EUROPEAN
SPALLATION
SOURCE

Free-Neutron Oscillation Searches at the European Spallation Source

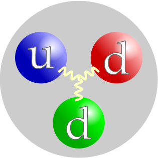
PRESENTED BY UDO FRIMAN-GAYER ON BEHALF OF THE HIBEAM / NNBAR COLLABORATION

14-06-2023

Contents

ESS Aerial View 22.2.2022. Photo courtesy of ESS

Baryogenesis and Dark Matter



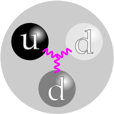
Matter-Antimatter Asymmetry

Evidence

Anomalies in Astrophysics

Baryon-Number Violation

Hypothesis



"Dark Matter"

Neutron-Antineutron Oscillations $n \to \bar{n}$

Possible Observable

Neutron-Dark Matter Oscillations $n \to n'$ (here: "Mirror Matter")

D. Bödeker and W. Buchmüller, "Baryogenesis from the weak scale to the grand unification scale", Rev. Mod. Phys. **93**, 035004 (2021)
G. Bertone and D. Hooper, "History of dark matter", Rev. Mod. Phys. **90**, 045002 (2018)
Z. Berezhiani and L. Bento, "Neutron–Mirror-Neutron Oscillations: How Fast Might They Be?", Phys. Rev. Lett. **96**, 081801 (2006)

Free Neutron Oscillation

$$\hat{\mathcal{H}} = \begin{pmatrix} E_n & \epsilon_{n\bar{n}} & \epsilon_{nn'} \\ \vdots & E_{\bar{n}} & \epsilon_{\bar{n}n'} \\ & \cdots & E_{n'} \end{pmatrix}$$

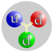
Current lower half-life limits

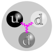
- $\tau_{n\to\bar{n}} > 8.6 \times 10^7\,\mathrm{s}$ [2]
- $\tau_{n\to n'} > 10^1 - 10^2\,\mathrm{s}$ [3]

- Mixing of neutron (n), antineutron ($\bar{n}$), and mirror neutron (n') states[4]

[2] M. Baldo-Ceolin *et al.*, "A new experimental limit of neutron-antineutron oscillations", Z. Phys. C **63**, 409-416 (1994)
[3] Z. Berezhiani *et al.*, "New experimental limits on neutron - mirror neutron oscillations in the presence of mirror magnetic field", Eur. Phys. J. C **78**, 717 (2018)
[4] Possible mirror antineutron state omitted for better visibility.
A. Addazi *et al.*, "New high-sensitivity searches for neutrons converting into antineutrons and/or ...", J. Phys. G Nucl. Part. Phys. **48**, 070501 (2021)

Free Neutron Oscillation





$$\hat{\mathcal{H}} = \begin{pmatrix} E_n + \vec{\mu}_N \vec{B} & \epsilon_{n\bar{n}} & \epsilon_{nn'} + \kappa \vec{\mu}_N \vec{B} + \kappa' \vec{\mu}_N \vec{B}' \\ \vdots & E_{\bar{n}} - \vec{\mu}_N \vec{B} & \epsilon_{\bar{n}n'} - \kappa \vec{\mu}_N \vec{B} + \kappa' \vec{\mu}_N \vec{B}' \\ & \cdots & E_{n'} + \vec{\mu}_N \vec{B}' \end{pmatrix}$$

- Mixing of neutron (n), antineutron ($\bar{n}$), and mirror neutron (n') states[4]
- Impact of magnetic fields on energies and transition matrix elements.

[2] M. Baldo-Ceolin *et al.*, "A new experimental limit of neutron-antineutron oscillations", Z. Phys. C **63**, 409-416 (1994)
[3] Z. Berezhiani *et al.*, "New experimental limits on neutron - mirror neutron oscillations in the presence of mirror magnetic field", Eur. Phys. J. C **78**, 717 (2018)
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Figure of Merit (FOM)

$$P_{n\bar{n}}(t) = \underbrace{\frac{\epsilon_{n\bar{n}}^2}{(\Delta E/2)^2 + \epsilon_{n\bar{n}}^2} \sin\left[\frac{t}{\hbar}\sqrt{(\Delta E/2)^2 + \epsilon_{n\bar{n}}^2}\right]^2}_{\text{Neutron-Antineutron Oscillation}} \underbrace{\exp\left(-\frac{t}{\tau_\beta}\right)}_{\text{Beta Decay}}$$

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- $n \to \bar{n}$: $\Delta E = 2\mu_n B$

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- $n \to \bar{n}$: $\Delta E = 2\mu_n B$
- Time of flight $t_{\mathrm{TOF}} \approx 0.1\,\mathrm{s} \ll \tau_\beta = 879\,\mathrm{s}$

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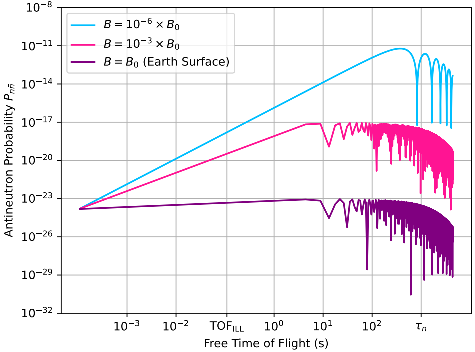

- $n \to \bar{n}$: $\Delta E = 2\mu_n B$
- Time of flight $t_{\mathrm{TOF}} \approx 0.1\,\mathrm{s} \ll \tau_\beta = 879\,\mathrm{s}$
- Order-of-magntiude estimates:

$$\mu_n B \approx 5 \times 10^{-10}\,\mathrm{eV} \quad [5]$$

$$\epsilon_{n\bar{n}} < 8 \times 10^{-24}\,\mathrm{eV} \quad [5]$$

$$\mathrm{TOF}/\hbar \approx 2 \times 10^{14}\,\mathrm{eV}^{-1} \quad [6]$$

[5] A. Addazi *et al.*, “New high-sensitivity searches for neutrons converting into antineutrons and/or ...”, J. Phys. G Nucl. Part. Phys. **48**, 070501 (2021)

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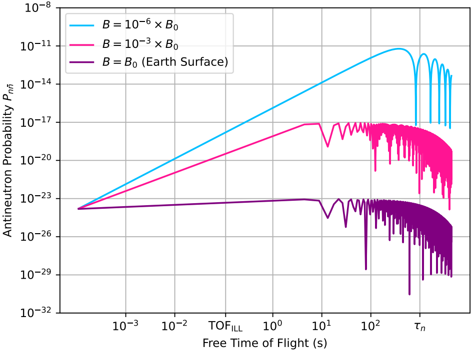

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- Magnetic shielding: $t_{\mathrm{TOF}}\mu_n B/\hbar \ll 1$

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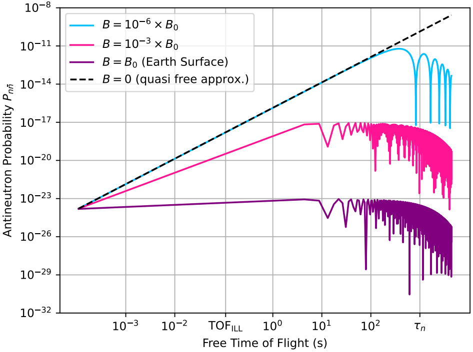
Figure of Merit (FOM)

$$P_{n\bar{n}}(t) \approx \frac{\epsilon_{n\bar{n}}^2 t^2}{\hbar^2}$$

"Quasi-free approximation"



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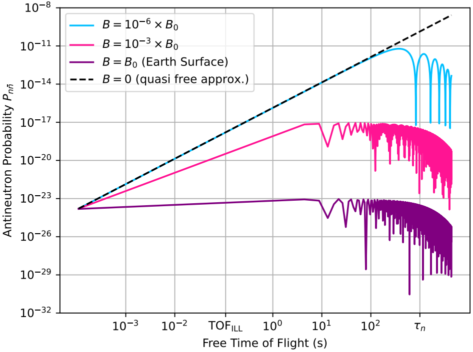

$$\text{FOM} = \text{Number of Neutrons}(N) \times \text{Conversion Probability} = Nt^2$$

- $n \to \bar{n}$: $\Delta E = 2\mu_n B$
- Time of flight $t_{\mathrm{TOF}} \approx 0.1\,\mathrm{s} \ll \tau_\beta = 879\,\mathrm{s}$
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[6] M. Baldo-Ceolin *et al.*, "A new experimental limit of neutron-antineutron oscillations", Z. Phys. C **63**, 409-416 (1994)

European Spallation Source (ESS)

- Neutron Source, User Facility, 15+ Instruments
- European Research Infrastructure Consortium
- First Science in 2027
- Located in Lund, Skåne

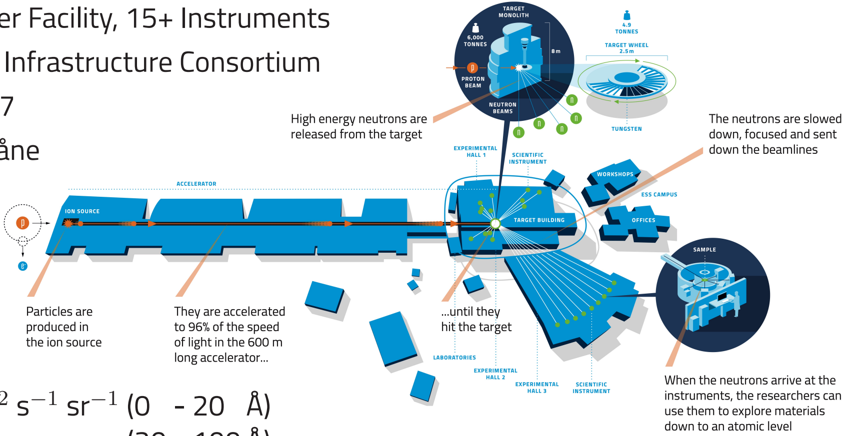


Figure courtesy of ESS

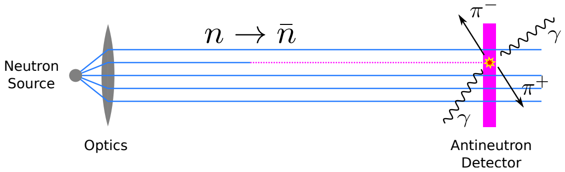
- Brightness[7]:
  $\approx 5.5 \times 10^{13}$ n cm^{-2} s^{-1} sr^{-1} (0 - 20 Å)
  $\approx 2.5 \times 10^{13}$ (20 - 100 Å)

`https://ess.eu`

L. Zanini *et al.*, "Design of the cold and thermal neutron moderators for the European Spallation Source" , NIM A **925**, 33-52 (2019)

[7] Design value, time averaged, wavelength integrated

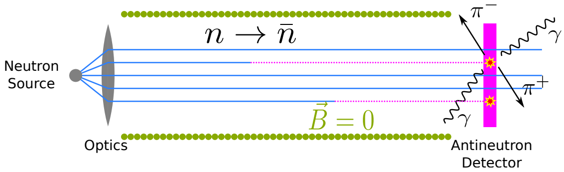
General Concept



Direct $n \to \bar{n}$ search

- Particle detector for reconstruction of $n\bar{n}$ event in thin annihilation target.

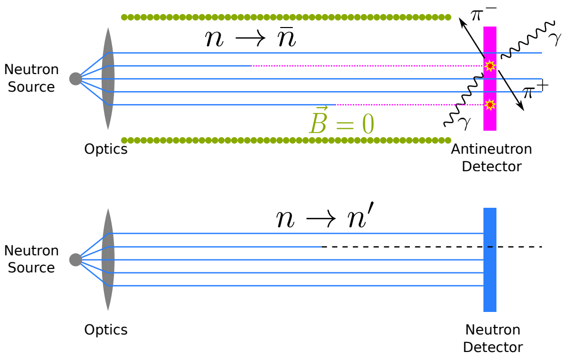
General Concept



Direct $n \to \bar{n}$ search

- Particle detector for reconstruction of $n\bar{n}$ event in thin annihilation target.
- Magnetic-field cancellation

General Concept



Direct $n \to \bar{n}$ search

- Particle detector for reconstruction of $n\bar{n}$ event in thin annihilation target.
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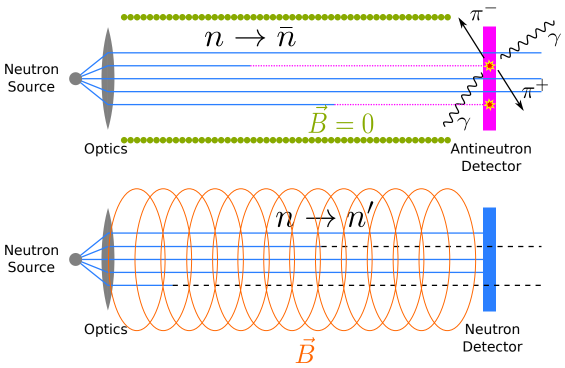
Direct dark-matter search via "Disappearance"

- Count-rate reduction in neutron detector.

General Concept



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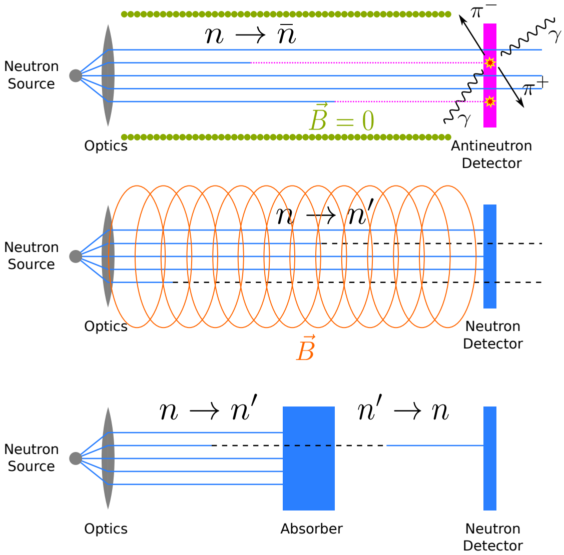

Direct $n \to \bar{n}$ search

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Direct dark-matter search via "Disappearance"

- Count-rate reduction in neutron detector.
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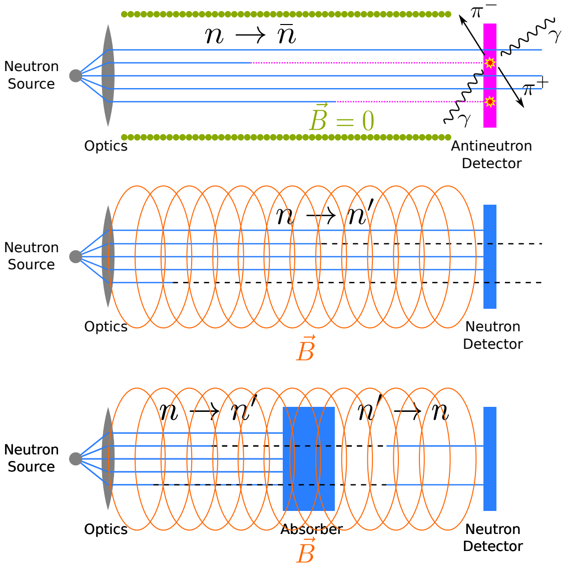
Dark-matter search via "Regeneration"

- Count-rate increase in neutron detector.

General Concept



Direct $n \to \bar{n}$ search

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Dark-matter search via "Regeneration"

- Count-rate increase in neutron detector.
- Magnetic-field control.

Program Overview

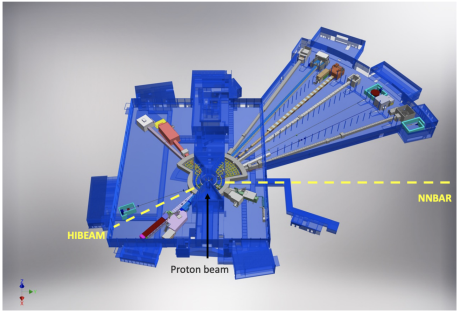
HIBEAM[8]

Versatile $n \to n'$ / $n \to \bar{n}$ search

- Beamline E6
- $\approx 60\,\mathrm{m}$ flight path
- "Butterfly" moderator (thermal + cold)

Goals:

- Pioneer $n \to n'$
- Competitive $n \to \bar{n}$



NNBAR

High-sensitivity $n \to \bar{n}$ search

- Custom beamline
- $\approx 200\,\mathrm{m}$ flight path
- (Mainly) Lower moderator (cold + very cold)

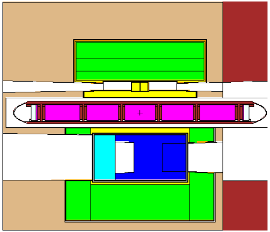
Goal:

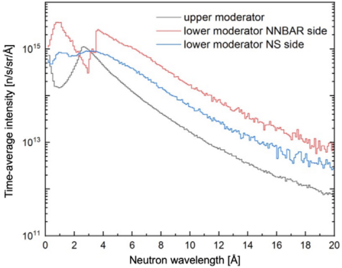
- Increase $n \to \bar{n}$ sensitivity by 10^3

[8] High-Intensity Baryon Extraction and Measurement

A. Addazi *et al.*, "New high-sensitivity searches for neutrons converting into antineutrons and/or ...", J. Phys. G Nucl. Part. Phys. **48**, 070501 (2021)

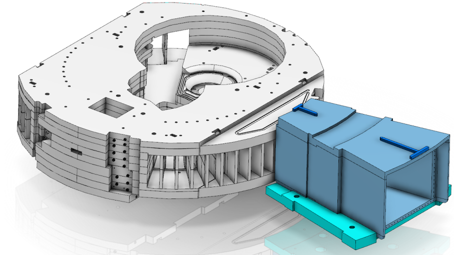
Developments for NNBAR





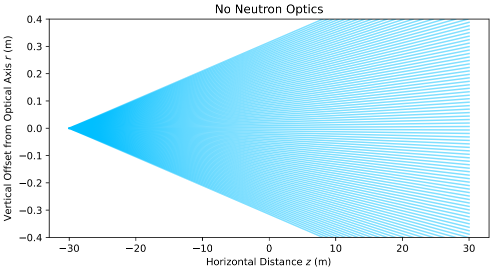
Upgrades for NNBAR experiment at ESS

- Large beam port
- Very cold neutron source at lower moderator position (HighNESS project)



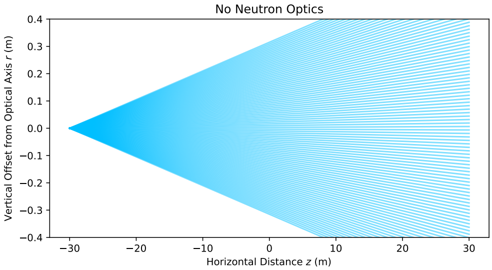
V. Santoro *et al.*, "Development of high intensity neutron source at the European Spallation Source", J. Neutr. Res. **22**, 209 (2020)
L. Zanini *et al.*, "Very cold and ultra cold neutron sources for ESS" , J. Neutr. Res. **24**, 77-93 (2022)

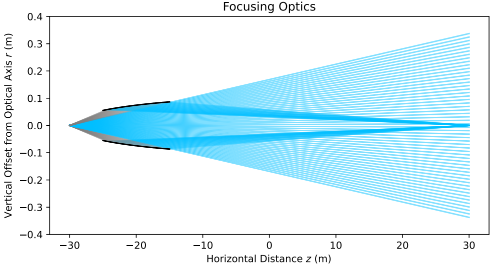
Neutron Optics - General



- **Goal**: Compact target/detection setup

Neutron Optics - General





- **Goal**: Compact target/detection setup
- **General Solution**: Supermirror-based focusing optics

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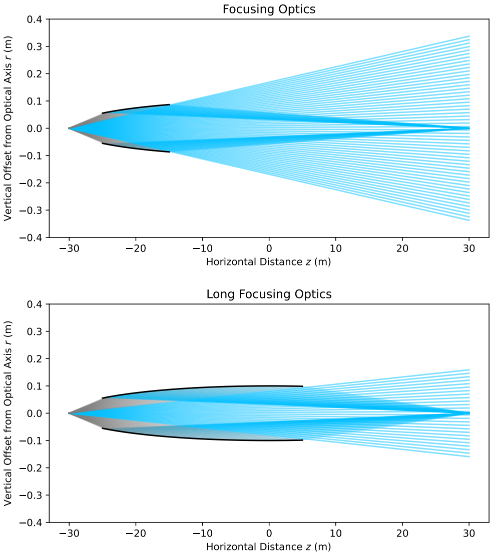
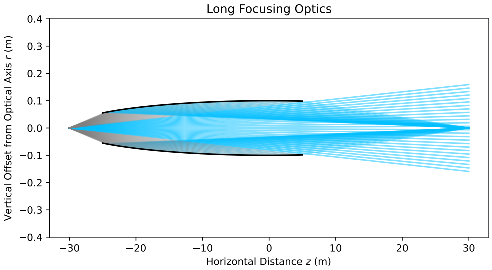
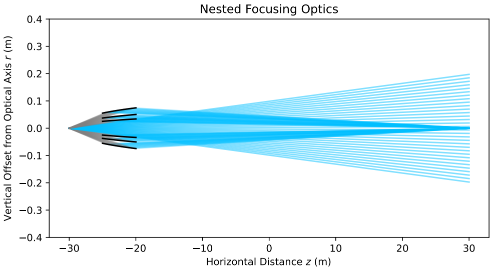


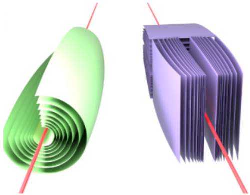
- **Goal**: Compact target/detection setup
- **General Solution**: Supermirror-based focusing optics
- **Problem**: Conventional elliptic mirrors limit free-flight time

Neutron Optics - General



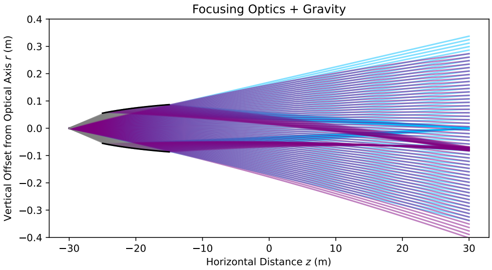


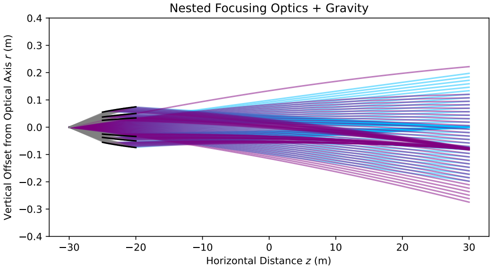
- **Goal**: Compact target/detection setup
- **General Solution**: Supermirror-based focusing optics
- **Problem**: Conventional elliptic mirrors limit free-flight time
- **Special Solution**: Nested elliptic mirrors



C. Herb, "Nested mirror optics for neutron extraction, transport, and focusing", NIM A **1040**, 167154 (2022)
O. Zimmer, "Imaging nested-mirror assemblies — A new generation of neutron delivery systems?", J. Neutr. Res. **20**, 91-98 (2018)

Neutron Optics - General

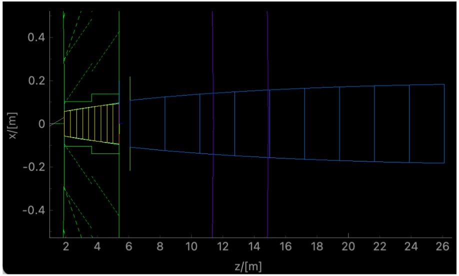




- **Goal**: Compact target/detection setup
- **General Solution**: Supermirror-based focusing optics
- **Problem**: Conventional elliptic mirrors limit free-flight time
- **Special Solution**: Nested elliptic mirrors
- **Limitation**: Gravity

Neutron Optics - HIBEAM / NNBAR

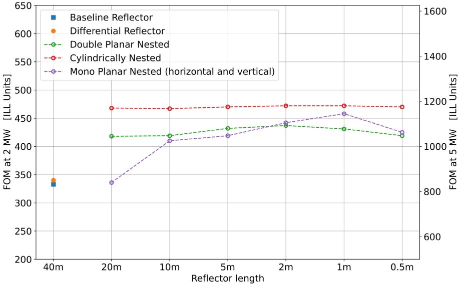
HIBEAM



- $n \to \bar{n}$ @ HIBEAM
- $\approx 25\,\mathrm{m}$ long elliptic mirror
- Competitive with ILL experiment[7]

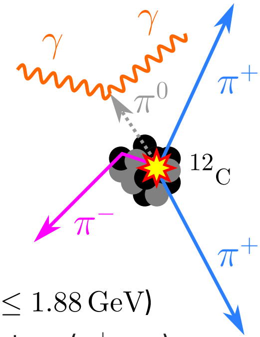
NNBAR

- $\approx 2 \times 2 \times 1\,\mathrm{m}^3$ nested-mirror array
- Factor 10^3 sensitivity increase compared to ILL experiment[9]



[9] M. Baldo-Ceolin *et al.*, "A new experimental limit of neutron-antineutron oscillations", Z. Phys. C **63**, 409-416 (1994)
L. Björk, "Development of a guide system for free neutron oscillation searches at the European Spallation Source", M.Sc. Thesis, Lund University (2023)
R. Wagner *et al.*, "Design of an optimized nested-mirror neutron reflector for a NNBAR experiment", NIM A **1051**, 168235 (2023)

Antineutron Detector

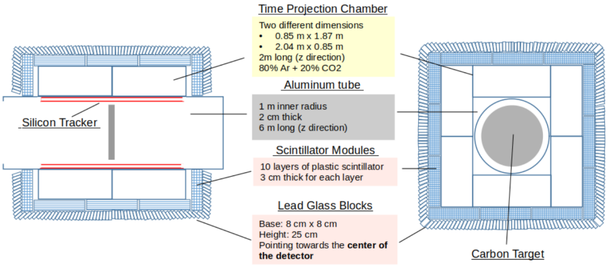


Detector Components

- Thin carbon target
- Time projection chamber
- Scintillator
- Lead-glass calorimeter

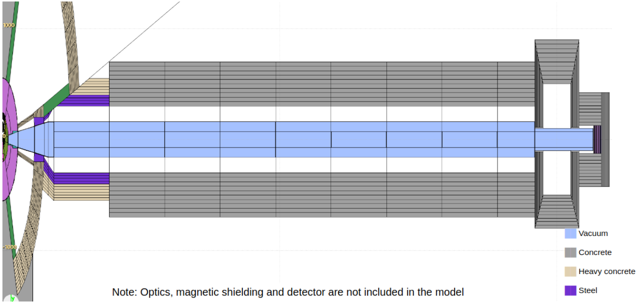
Final state ($E \leq 1.88\,\mathrm{GeV}$)

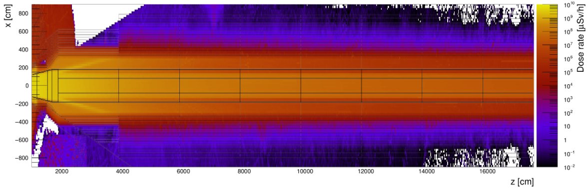
- Charged pions (π^+, π^-)
- Photons from neutral-pion decays ($\pi^0 \to \gamma\gamma$)
- *Nucleons (p, n)*



S.-C. Yiu *et al.*, "Status of the Design of an Annihilation Detector to Observe Neutron-Antineutron Conversions at the European Spallation Source", Symmetry **14**, 76 (2022)

Radiation Shielding





Shielding optimization for 200-m long NNBAR experiment.

- **Goal**: Dose rate $\leq 1.5\,\mu\mathrm{Svh}^{-1}$ in exterior
- Advanced variance-reduction techniques in Monte Carlo simulations[10]

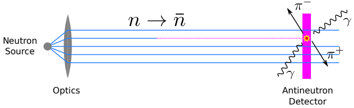
Also:

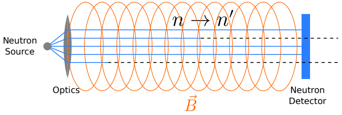
- Simulation of background at detector site
- Cosmic-ray veto

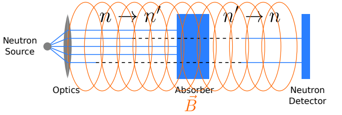
[10] D. D. DiJulio *et al.*, "Simulating neutron transport in long beamlines at a spallation neutron source using Geant4", J. Neutr. Res. **22**, 183-189 (2020)

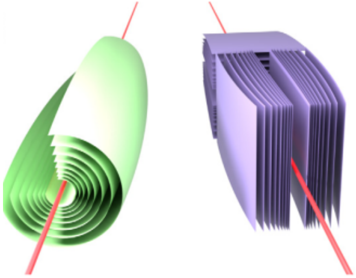
Summary

- HIBEAM / NNBAR program to study neutron oscillations
- Increase $n \to \bar{n}$ sensitivity
- Pioneer $n \to n'$ searches









Developments in

- Cold-neutron moderators (HighNESS project)
- Neutron optics and magnetic-field control
- Antineutron detection and cosmic-ray veto
- Radiation Shielding

Appendix

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