From Antineutron Scattering to Neutron–Antineutron Oscillation Searches

Hiroyuki Fujioka (Institute of Science Tokyo)

Institute of
SCIENCE TOKYO

Antineutrons

- Discovered at the Bevatron [Phys. Rev. 104, 1193 (1956)] soon after the discovery of antiprotons in 1955

  Antineutron production via the charge-exchange reaction

  $\bar{p} + p \rightarrow \bar{n} + n$

  Antineutron detection via annihilation

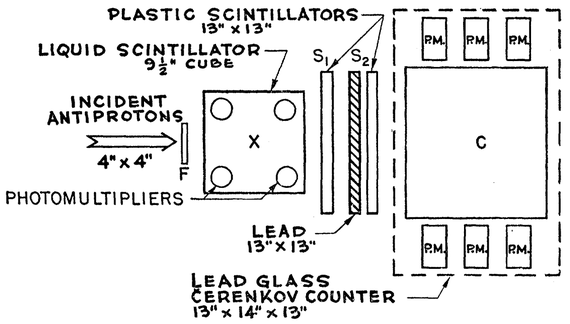
  $\bar{n} + N \rightarrow$ multiple π's (energy release of 1.9GeV)

Antineutrons Produced from Antiprotons in Charge-Exchange Collisions*

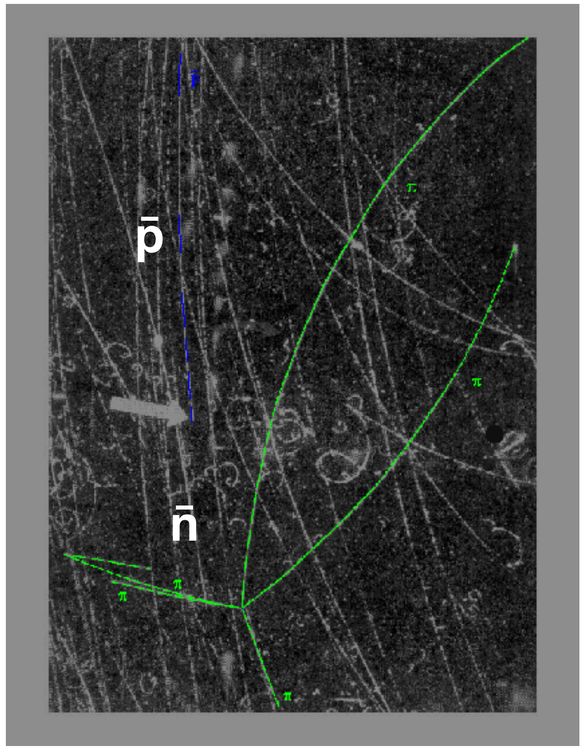
BRUCE CORK, GLEN R. LAMBERTSON, ORESTE PICCIONI,† AND WILLIAM A. WENZEL

Radiation Laboratory, University of California, Berkeley, California

(Received October 3, 1956)



(bubble chamber)



https://hst-archive.web.cern.ch/archiv/HST2002/Bubblech/an.html

(hadron physics)

antineutron scattering off protons and nuclei

- Low-energy strong interaction between antineutrons and protons/nuclei
- No Coulomb interaction, unlike in antiproton scattering
- s-wave scattering lengths can be extracted from cross sections

(particle physics)

neutron–antineutron oscillation search

- BSM physics: baryon-number non-conserving ($|\Delta B| = 2$) process
- Searches with free neutrons (ILL reactor etc.) and bound neutrons (Super-K etc.)
- signal: antineutron annihilation in a material or nucleus

antineutron–nucleus scattering length $a_{\bar{n}A}$

(hadron physics)

antineutron scattering off protons and nuclei

- Low-energy strong interaction between antineutrons and protons/nuclei
- No Coulomb interaction, unlike in antiproton scattering
- s-wave scattering lengths can be extracted from cross sections

(particle physics)

neutron–antineutron oscillation search

- BSM physics: baryon-number non-conserving ($|\Delta B| = 2$) process
- Searches with free neutrons (ILL reactor etc.) and bound neutrons (Super-K etc.)
- signal: antineutron annihilation in a material or nucleus

antineutron–nucleus scattering length $a_{\bar{n}A}$

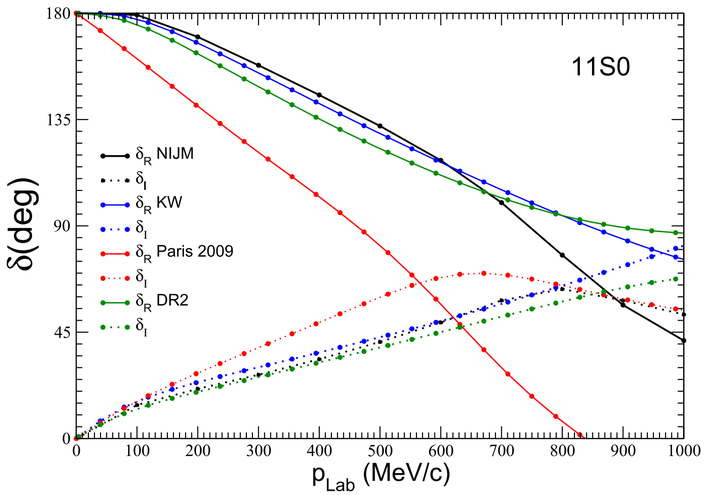
NN interaction and N$\bar{N}$ interaction

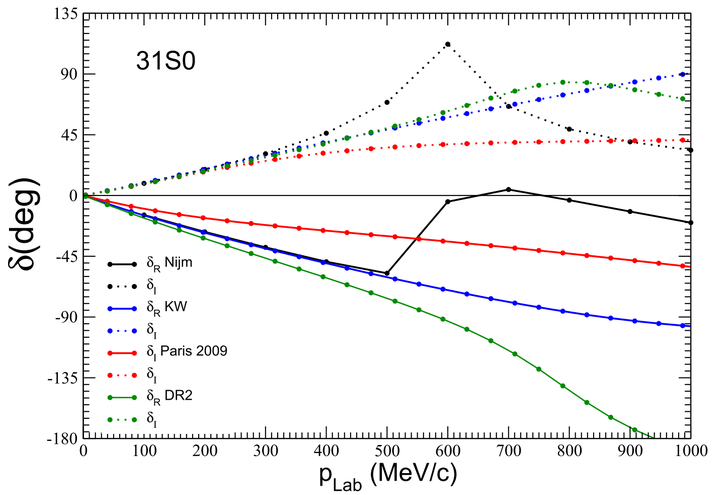
- One-boson-exchange models
  - $V_{NN} = V_\pi + V_{2\pi} + V_\eta + V_\rho + V_\omega + \cdots$

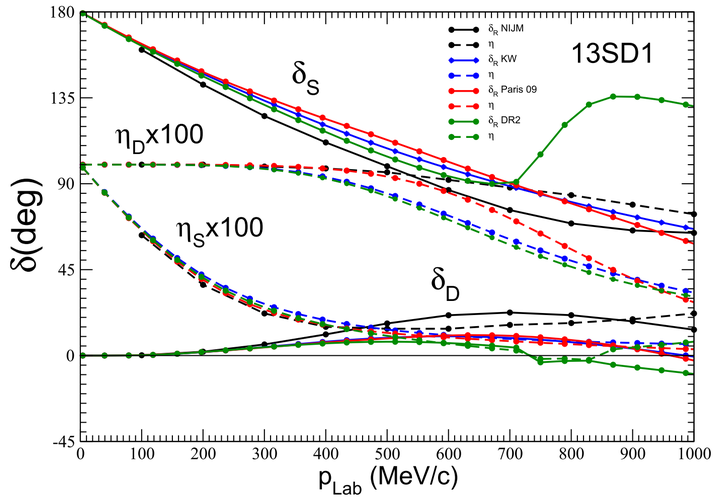
    ↓ G-parity transformation

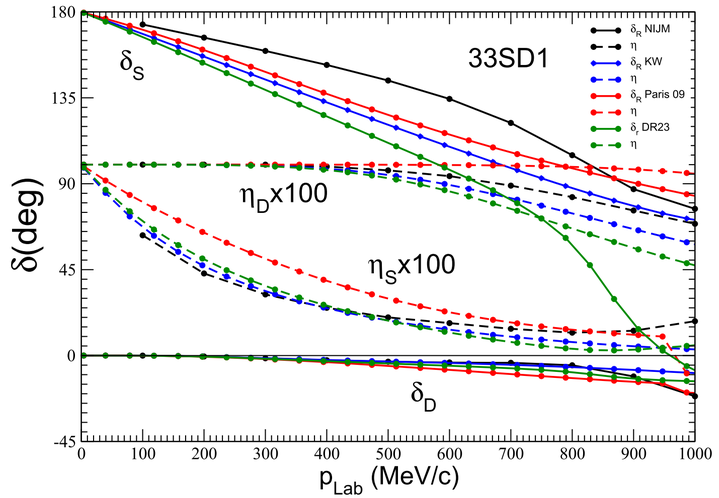
    $V_{N\bar{N}} = -V_\pi + V_{2\pi} + V_\eta + V_\rho - V_\omega + \cdots$
  - The short-range part is replaced by an annihilation potential $V_0 + iW_0$
    - NN Paris potential → N$\bar{N}$ Paris potential
    - Dover-Richard, Kohno-Weise, …
- Partial Wave Analysis [PRC 86 (2012) 044003]
- Chiral Effective Field Theory [up to N^{3}LO, JHEP 07(2017) 078]
- no Lattice QCD calculation
- All these approaches rely on experimental data, that are more than three decades old.

NN̄ optical potential and phase shift









J. Carbonell et al., EPJ A 59 (2023) 259

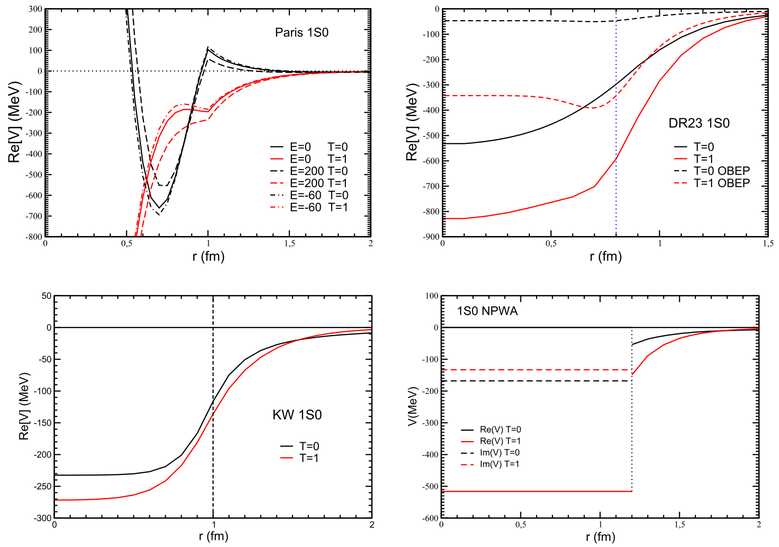


Fig. 15 Real parts of $^1S_0$ potentials for both isospins (T)

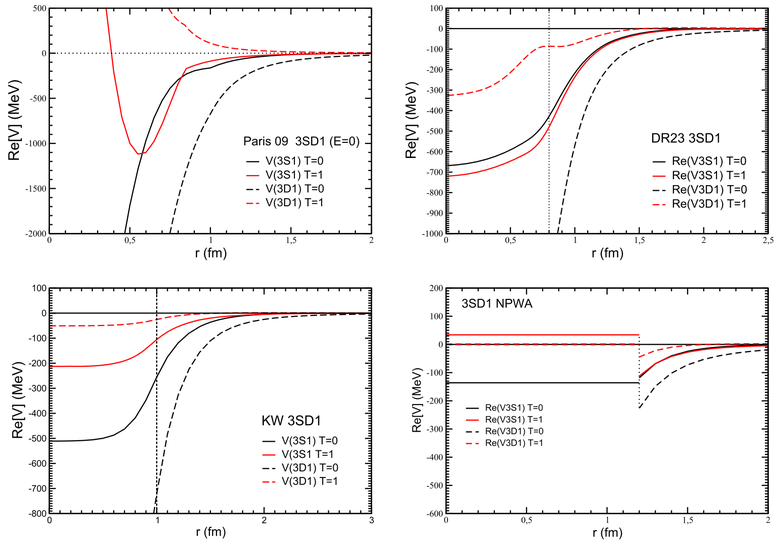


Fig. 16 Real parts of $^3S_1$ and $^3D_1$ potentials for both isospins (T)

Low-energy $\bar{p}p$ scattering (annihilation)

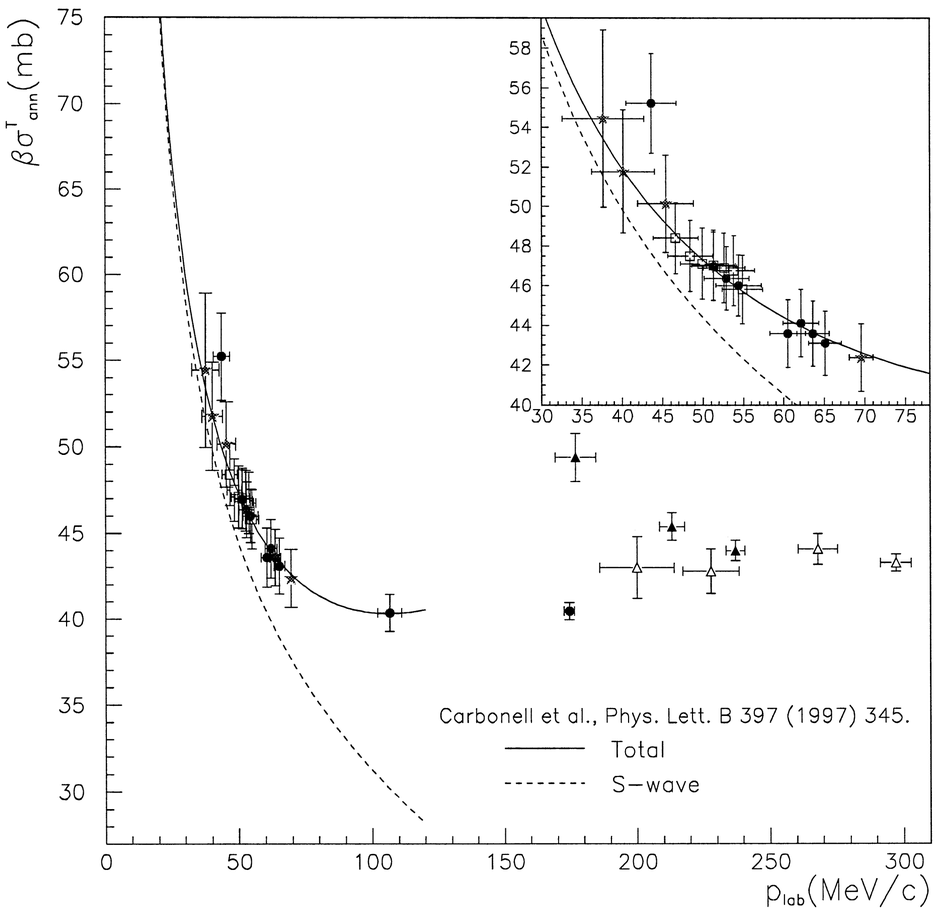
- Due to the attractive Coulomb interaction
  - $\sigma \propto v^{-2}$ instead of $\sigma \propto v^{-1}$
  - p-wave doesn't vanish even when E→0
  - Coulomb-corrected scattering length a_{sc} can be deduced as follows:

$$q^2\sigma_{\text{ann}}^{\text{sc}}(\text{S-wave}) = \frac{8\pi^2}{1-e^{2\pi\eta}}\,\frac{\text{Im}\,(-a_{\text{sc}}/B)}{|1+iqw(\eta)a_{\text{sc}}|^2}, \quad (1)$$

where:
- $\eta = -1/qB$ is the dimensionless Coulomb parameter with B the $\bar{p}p$ Bohr radius;
- $w(x) = c_0^2(x) - 2ixh(x)$ is an auxiliary function with $qBw(\eta) \to 2\pi$ when $q \to 0$;
- c_0^2 and h are the usual functions in the Coulomb scattering theory

$$c_0^2(x) = \frac{2\pi x}{\exp(2\pi x)-1};$$

$$h(x) = \tfrac{1}{2}\left[\Psi(-ix)+\Psi(ix)\right] - \tfrac{1}{2}\ln\left(x^2\right)$$



J. Carbonell et al., PLB 397 (1997) 345
A. Zenoni et al., PLB 461 (1999) 405

Low-energy $\bar{n}p$ scattering

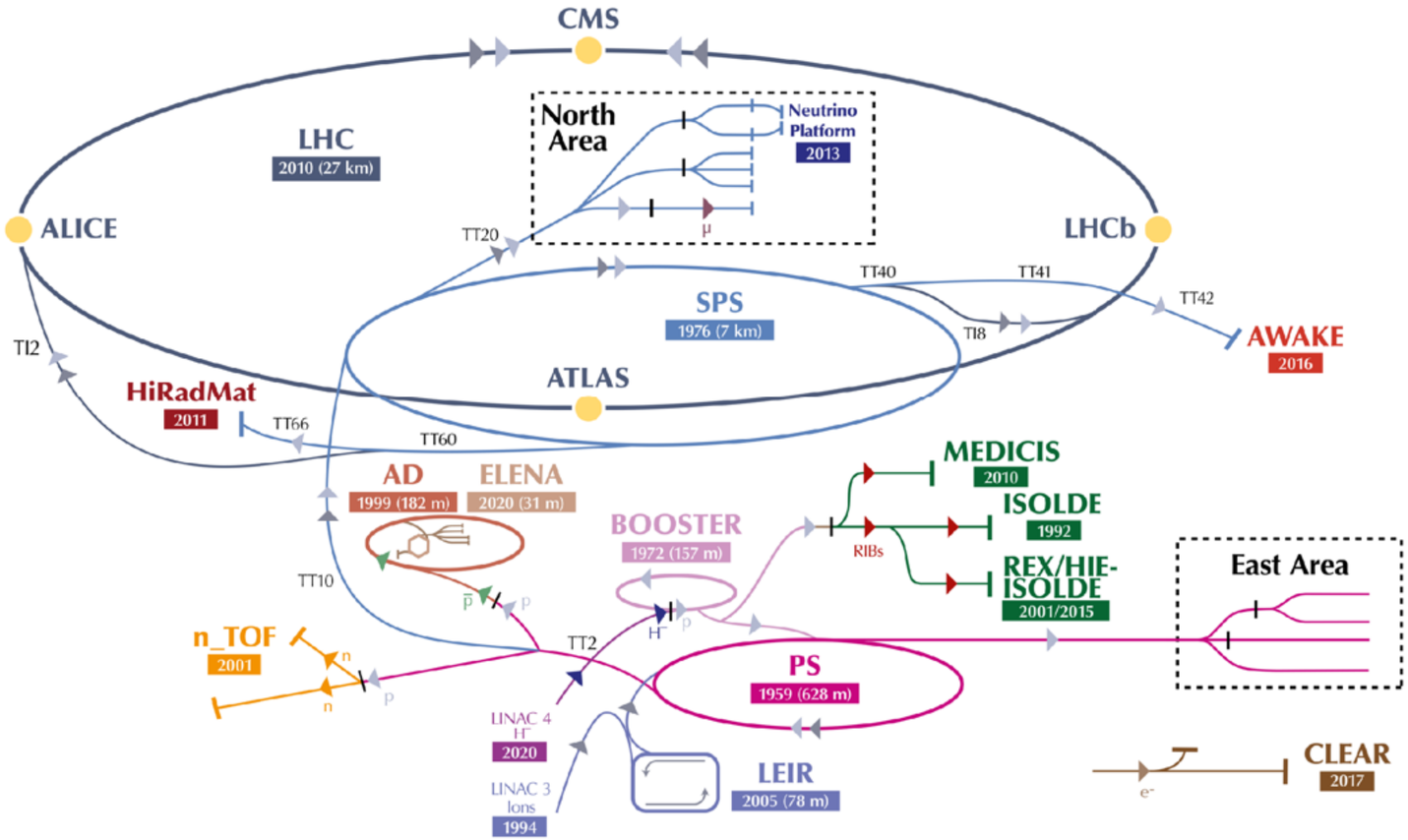
- s-wave scattering dominates for $\hbar k = p_{\mathrm{Lab}}/2 \lesssim 25\,\mathrm{MeV}/c$
- scattering amplitude: $f_{\ell=0} = 1/(k\cot\delta - ik)$
  - $k\cot\delta \approx -1/a \equiv \alpha = \alpha_{\mathrm{R}} - i\alpha_{\mathrm{I}}\ (\alpha_{\mathrm{I}} > 0)$ in the low-energy limit
  - scattering length: $a = a_{\mathrm{R}} - ia_{\mathrm{I}}\ (a_{\mathrm{I}} > 0)$

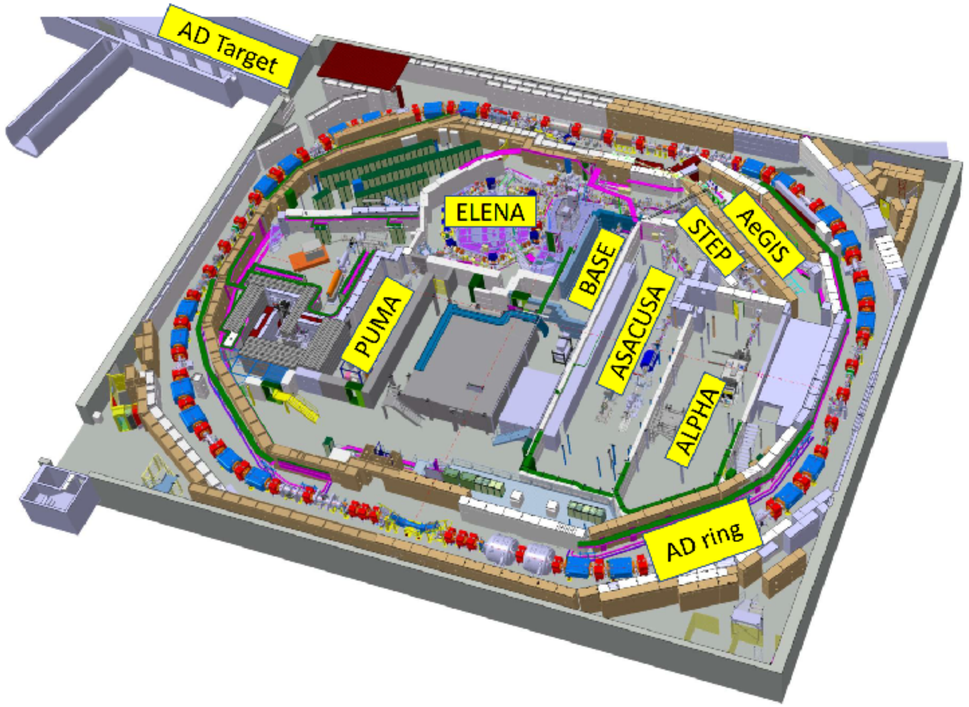
- elastic scattering cross section: $\sigma_{\mathrm{el}} = \dfrac{4\pi}{\alpha_R^2 + (\alpha_I + k)^2} \approx 4\pi|a|^2(1 - 2a_{\mathrm{I}}k)$
- annihilation cross section: $\sigma_{\mathrm{ann}} = \dfrac{4\pi}{k}\dfrac{\alpha_{\mathrm{I}}}{\alpha_R^2 + (\alpha_I + k)^2} \approx \underline{\dfrac{4\pi}{k}a_{\mathrm{I}}} - 8\pi a_{\mathrm{I}}^2$

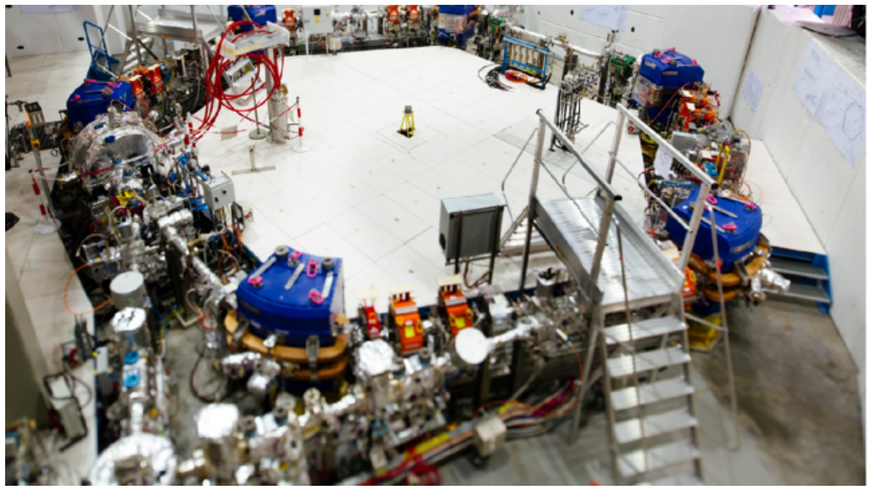
proportional to $1/v$

CERN AD (Antiproton Decelerator)

Institute of SCIENCE TOKYO





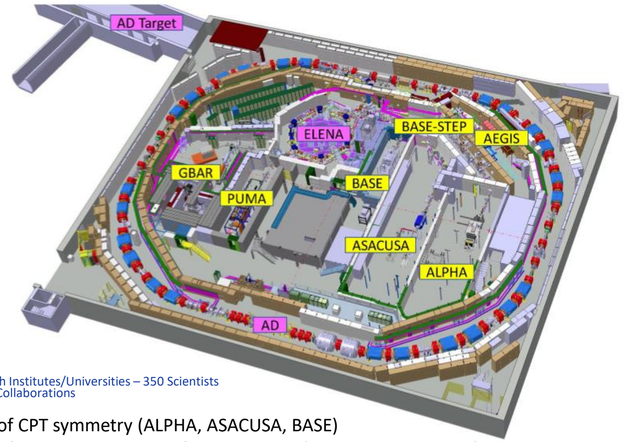


AD (Antiproton Decelerator) Facility

Institute of SCIENCE TOKYO

The AD/ELENA-Facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.



60 Research Institutes/Universities – 350 Scientists
– 6 Active Collaborations

- Tests of CPT symmetry (ALPHA, ASACUSA, BASE)
- Tests of ballistic properties of antihydrogen (ALPHA, GBAR, AEGIS)
- Searches for asymmetric dark matter / antimatter coupling (BASE, ASACUSA)
- Nuclear Physics Projects (PUMA)

antihydrogen

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

antiprotons

ASACUSA
Antiprotonic helium spectroscopy

BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

PUMA
Antiproton/nuclei scattering to study neutron skins

M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

Future Perspectives – RUN-4 Activities

- *CERN AD/ELENA Antimatter Program* input at the European Strategy for Particle Physics 2026 – link
- *Minutes of the 157th Meeting of the SPSC* - cds
  - Letter of Intent to the SPSC for the continuation of the AD-7/GBAR experiment at the AD-ELENA facility after LS3 – cds
  - **ASACUSA** Proposal for Run4 and Beyond – cds
  - Experiments on a Lower-Energy and Slow Extraction Antiproton Beam - cds
  - Letter of Intent to the CERN SPSC Physics with Antihydrogen Beyond LS3 – cds
  - Technology for Antiproton Cancer Therapy, TACT – cds
  - **BASE** - Future Physics Program: From 2025 to 2034 and Beyond – cds
  - Precision Measurement of the Cross-Sections for Inelastic Interactions of Antiprotons and Antideuterons with Nuclei for Cosmic-Ray Research – cds
  - Long-term outlook for the **AEgIS** experimental program – cds
  - **HYPER**: a single-Lambda hypernuclei factory at the Antimatter-Factory – cds
  - **PUMA**: antiProton Unstable Matter Annihilation – cds
  - Molecular Antimatter Confinement Experiment (MACE): Proposal to investigate synthesis of pbar@C60 antimatter endohedral fullerenes by ion implantation at ELENA-TELMAX – cds
  - Low-Energy Antineutron Beamline at the Antiproton Decelerator for Scattering Experiments – cds

Stefan Ulmer (AD Chair), Academic Training Lecture
https://indico.cern.ch/event/1729071/

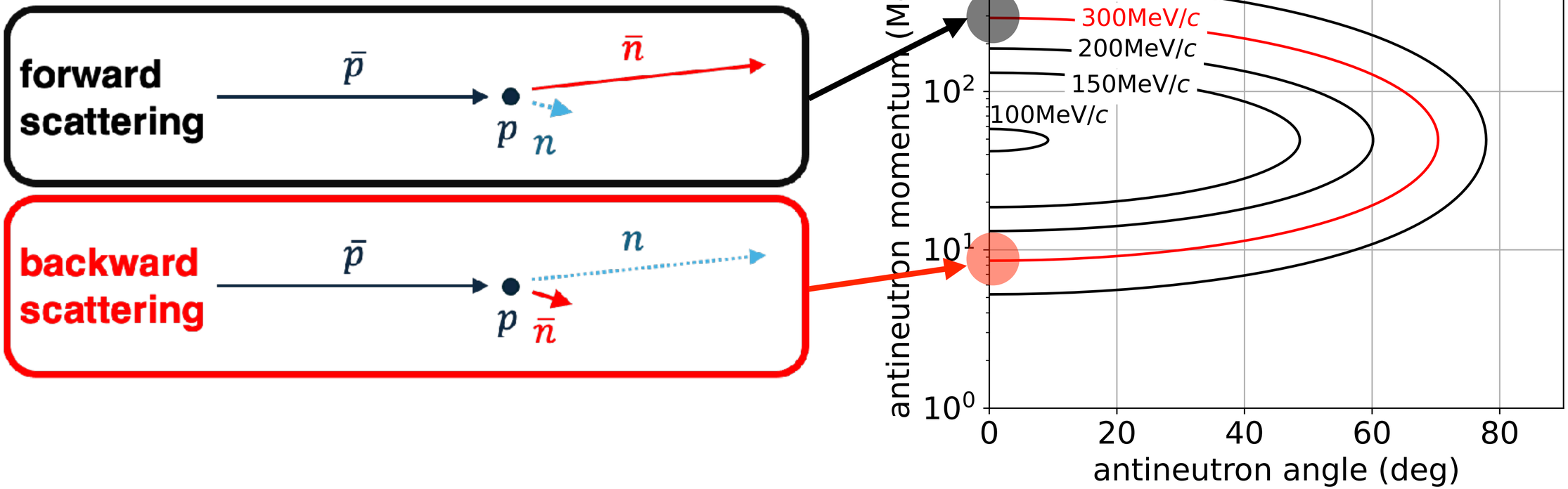
Letter of Intent (https://cds.cern.ch/record/2930906) submitted in May 2025

Novel concept: low-energy antineutron production

Institute of SCIENCE TOKYO

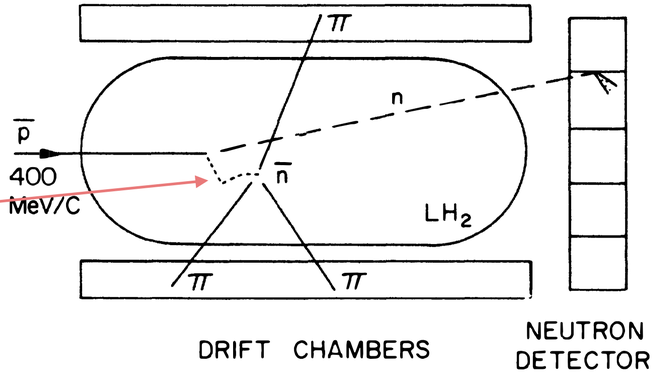
arXiv:2503.06972

- 300 MeV/c antiprotons from CERN-AD (Antiproton Decelerator)
- $p_{\mathrm{lab}} = 9\,\mathrm{MeV}/c$ (40 keV) antineutrons can be produced at backward angles in the CM frame via charge-exchange reaction ($p\bar{p} \rightarrow n\bar{n}$)
- 1.0 antineutrons per AD cycle (~2min.) → scattering experiments feasible

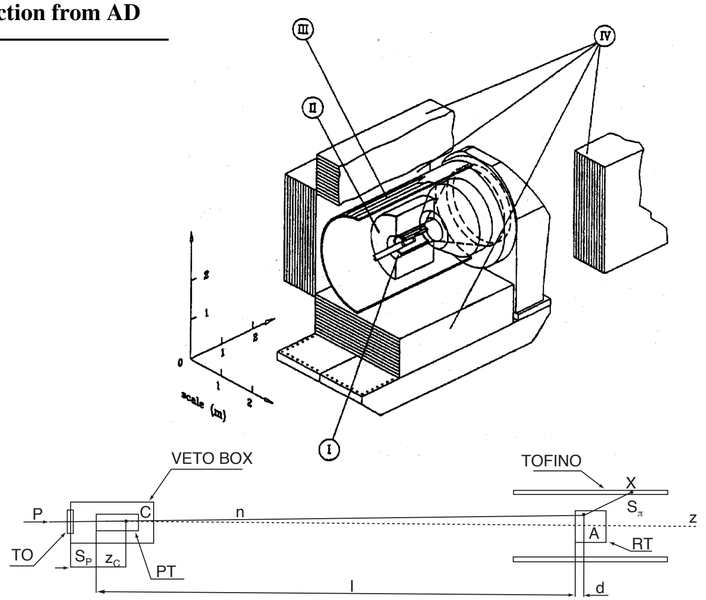


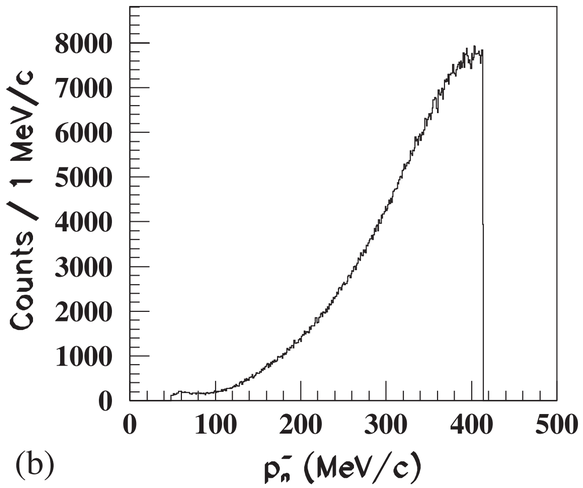
Past antineutron experiments

Experiment	Target	$\bar{p}$ mom. (MeV/c)	$\bar{n}$ mom. (MeV/c)	Remarks
Gunderson *et al.* [37]	CH_2	1000	250–880	
CERN PS178 [38]	LH_2	300	100–270	slow $\bar{p}$ extraction from LEAR tagged $\bar{n}$ beam
BNL E-767 [22]	CH_2	505, 520	100–500	
BNL E-795 [23]	LH_2	415	10–75	tagged $\bar{n}$, not extracted
CERN PS201 [39]	LH_2	305, 412	50–406	slow extraction from LEAR
proposed (option-1)	**LH_2 or CH_2**	**300**	**> 9**	**fast $\bar{p}$ extraction from AD**
proposed (option-2)	**LH_2 or CH_2**	**300**	**> 9**	**slow $\bar{p}$ extraction from AD**



- The OBELIX (PS201) exp. @ LEAR
  - n̄p scattering
  - n̄A scattering
  - n̄p annihilation
  - meson spectroscopy





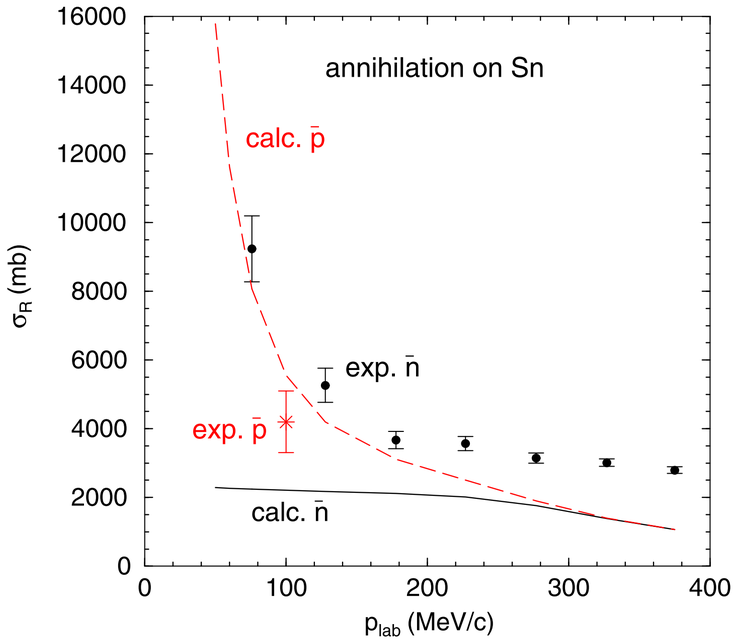
Review: T. Bressani and A. Filippi, Phys. Rep. 383 (2003) 213

- No antineutron beam for three decades. Low-energy (<50MeV/c) data missing!

Antineutron–nucleus annihilation

- $\sigma^{\mathrm{ann}}(\bar{n} - \mathrm{Sn}) > \sigma^{\mathrm{ann}}(\bar{p} - \mathrm{Sn})$

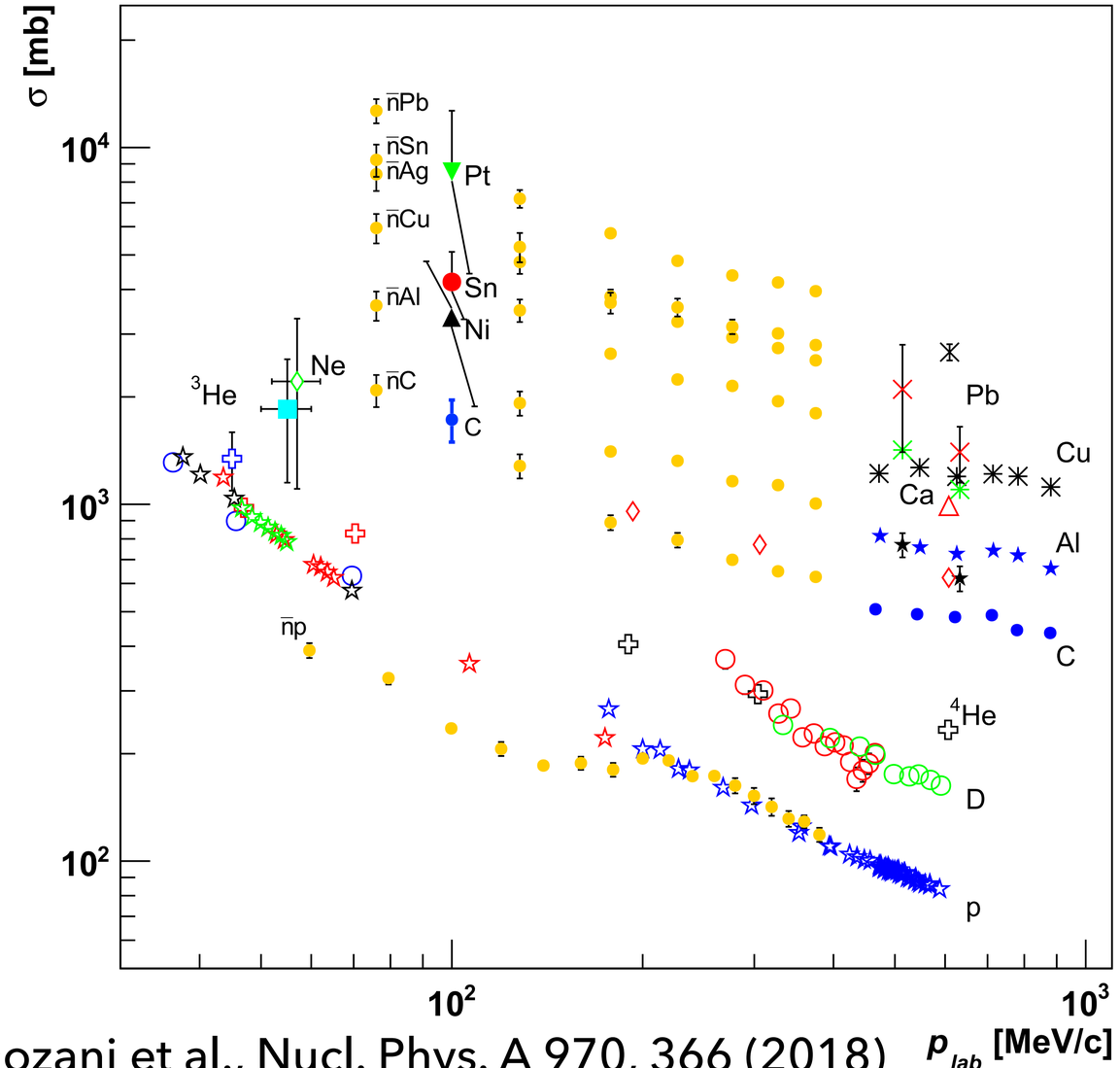
  despite Coulomb enhancement of antiproton annihilation
- What happens at lower energies?



E. Friedman, Nucl. Phys. A 925, 141 (2014)

Our proposal: >9 MeV/c antineutrons

cf. ASACUSA exp.: ~ 13.7 MeV/c antiprotons



H. Aghai-Khozani et al., Nucl. Phys. A 970, 366 (2018)

Antineutron–nucleus scattering length

- antinucleon–nucleus optical potential: $V(r) = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m_N}\right) b_0 \rho(r)$,

  where $\rho(r)$ is the nucleon density distribution
- The b_0 parameter was fitted to strong-interaction shifts and widths measured in antiprotonic atoms.
- The antineutron–nucleus scattering length was calculated using this optical potential:

slightly larger than the nuclear radii almost independent of nuclides

$$a_{\bar{n}A} = (1.54 \pm 0.03)A^{0.311\pm0.005} - (1.00 \pm 0.04)i\,\mathrm{fm}$$ (global fit)

C. J. Batty et al., Nucl. Phys. A 689, 721 (2001)

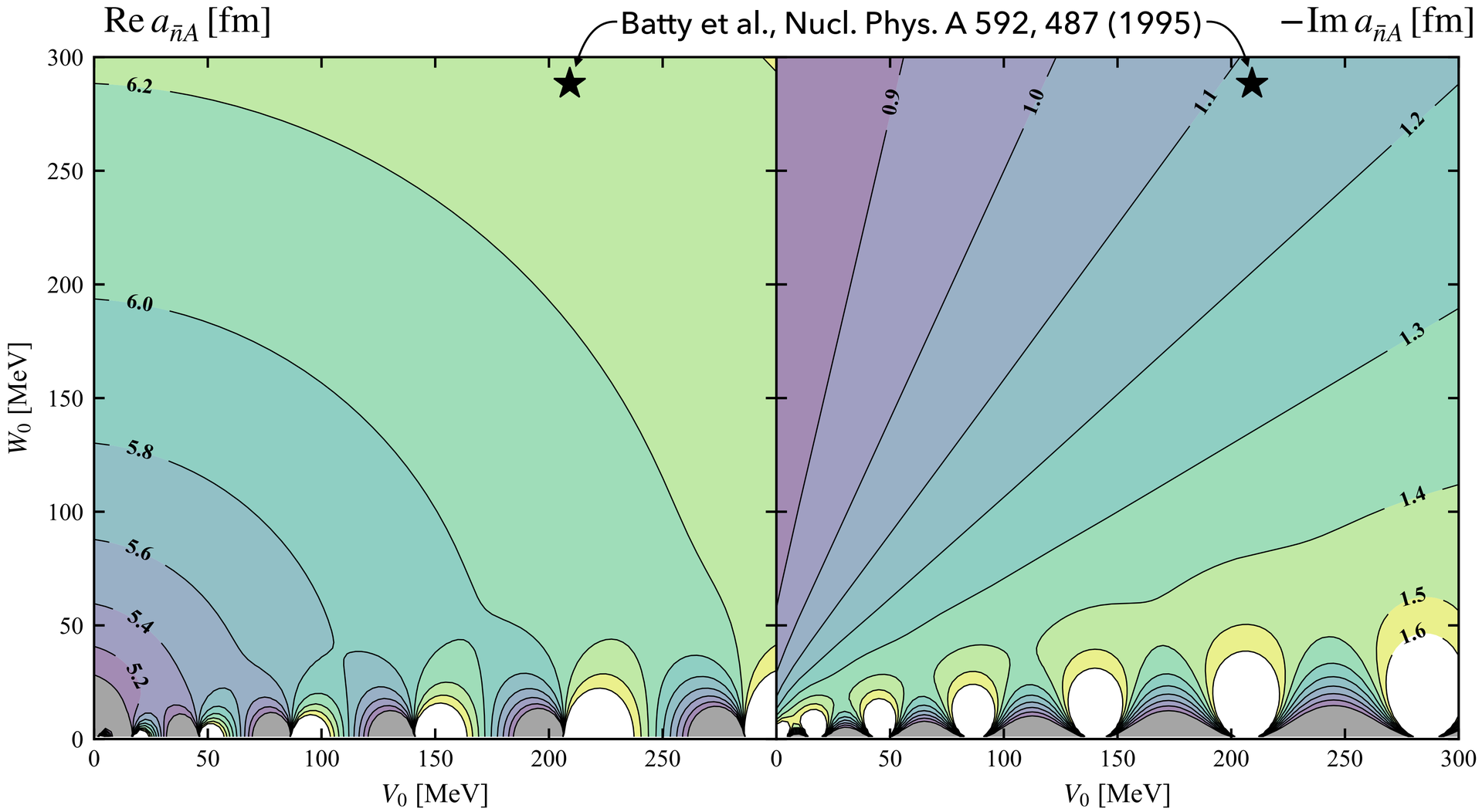
- Direct scattering-length measurements can test and constrain these optical potentials.

Calculated scattering length

Institute of SCIENCE TOKYO

HF, S. Ishii, arXiv:2608.18668

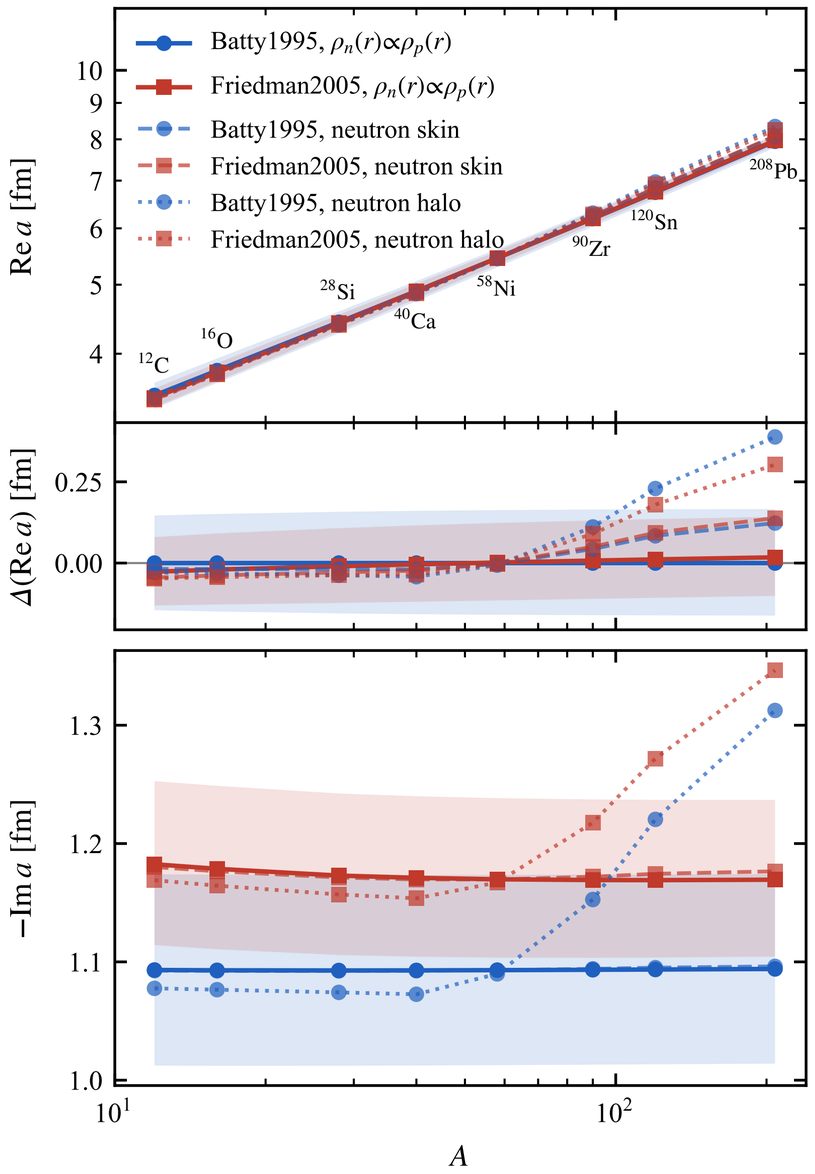
for an optical potential of $V(r) = -\dfrac{V_0 + iW_0}{1 + \exp[(r-c)/z]}$ with $c = 5\,\mathrm{fm}$, $z = 0.5\,\mathrm{fm}$



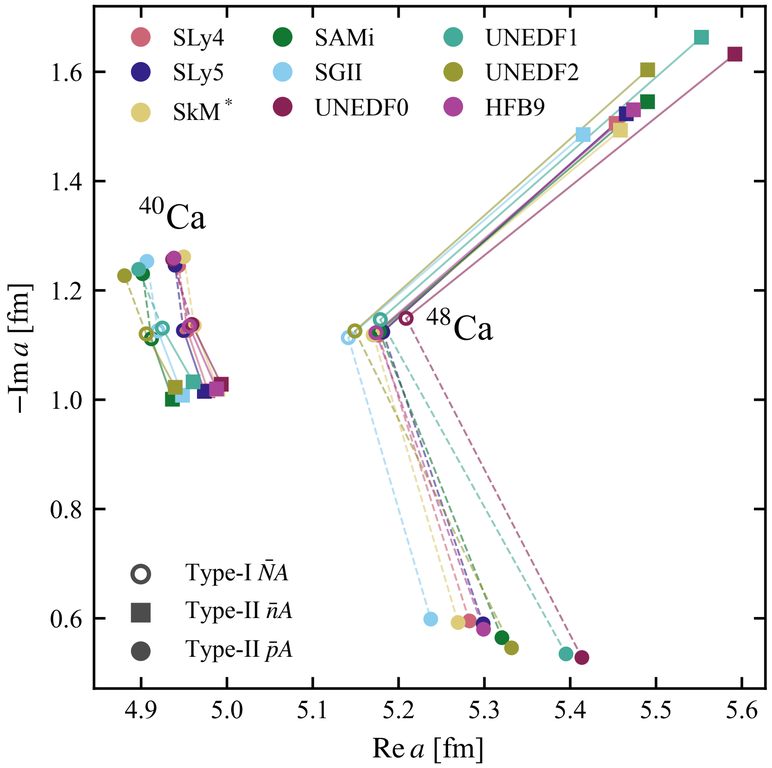
Calculated scattering length

Institute of SCIENCE TOKYO

HF, S. Ishii, arXiv:2608.18668



The calculated scattering length is sensitive to both the optical potential and the assumed nucleon density distributions.



Short summary of antineutron scattering

- **We are proposing antineutron production and antineutron scattering experiments at the CERN AD facility.**
- **Antineutrons at unprecedentedly low energies can be produced via the charge-exchange reaction $p\bar{p} \rightarrow n\bar{n}$ at backward angles in the CM frame.**
- **The s-wave scattering cross section is described as a function of the scattering length.**
- **We will investigate antineutron–proton and antineutron–nucleus interactions from hadron- and nuclear-physics viewpoints.**

Letter of Intent: https://cds.cern.ch/record/2930906
physics cases with antineutrons: A. Filippi, HF, T. Higuchi, L. Venturelli, arXiv:2503.06972

Funded by the European Union

HADRON-2030 receives funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101292522.

Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

(hadron physics)

antineutron scattering off protons and nuclei

- Low-energy strong interaction between antineutrons and protons/nuclei
- No Coulomb interaction, unlike in antiproton scattering
- s-wave scattering lengths can be extracted from cross sections

(particle physics)

neutron–antineutron oscillation search

- BSM physics: baryon-number non-conserving ($|\Delta B| = 2$) process
- Searches with free neutrons (ILL reactor etc.) and bound neutrons (Super-K etc.)
- signal: antineutron annihilation in a material or nucleus

antineutron–nucleus scattering length $a_{\bar{n}A}$

Baryon asymmetry in the universe

Sakharov conditions
1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

- proton decay (e.g. $p \to e^+\pi^0$) $|\Delta B| = |\Delta L| = 1,\ |\Delta(B-L)| = 0$
- neutrinoless double-beta decay $|\Delta L| = |\Delta(B-L)| = 2$
- neutron–antineutron oscillation $|\Delta B| = |\Delta(B-L)| = 2$

note : electroweak sphalerons violate $B+L$ but conserve $B-L$.

$$\mathcal{H} = \begin{pmatrix} E-\Delta E & \delta m \\ \delta m & E+\Delta E \end{pmatrix}$$

n → n?

energy splitting $\Delta E = |\mu_n| B$
due to a magnetic field

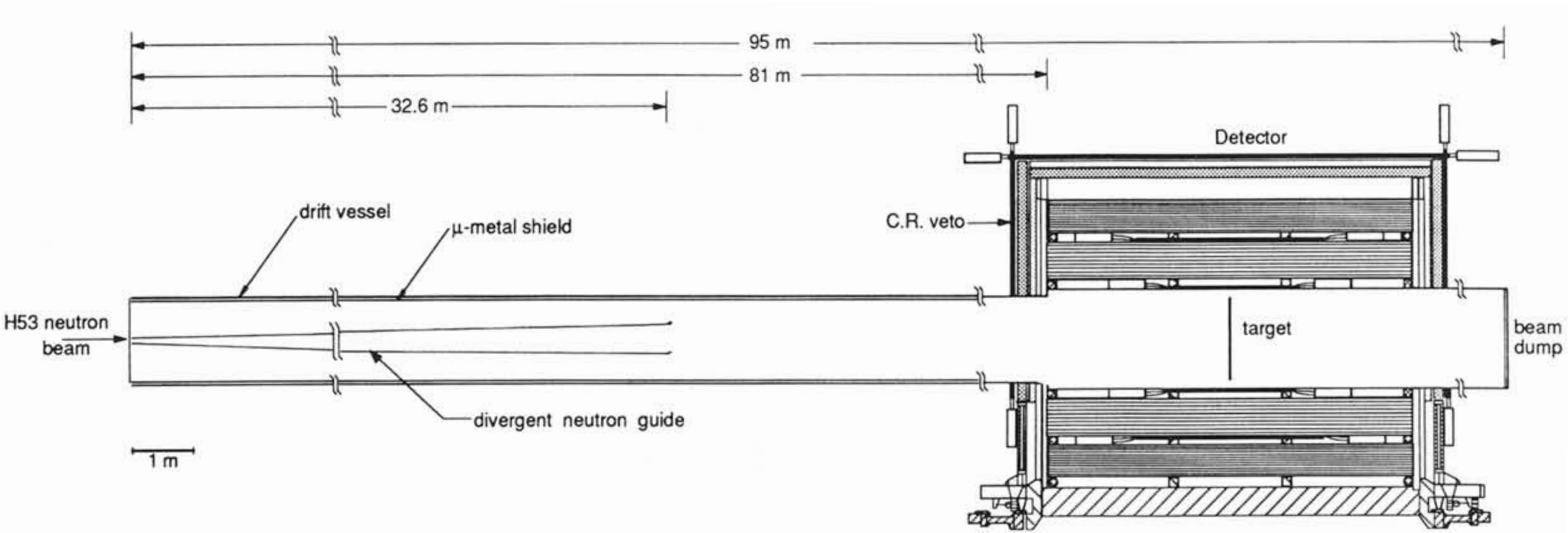
$$\begin{pmatrix} \psi_n(0) \\ \psi_{\bar{n}}(0) \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$\begin{pmatrix} \psi_n(t) \\ \psi_{\bar{n}}(t) \end{pmatrix} = \begin{pmatrix} \exp[-i(E-\Delta E)t/\hbar] \\ -i\frac{\delta m}{\Delta E}\sin\frac{\Delta E t}{\hbar}\exp(-iEt/\hbar) \end{pmatrix}$$

antineutron appearance if $\delta m \neq 0$

Under the quasi-free condition $\Delta E\, t \ll \hbar$, $\quad P_{\bar{n}}(t) = |\psi_{\bar{n}}(t)|^2 \approx \left(\frac{\delta m\, t}{\hbar}\right)^2 = \frac{t^2}{\tau_{n-\bar{n}}^2}$

Experiment at the ILL reactor



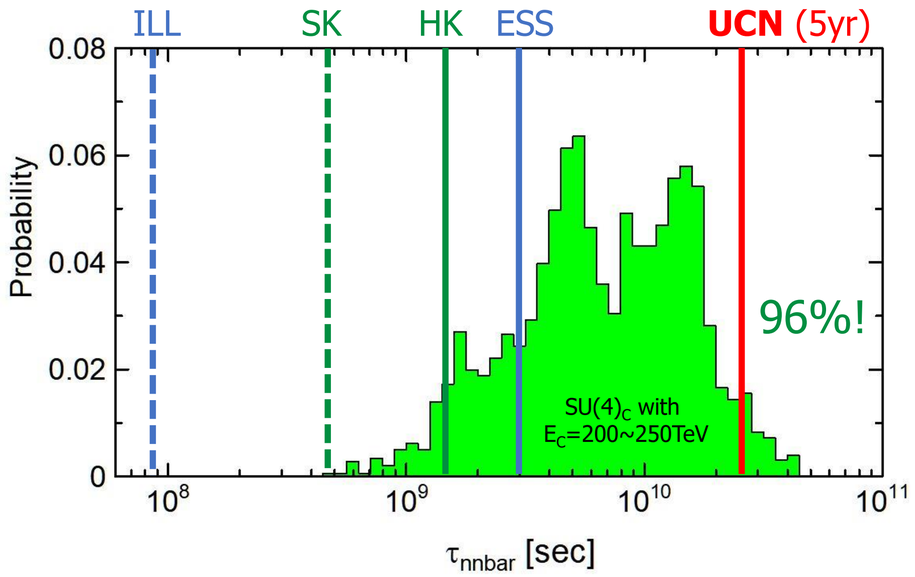
quasi-free condition satisfied : $B < 10\,\mathrm{nT}$ and $t = 0.1\,\mathrm{sec}$ (flight time)

[Result] no antineutron candidate observed in an exposure of $10^{11}\mathrm{s}^{-1} \times 2 \cdot 10^{7}\,\mathrm{s}$ cold neutrons →$\tau_{n-\bar{n}} > 8.6 \times 10^{7}\,\mathrm{s}$ (90% C.L.)

M. Baldo-Ceolin et al., Z. Phys. C 63, 409 (1994).

Post-sphaleron baryogenesis

- based on Pati–Salam GUT model $SU(2)_L \times SU(2)_R \times SU(4)_C$
  - $\tau_{n-\bar{n}} < 5 \times 10^{10}$ sec (using cosmological constraints)



Babu et al., Phys. Rev. D 87, 115019 (2013)

n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Mass $m = 1.0086649161 \pm 0.0000000004$ u
Mass $m = 939.5654219 \pm 0.0000005$ MeV [a]
$(m_n - m_{\overline{n}})/\, m_n = (9 \pm 5) \times 10^{-5}$
$m_n - m_p = 1.2933325 \pm 0.0000004$ MeV
$= 0.0013884495 \pm 0.0000000004$ u
Mean life $\tau = 878.3 \pm 0.4$ s (S = 1.8)
$c\tau = 2.6332 \times 10^8$ km
Magnetic moment $\mu = -1.9130428 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.18 \times 10^{-25}\ e$ cm, CL = 90%
Mean-square charge radius $\langle r_n^2 \rangle = -0.1155 \pm 0.0017$ fm^2
Magnetic radius $\sqrt{\langle r_M^2 \rangle} = 0.864^{+0.009}_{-0.008}$ fm
Electric polarizability $\alpha = (11.8 \pm 1.1) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (3.7 \pm 1.2) \times 10^{-4}$ fm^3
Charge $q = (-0.2 \pm 0.8) \times 10^{-21}\ e$
Mean $n\overline{n}$-oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free n)
Mean $n\overline{n}$-oscillation time $> 4.7 \times 10^8$ s, CL = 90% [f] (bound n)
Mean nn'-oscillation time > 448 s, CL = 90% [g]

Super-K

Particle Data Group

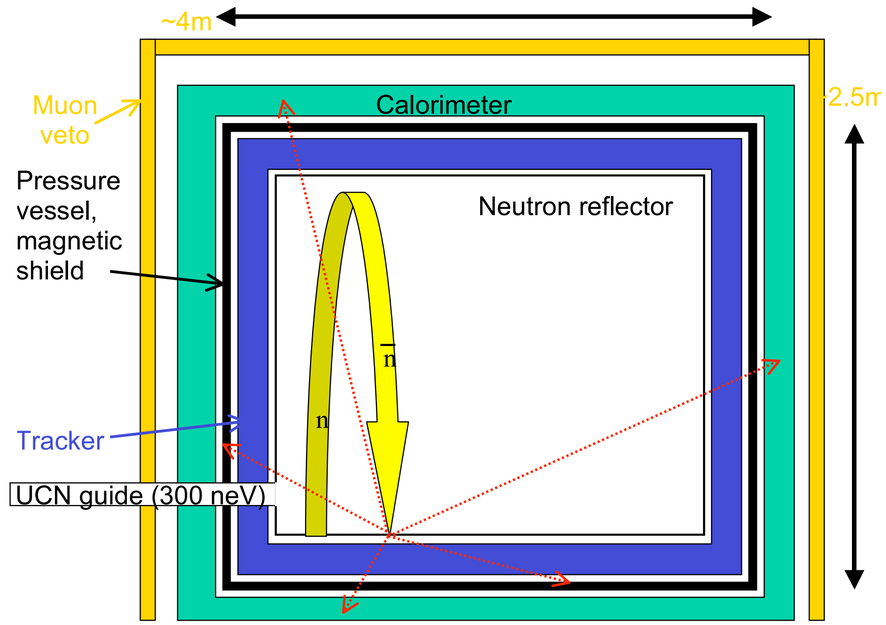
Mohapatra, Marshak, Phys. Rev. Lett. 44, 1316 (1980); Mohapatra, NIM A 284, 1 (1989);

n–n̄ oscillation search using UCNs

- Ultra-cold neutrons (UCNs) : kinetic energies below a few 100neV
- can be stored in a UCN storage bottle
  - UCNs are reflected by a Fermi pseudo-potential

$$U_n = \frac{2\pi\hbar^2}{m} N \frac{A+1}{A} a_{nA}$$ of the material

- has long been proposed, but yet to be realized



D. G. Phillips II et al., Physics Reports 612, 1 (2016)

K. G. Chetyrkin et al., Phys. Lett. B, 99, 358 (1981)

R. Golub and H. Yoshiki, Nucl. Phys. A, 501, 869 (1989)

H. Yoshiki and R. Golub, Nucl. Phys. A, 536, 648 (1992)

B. O. Kerbikov, Phys. At. Nucl., 66, 2178 (2003)

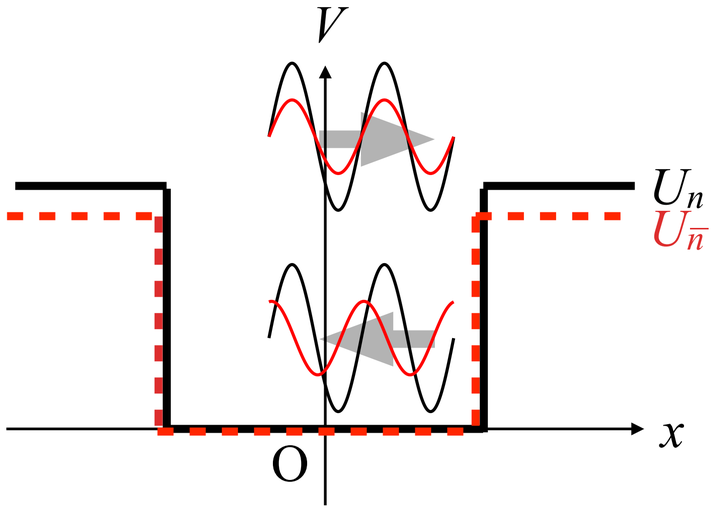
B. O. Kerbikov, A. E. Kudryavtsev, and V. A. Lensky, J. Exp. Theor. Phys., 98, 417–426 (2004)

T. Shima, Symmetry 17, 1524 (2025)

H. Fujioka and T. Higuchi, Prog. Theor. Exp. Phys. 2026, 023C01 (2026)

The role of antineutron-nucleus scattering lengths

- We calculated the time evolution of the wavefunction in a 1D potential.
- The antineutron annihilation rate (=signal rate) depends on the reflectivity of antineutrons and the phase difference upon reflection.
- Accurate knowledge of the neutron and antineutron pseudopotentials is essential for predicting the sensitivity.



$$U_{\bar{n}} = \frac{2\pi\hbar^2}{m} N \frac{A+1}{A} a_{\bar{n}A}$$

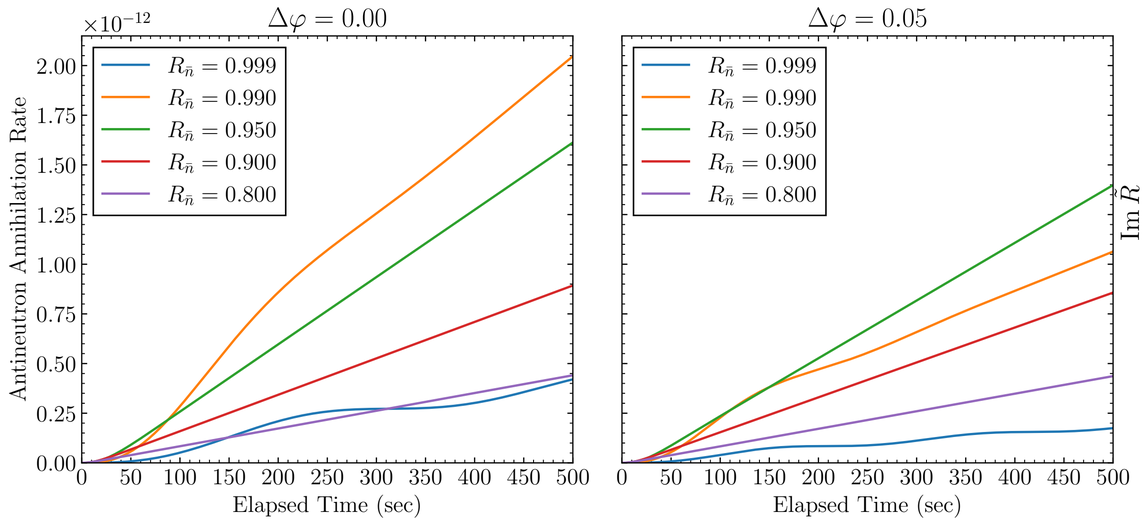
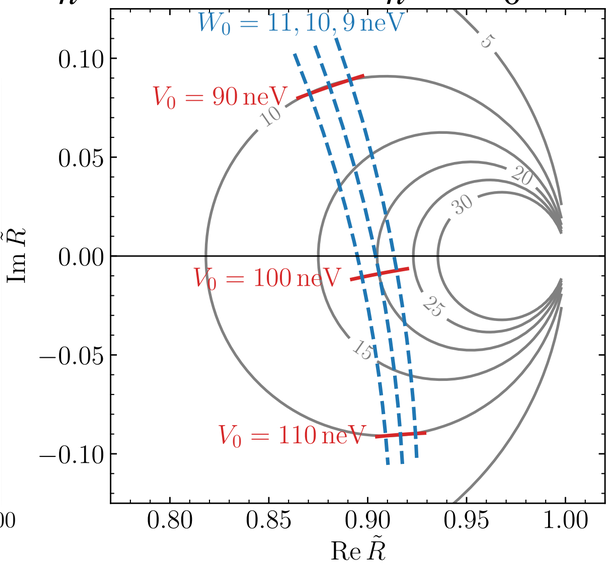


Figure of merit for

$V_n = 100\,\mathrm{neV},\ V_{\bar{n}} = V_0 - iW_0$



HF and T. Higuchi, Prog. Theor. Exp. Phys. 2026, 023C01 (2026)

Antineutron–nucleus scattering length

- antinucleon–nucleus optical potential: $V(r) = -\frac{2\pi}{\mu}\left(1+\frac{\mu}{m_N}\right) b_0 \rho(r)$,

  where $\rho(r)$ is the nucleon density distribution
- The b_0 parameter was fitted to strong-interaction shifts and widths measured in antiprotonic atoms.
- The antineutron–nucleus scattering length was calculated using this optical potential:

slightly larger than the nuclear radii almost independent of nuclides

$$a_{\bar{n}A} = (1.54 \pm 0.03)A^{0.311\pm0.005} - (1.00 \pm 0.04)i\,\mathrm{fm}$$ (global fit)

C. J. Batty et al., Nucl. Phys. A 689, 721 (2001)

- Direct scattering-length measurements can test and constrain these optical potentials.

The low energy $\bar{n}A$ scattering is described by a scattering length $b_{\bar{n}A}$. Where direct experimental data on $\bar{n}$ were not available, the similarity between the theoretical description of $\bar{p}$ and $\bar{n}$ low-energy scattering on nuclei allowed us to adapt the fitting formula for $b_{\bar{p}A}$, derived by the authors of Ref. [76] from $\bar{p}$ experimental data to $\bar{n}$

$$b_{\bar{p}(\bar{n})A} = (1.54A^{1/3} - i1.0)\ \text{fm}, \qquad (6)$$

where A the mass number. The $\sim$1 fm size of $\mathrm{Im}(b_{\bar{p}(\bar{n})A})$ comes from the diffusive tail of the $\bar{n}A$ potential and is similar for all nuclei [100]. $\mathrm{Re}(b_{\bar{p}(\bar{n})A})$ is proportional to the nuclei radius; the $\bar{n}A$ interaction is restricted to the nuclear surface and is therefore insensitive to nuclear structure [76,100]. There is no $\bar{n}$ counterpart to compound nA fluctuations. This fact justifies a similar approximation for the theoretically predicted values of real parts of antineutron scattering lengths

$$b_{\bar{n}A} = 1.54A^{1/3}, \qquad (10)$$

which was used in [84] (imaginary parts appear to be close to 1 fm). Unfortunately, there are no experimental measurements of $b_{\bar{n}A}$.

V.V. Nesvizhevsky et al., Phys. Rev. Lett. 122 (2019) 221802

The scattering length has never been determined directly.
The values were inferred from the optical potentials fitted to antiprotonic-atom data.

V. Gudkov et al., Phys. Lett. B 808 (2020) 135636

> This model has a very large imaginary part of nuclear potential (imaginary part of b_0) and produces results which have a quite simple geometrical interpretation. The strong annihilation practically "kills" the wave function inside the nucleus, and the results are, therefore, mostly sensitive to the periphery of potential. The real part has a pure $A^{1/3}$ dependence corresponding to a black sphere. We will refer to this approach as a *model with strong annihilation*. For the scattering length without Coulomb interactions, $\mathrm{Re}a_0^s = (1.54 \pm 0.03) \cdot A^{0.311\pm0.05}$ fm. The imaginary part is practically A independent and proportional to the diffuseness of the potential: $\mathrm{Im}a_0^s = (1.00 \pm 0.04)$ fm. Such dependence is typical for the case of a potential with very *strong annihilation* [73] and similar results were also found for other hadronic-nucleus systems.

K.V. Protasov et al., Phys. Rev. D 102 (2020) 075025

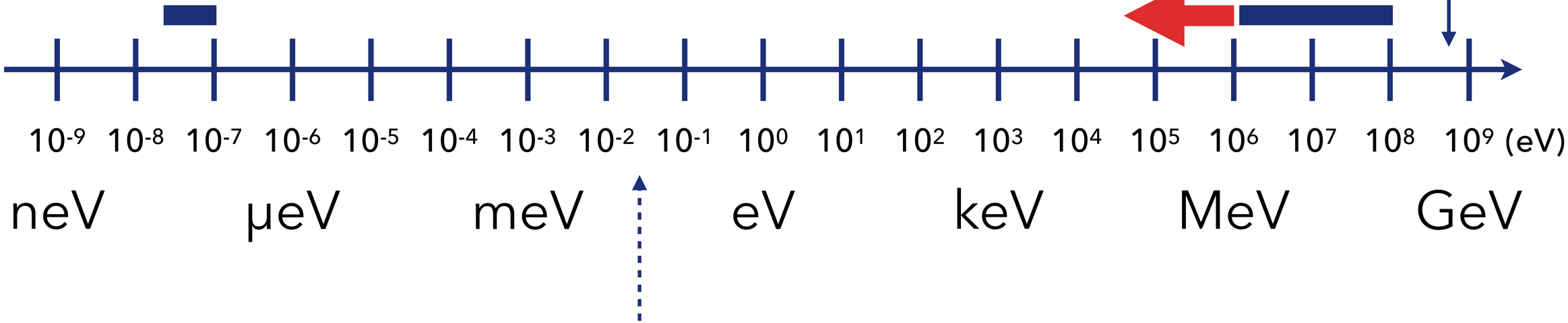
s-wave scattering

p-wave,
d-wave, …

The first antineutron at Bevatron

many experiments at BNL, CERN (LEAR)

n-n̄ oscillation search



$$U_{\bar{n}} = \frac{2\pi\hbar^2}{m} N \frac{A+1}{A} a_{\bar{n}A}$$

$$\sigma_{\mathrm{el}} = 4\pi |a|^2 (1 - 2a_{\mathrm{I}}k) + \mathcal{O}(k^2)$$

$$k\sigma_{\mathrm{ann}} = 4\pi a_{\mathrm{I}} - 8\pi a_{\mathrm{I}}^2 k + \mathcal{O}(k^2)$$

Conclusion

- Neutron–antineutron oscillations violate both B and B-L by two units and provide a probe of physics beyond the Standard Model.
- Accurate knowledge of antineutron–nucleus interactions is essential for optimizing searches using stored ultracold neutrons and interpreting their results.
- Our study highlights the importance of the complex antineutron–nucleus scattering length, particularly its real part, and motivates direct measurements with low-energy antineutrons at CERN.