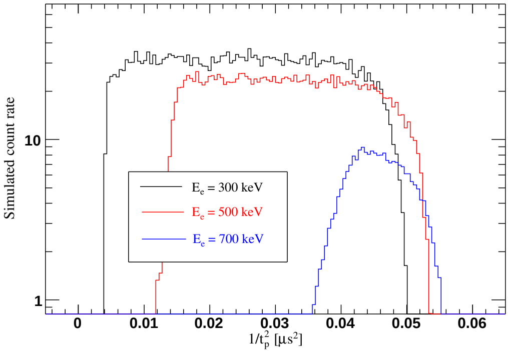


$E_e = 550\,\text{keV}$

Measurement principles: Detection function (IV)



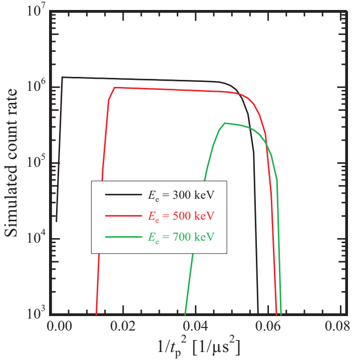
Theoretical calculation
(method "B")



Realistic Monte Carlo simulation
(1M decays, GEANT4)

Note:
1. central, straight portion sensitive to physics (a),
2. edges sensitive to detection function and calibration.

Measurement principles: Detection function (IV)



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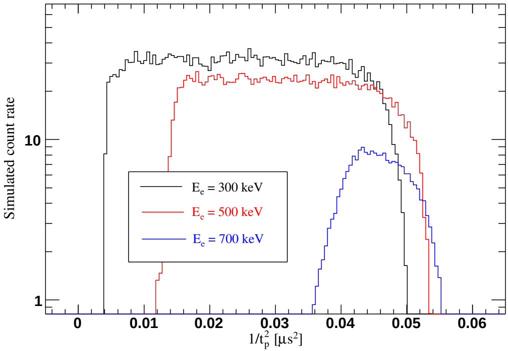

Realistic Monte Carlo simulation (1M decays, GEANT4)

Note:
1. central, straight portion sensitive to physics (**a**),
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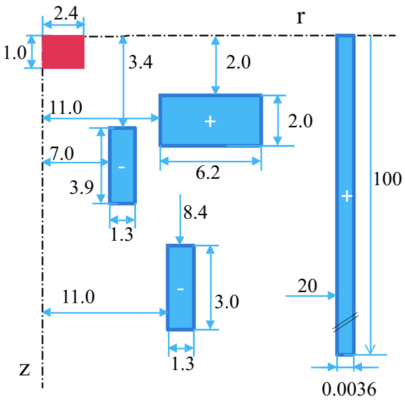
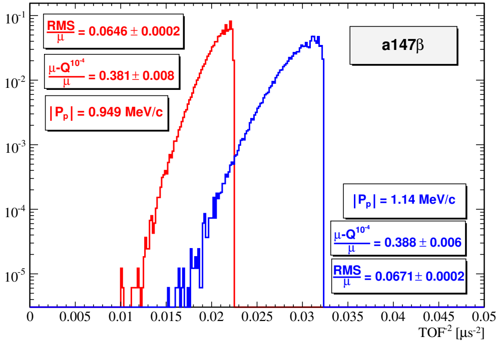
Optimized symmetric spectrometer



dimensions in cm

Current density: 3500 A/cm^2

The “a-147-beta” Configuration



Statistical uncertainties for a and b

Statistical uncertainties for **a**

$E_{\mathrm{e,min}}$	0	100 keV	100 keV	300 keV
$t_{\mathrm{p,max}}$	–	–	10 μs	10 μs
$\sigma_{\mathbf{a}}$	$2.4/\sqrt{N}$	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	$3.5/\sqrt{N}$
$\sigma_{\mathbf{a}}{}^{\dagger}$	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	–	–

† with $\mathbf{E}_{\mathbf{cal}}$ and **l** variable.

Statistical uncertainties for **b**

$E_{\mathrm{e,min}}$	0	100 keV	200 keV	300 keV
$\sigma_{\mathbf{b}}$	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.3/\sqrt{N}$
$\sigma_{\mathbf{b}}{}^{\dagger\dagger}$	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

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σ_a †	$2.5/\sqrt{N}$	$2.6/\sqrt{N}$	–	–

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Statistical uncertainties for b

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Event rates, statistics and running times

FnPB **n** decay rate w/nominal 1.4 MW SNS operation: $r_n \simeq 19.5/(\mathrm{cm}^3\mathrm{s})$.

Nab fiducial volume is: $V_f \simeq \frac{\pi}{2} 2.4^2 \times 2\mathrm{cm}^3 \simeq 18\,\mathrm{cm}^3$.

This gives a rate of about 350 evts./s.

In a typical ∼10-day run of 7×10^5 s of net beam time we would achieve

$$\frac{\sigma_a}{a} \simeq 2 \times 10^{-3} \qquad \text{and} \qquad \sigma_b \simeq 6 \times 10^{-4}$$

We plan to collect several samples of 10^9 events in several 6-week runs.

Consequently, overall accuracy will **not be statistics-limited**.

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Systematic uncertainties and checks

- Uncertainties due to spectrometer response
  - Neutron beam profile: 100 μm shift of beam center induces $\Delta a/a \sim 0.2\,\%$; cancels when averaging over detectors; measurement of asymmetry pins it down sufficiently;
  - Magnetic field map:
    field expansion ratio $r_{\mathrm{B}} = B_{\mathrm{TOF}}/B_0$;
    $\Delta a/a \sim 10^{-3} \Rightarrow \Delta r_{\mathrm{B}}/r_{\mathrm{B}} = 10^{-3}$, (use calibrated Hall probe);
    field curvature α, (via proton asymmetry measurement);
    field bumps $\Delta B/B$ must be kept below 2×10^{-3} level;
  - Flight path length: $\Delta l \leq 30\,\mu$m $\Rightarrow$ fitting parameter; ($\exists$ consistency check);
  - Homogeneity of the electric field;
  - Rest gas: requires vacuum of 10^{-9} torr or better;
  - Doppler effect;
  - Adiabaticity;

Systematic uncertainties and checks (II)

- Uncertainties due to the detector
  - Detector alignment;
  - Electron energy calibration: requirement 10^{-4}; we'll use radioactive sources, other strategies, also as fitting parameter;
  - Trigger hermiticity: affected by impact angle, backscattering, TOF cutoff (to reduce accid. bgd.);
  - TOF uncertainties;
  - Edge effects;
- Backgrounds
  - Neutron beam related background;
  - Particle trapping;
- Uncertainties in **b**: fewer than for **a** (no proton detection); dominant are energy calibration and electron backgrounds.

Asymmetric spectrometer

Four serious challenges can be relieved in an asymmetric spectrometer:

- Achieving a long flight path for protons and, hence, high t_p (TOF) resolution,
- Achieving a high degree of proton momentum linearization, and, hence, accuracy of the p_p–t_p relationship (narrow detection function),
- Greatly reducing the sensitivity to particle trapping in small field imperfections in the neutron decay region, and
- Reducing the influence of small nonuniformities in electric potential from $\sim \mu$V level to a more controllable $\sim$mV level.

Key strategy:

- Move the high-field pinch away from the neutron decay region,
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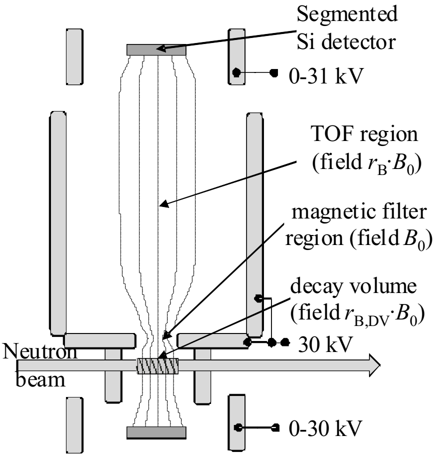
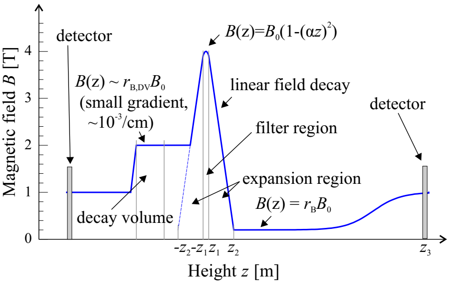
Basic design and features of asymmetric Nab



Stefan Baeßler, March 2009

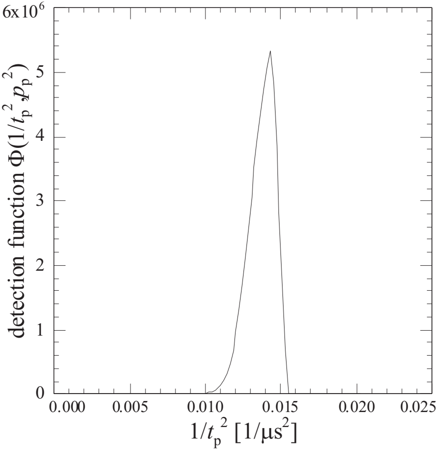
Features:

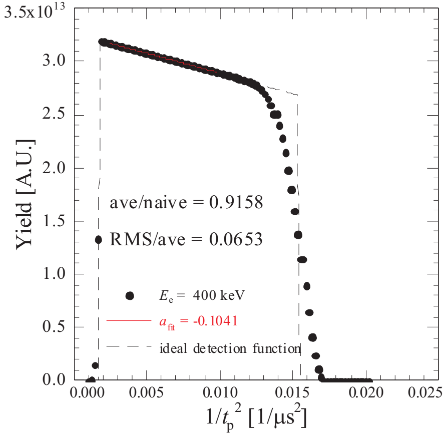
- long TOF above n beam,
- displaced magnetic $\cos\theta$ filter,
- no count rate penalty viz. symmetric Nab.



Asymmetric Nab: expected performance

Simulated detection function and $1/t_p$ distribution:





(using $r_B = 0.05$ and $r_{B,DV} = 0.5$)

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- Basic properties of the symmetric Nab spectrometer are well understood and highly optimized.
- The new asymmetric Nab idea looks very promising; details are under extensive analytical and Monte Carlo study.
- Elements of spectrometer may be shared with other neutron decay experiments, e.g., abBA.
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Current experiments aiming to measure *a*

1. **Nab**: goal is to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Best statistical sensitivity,
   - Challenging but manageable systematics, esp. in asymm. design.
2. **abBA**: goal is to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Similar to Nab, but with a spectrometer optimized for **A**,**B**,
   - Detection function is very broad, syst. uncert. for **a** very demanding.
3. **aCORN**: goal is to measure $\mathbf{\Delta a/a \sim 0.5 - 2\,\%}$
   - Funded, under construction,
   - Uses only part of neutron decays.
4. **aSPECT**: aims to measure $\mathbf{\Delta a/a \sim 10^{-3}}$
   - Funded and running; recently overcame trapping problems,
   - Stat. sensitivity not as good as Nab due to integration; presently $\sim \mathbf{2}\,\%$/day—will likely improve on publ. results, not $< \mathbf{1}\,\%$ this run,
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The Nab collaboration

R. Alarcon[1], L.P. Alonzi[2], S. Baeßler[2*], S. Balascuta[1], J.D. Bowman[3†], M.A. Bychkov[2], J. Byrne[4], J.R. Calarco[5], V. Cianciolo[3], C. Crawford[6], E. Frlež[2], M.T. Gericke[7], F. Glück[8], G.L. Greene[9], R.K. Grzywacz[9], V. Gudkov[10], F.W. Hersman[5], A. Klein[11], J. Martin[12], S.A. Page[6], A. Palladino[2], S.I. Penttilä[3], D. Počanić[2†], K.P. Rykaczewski[3], W.S. Wilburn[11], A.R. Young[13], G.R. Young[3].

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[†]Co-spokesmen

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