# Neutron-antineutron oscillation and antinucleon-nuclear interactions

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# Outline

1. Neutron-antineutron oscillation
    - Background and today's situations
    - New proposals to improve the sensitivity of the search

2. Antinucleon-nucleus interaction
    - Optical potential model for antiprotons/antineutrons
    - Discuss possible research that can be done in this context

# Background: neutron-antineutron oscillation

- Theoretical motivations:
  - Baryon number violation $|\Delta B|=2$
  - Could help distinguish SU(8) and SO(10) GUT models

- Previous measurements:
  - Free neutrons: ILL (1994)
  - Bound neutrons: Super-Kamiokande (2015)

$$\text{Mean } n\bar{n}\text{-oscillation time} > 8.6 \times 10^{7} \text{ s, CL} = 90\% \text{ (free } n\text{)}$$

$$\text{Mean } n\bar{n}\text{-oscillation time} > 4.7 \times 10^{8} \text{ s, CL} = 90\% \,^{[g]} \text{ (bound } n\text{)}$$

| GUT models | Oscillation period $\tau_{n\bar{n}}$ =$10^{6}$~$10^{10}$ sec ? |
|---|---|
| $SU(2)_L \times U(1)_Y$ (GWS) | forbidden |
| minimal SU(5) | forbidden |
| $SU(4)_C \times SU(2)_L \times SU(2)_R$ | yes |
| SO(10) | too slow |
| SO(10) with low-E (~100TeV) $SU(4)_C$ | yes |
| $E_6$ | too slow |
| SUSY-SU(5) | too rapid |
| SUSY-$E_6$ | yes |

R.N.Mohapatra, NIM A284 (1989) 1
K.S. Babu, R.N. Mohapatra, PLB518 (2001) 269

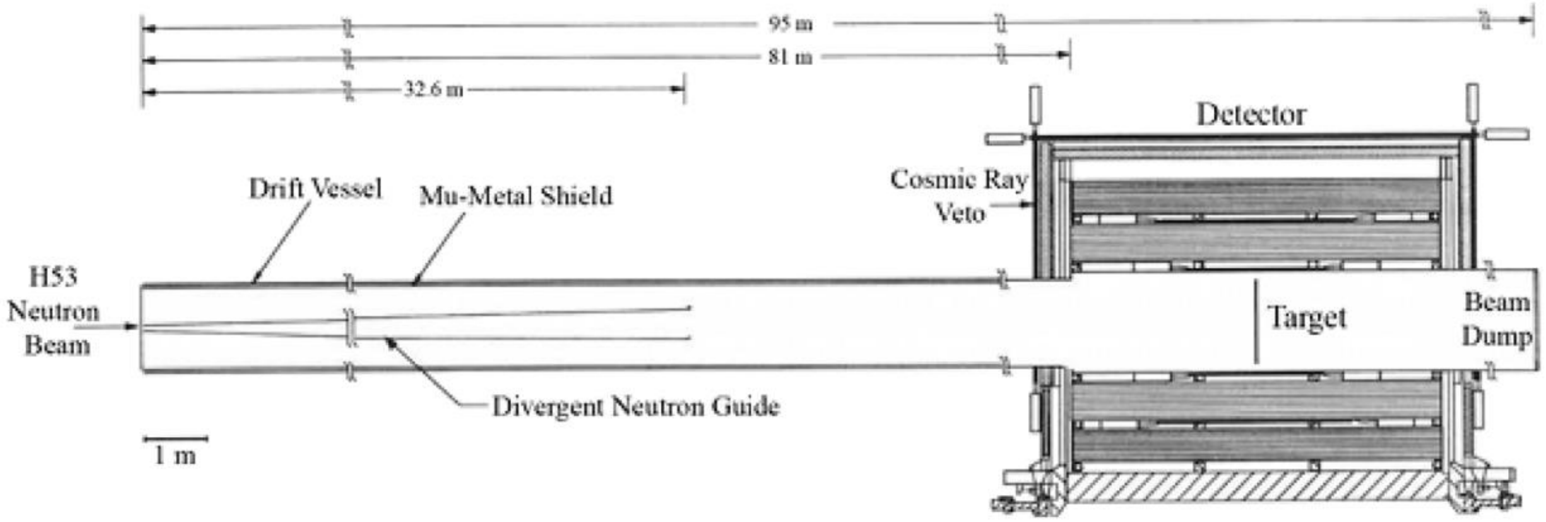
# Previous experiment at ILL (1994)

- Cold neutron flux: 2 meV, 1.25x$10^{11}$ n/s
- Flight path: 76.5 m, 0.1 s
- Magnetic field: < 10 nT, pressure: < 0.01 Pa
- Searched for nbar by annihilation to pions
  (130 um-thick graphite film as the annihilation target, $\varepsilon_{det}$=0.52)
- Accumulated observation time: $Y_{\bar{n}}$ = 2x$10^7$ s

$$P_{nn} \approx \left(\frac{t_{TOF}}{\tau}\right)^2$$

$$Y_{\bar{n}} = \varepsilon \cdot \Phi_n \cdot P_{nn} \cdot t_{\text{meas}}$$

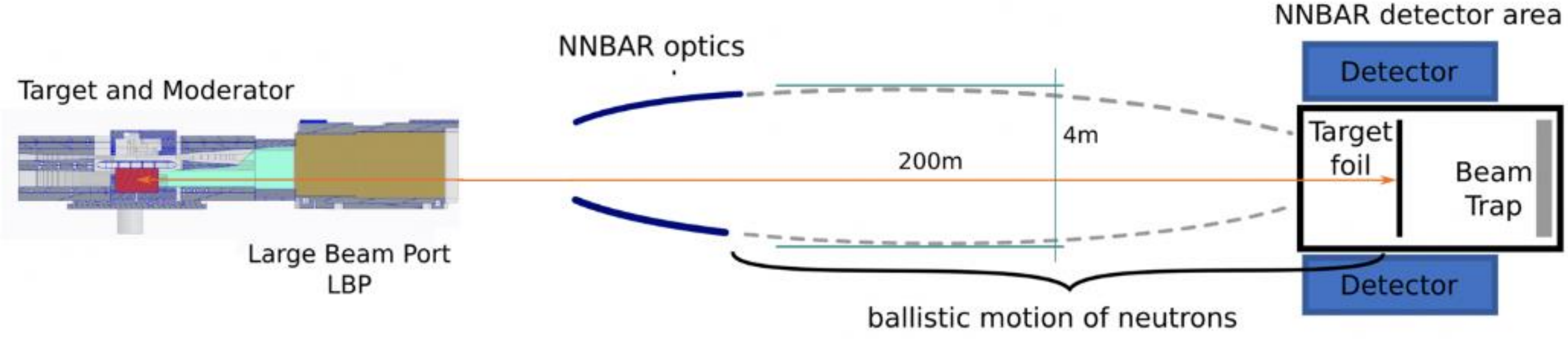
→ $\tau_{n\bar{n}} > 8.6 \times 10^7\text{s}\ (90\%\,\text{C.L.})$



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

# Future experiment at ESS

- Spallation neutrons moderated by a cold source: 2.7x $10^{15}$ n/sr/s
- Large-aperture neutron guides (4 m diameter) with neutron optics (> 4 Å) , Flight path of 200 m
- Factor of $(1000)^{1/2}$~ 32 improved figure of merit $\sqrt{(N^* t^2)}$ compared to the ILL experiment



F. Backman et al, JINST **17,** P10046 (2022)

**Recent developments:**

New proposals in view of the future opportunities (ESS in Sweden, new research reactor in Japan) that involve knowledge of low-energy antineutron-nucleus interactions

# Low energy neutron-nucleus interaction (neutron optics)

- At low energy ($\lesssim$ 10 meV), neutron-nucleus scattering dominated by the s-wave → Fermi potential

**Fermi pseudo-potential**

$$\boxed{V_{\mathrm{F}} = \frac{2\pi\hbar^2 N a_0}{\mu}}$$

- $N$: number density of nuclei
- $a_0$: the *s*-wave scattering length
- $\mu$: the neutron-nucleus reduced mass
- For alloy/compound (e.g. NiP):
  $a_0 \rightarrow (a_{0,1}n_1 + a_{0,2}n_2)/(n_1+n_2)$

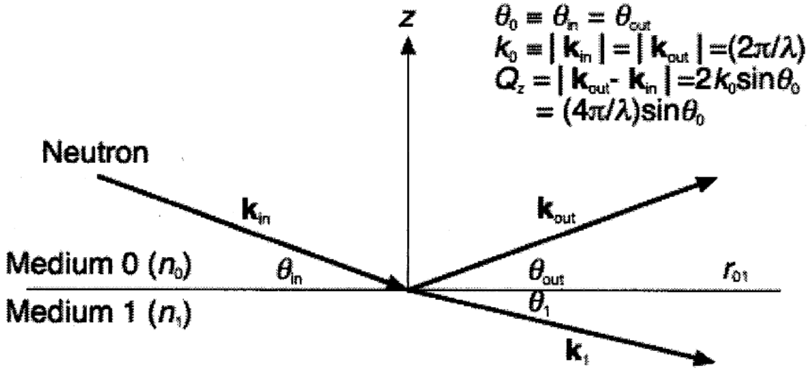
| Material | s-wave scattering length *b* (fm) | Fermi potential $V_F$ (neV) |
|---|---|---|
| Be | 7.778−0.002 *i* | 249.01−0.068 *i* |
| C | 6.648−0.0009732 *i* | 195.3−0.029 *i* |
| P | 5.130−0.0478 *i* | 47.53−0.443 *i* |
| Ni | 10.30−1.248 *i* | 243.5−29.52 *i* |
| NiP | — | 213.2−0.0229 *i* |

*b*: bound scattering length $b = \frac{A+1}{A}a$

- Totally reflection of neutron with an incident angle $\vartheta \leq \vartheta_c$:

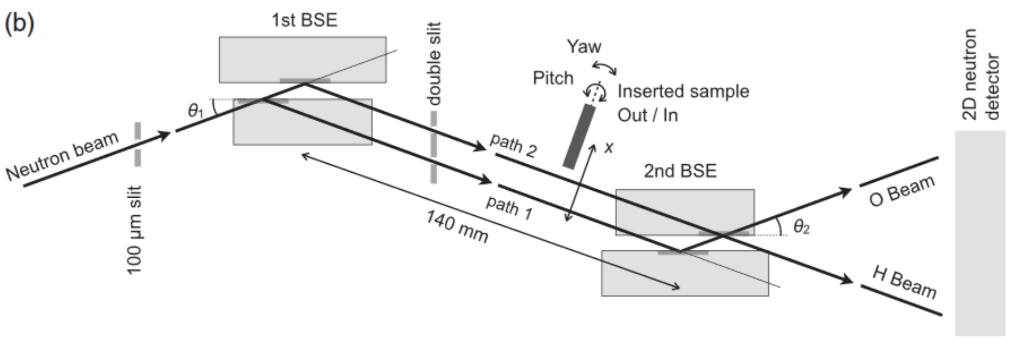
$$E_\perp = E\,(\sin\theta)^2 \leq V_{\mathrm{F}},$$ the critical angle $\theta_c = \sin^{-1}(\sqrt{V_{\mathrm{F}}/E})$

- *Ultracold neutrons (UCNs):* neutrons with energies $\lesssim$ 300 neV
  → totally reflected with any incident angle
  → can be stored for time ~100 s in material containers

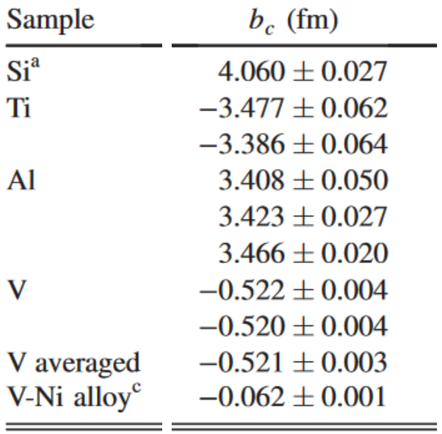


# Low energy neutron-nucleus interaction (neutron optics)

- Experimental determination:
  - Measured by neutron interferometry



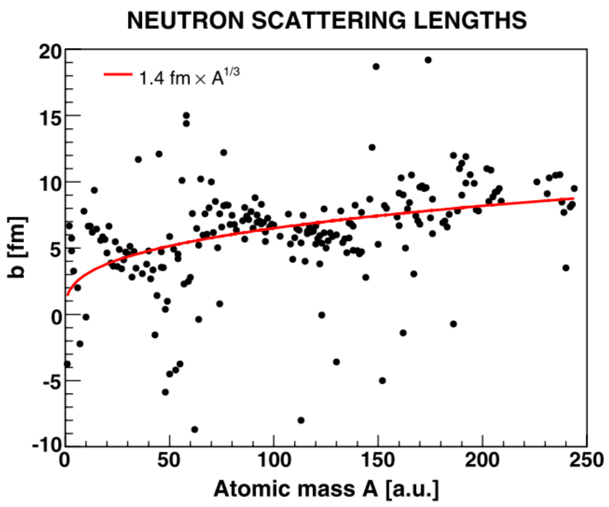
- Determined with precision of ~0.1-1%

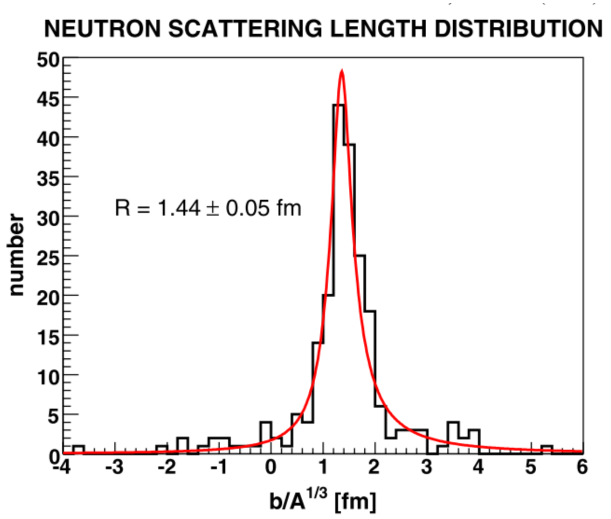


| Sample | $b_c$ (fm) |
|---|---|
| Si[a] | $4.060 \pm 0.027$ |
| Ti | $-3.477 \pm 0.062$ |
| | $-3.386 \pm 0.064$ |
| Al | $3.408 \pm 0.050$ |
| | $3.423 \pm 0.027$ |
| | $3.466 \pm 0.020$ |
| V | $-0.522 \pm 0.004$ |
| | $-0.520 \pm 0.004$ |
| V averaged | $-0.521 \pm 0.003$ |
| V-Ni alloy[c] | $-0.062 \pm 0.001$ |

T. Fujiie et al. Phs. Rev. Lett. **132**, 023402 (2024)

- Nuclide dependence:





- Largely scales as $A^{1/3}$, but scatters due to the nuclear structures

V.V. Nesvizhevsky, G. Pignol & K.V. Protasov, PRD **77**, 034020 (2008)

# Recent proposals for the n-nbar oscillation search

- **Antineutron mirror:**
  - (Anti)neutron mirrors to extend the observation time by $10^4$
  - **10-20%** error on nbar-A scattering length is acceptable

V. V. Nesvizhevsky et al. *Phys. Rev. Lett.*, **122**, 221802 (2019
K. V. Protasovet al. *Phys. Rev. D*, **102**, 075025 (2020)

- **Use of ultracold neutrons** (T. Shima 2023):
  - Use of stored ultracold neutrons instead of a neutron beam
  - Design a material vessel coating which has the identical n/nbar Fermi potential to **a few %**

T. Shima: NEWS colloquium, RCNP Osaka (2023)

- **Neutron-gas interaction to compensate the magnetic field:**
  - Pre-select the spin state of a neutron beam, fill the neutron path with gas which cancels the magnetic potential (loosen the magnetic field requirement $S = (2\vec{\mu}_n \cdot \vec{B} - V_n + V_{\bar{n}})$

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

→ **Key: <u>the scattering length of antineutrons with nucleus</u>**

→ **Next pages: neutron-material interaction in the n-nbar oscillation**

# Formalism of n-nbar oscillation (in vacuum)

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix} = \begin{pmatrix}E_n + U_n(t) - i\Gamma_\beta & \varepsilon \\ \varepsilon & E_{\bar{n}} + U_{\bar{n}}(t) - i\Gamma_\beta\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_n(t)\end{pmatrix}$$

- In vacuum, $U_n(t) = -|\mu_n| \cdot B, \quad U_{\bar{n}}(t) = |\mu_n| \cdot B \qquad \omega \equiv U_n - U_{\bar{n}}$
- Starting from $\psi_n(0) = 1$, the oscillation probability is

$$P_{n\bar{n}}(t) = |\psi_{\bar{n}}(t)|^2 = \frac{4\varepsilon^2}{\omega^2 + 4\varepsilon^2}\exp(-\Gamma_\beta t) \cdot \sin^2\left(\frac{1}{2}\sqrt{\omega^2 + 4\varepsilon^2}t\right)$$

- Quasi-free limit (the potential difference (sufficiently small magnetic field ≲ 10 nT):

$$\omega t \ll 1 \quad \Rightarrow P_{n\bar{n}}(t) \approx \epsilon^2 t^2 \cdot \exp(-\Gamma_\beta t) = (t/\tau_{n\bar{n}})^2 \cdot \exp(-\Gamma_\beta t)$$

\# of detected nbar over time : $Y_{\bar{n}} = \epsilon_{\text{et}} \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{\text{meas}}$

→ contains $P_{n\bar{n}}$ and thus $\tau_{n\bar{n}}$

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

# Wall interactions in n-nbar oscillation

$$i\frac{\partial}{\partial t}\begin{pmatrix}\psi_n(t)\\ \psi_{\bar{n}}(t)\end{pmatrix} = \begin{pmatrix}E_n + U_n(t) - i\Gamma_\beta & \varepsilon \\ \varepsilon & E_{\bar{n}} + U_{\bar{n}}(t) - i\Gamma_\beta\end{pmatrix}\begin{pmatrix}\psi_n(t)\\ \psi_n(t)\end{pmatrix}$$

- The n-nbar wall potential difference (quasi-free limit not applicable):

$$\omega_W \equiv U_n(t) - U_{\bar{n}}(t) = O\big(10^{-7}[\mathrm{eV}]\big) \gg \varepsilon < 10^{-12}\mathrm{eV} \qquad \nu \equiv \frac{1}{2}\sqrt{\omega_W^2 + 4\varepsilon^2}$$

- Solution of the differential equation:

$$\begin{pmatrix}\psi_n\,(t_W)\\ \psi_{\bar{n}}\,(t_W)\end{pmatrix} = \exp\left[-\left(iE_n + \frac{\Gamma_\beta}{2}\right)t_W\right]\cdot\begin{pmatrix}\cos\nu t_W + i\omega_W \sin\nu t_W/(2\nu) & -\frac{i\varepsilon}{\nu}\sin\nu t_W \\ -\frac{i\varepsilon}{\nu}\sin\nu t_W & \cos\nu t_W - i\omega_W\sin\nu t_W/(2\nu)\end{pmatrix}\begin{pmatrix}\psi_n(0)\\ \psi_{\bar{n}}(0)\end{pmatrix}$$

→ Suppression of oscillation inside the wall: ε/ν << 1

→ The wave function acquires a phase by going through the wall: $(\cos \nu t_W \pm i\omega_W/(2\nu)*\sin \nu t_W)$

- Sensitivity

$$P_{n\bar{n}} \approx (\cos\nu t_W)^{2N}\left(\frac{t_s}{\tau_{n\bar{n}}}\right)^2 \qquad Y_{\bar{n}} = \varepsilon_{\mathrm{det}}\cdot\Phi_n\cdot P_{n\bar{n}}\cdot t_{meas}$$

*N*: # of wall collisions, $t_W$: dwell time in the wall

$t_s$: free flight time between wall interaction

T. Shima: NEWS colloquium, RCNP Osaka (2023)

# Impact of nbar scattering length to the sensitivity (UCNs)

T. Shima: NEWS colloquium, RCNP Osaka (2023)

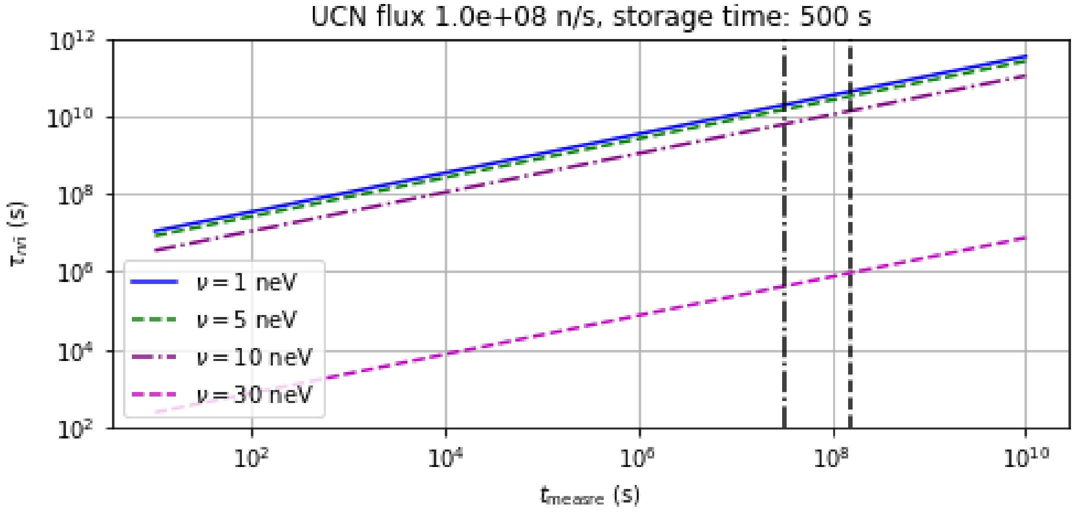
$$P_{n\bar{n}} \approx (\cos \nu t_W)^{2N} \left( \frac{t_s}{\tau_{n\bar{n}}} \right)^2 \qquad Y_{\bar{n}} = \varepsilon_{\text{det}} \cdot \Phi_n \cdot P_{n\bar{n}} \cdot t_{meas}$$

- Realistic numbers:

  Realistic numbers:
    - Free flight time $t_{\text{free}}$=1 s
    - Wall dwell time $t_W$~10 ns
    - Number of collisions: N =500
    - Storage lifetime: $t_{\text{free}}$ x N = 500 s
    - UCN flux: $\Phi_n$ ~ $10^8$/s
- Wall material:

  Al (59%) Mg (41%), theoretically $V_{F,n}$=58.3 neV ,ν = 0.5 neV

  E. Friedman & A. Gal, Phys. Rev. D **78**, 016002 (2008)

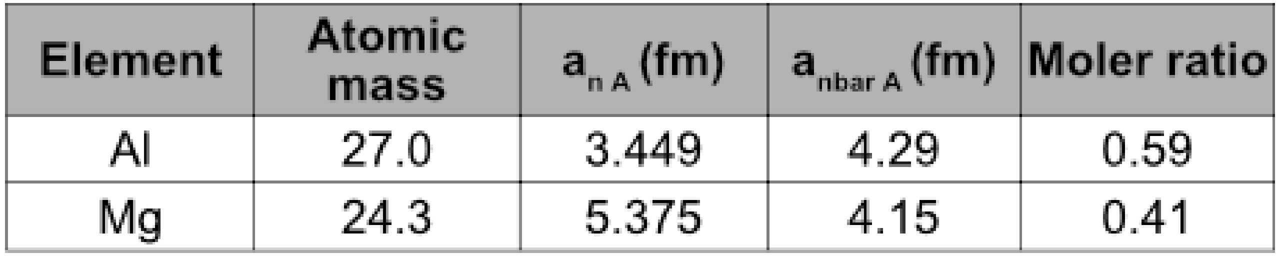


Very sensitive to the n-nbar potential difference!

→ $\tau_{n\bar{n}} > 10^{10}$ s in 1 year

# Other proposals for the n-nbar oscillation search

- Possible design of coating that has close potentials experienced by n and nbar:
  - Compound/alloy of elements: take number average of the scattering length (e.g. NiP)



| Element | Atomic mass | $a_{n\ A}$ (fm) | $a_{nbar\ A}$ (fm) | Moler ratio |
|---|---|---|---|---|
| Al | 27.0 | 3.449 | 4.29 | 0.59 |
| Mg | 24.3 | 5.375 | 4.15 | 0.41 |

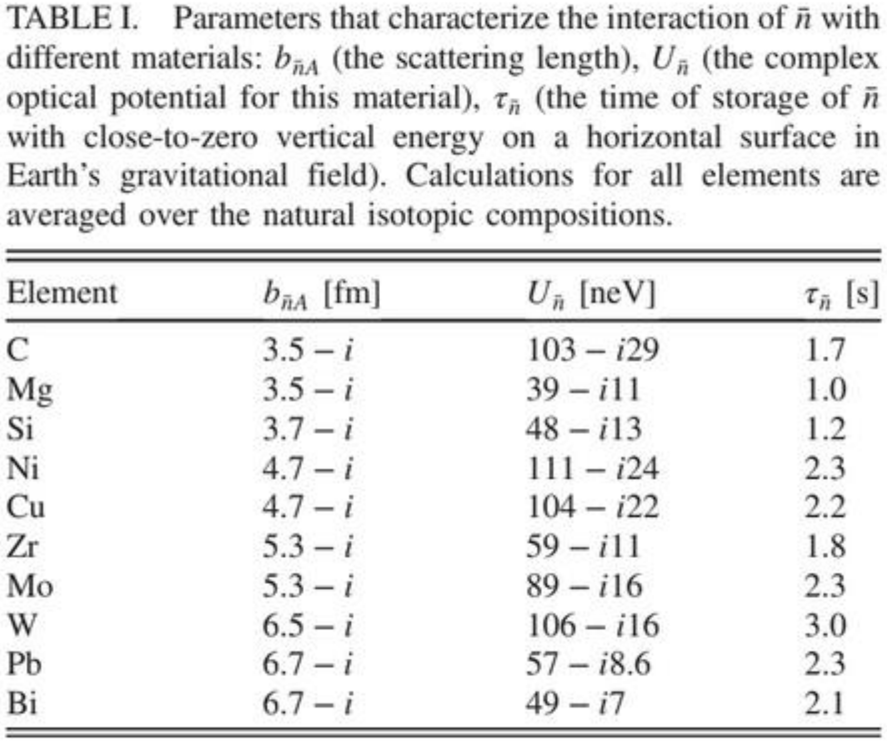


TABLE I. Parameters that characterize the interaction of $\bar{n}$ with different materials: $b_{\bar{n}A}$ (the scattering length), $U_{\bar{n}}$ (the complex optical potential for this material), $\tau_{\bar{n}}$ (the time of storage of $\bar{n}$ with close-to-zero vertical energy on a horizontal surface in Earth's gravitational field). Calculations for all elements are averaged over the natural isotopic compositions.

| Element | $b_{\bar{n}A}$ [fm] | $U_{\bar{n}}$ [neV] | $\tau_{\bar{n}}$ [s] |
|---|---|---|---|
| C | $3.5 - i$ | $103 - i29$ | 1.7 |
| Mg | $3.5 - i$ | $39 - i11$ | 1.0 |
| Si | $3.7 - i$ | $48 - i13$ | 1.2 |
| Ni | $4.7 - i$ | $111 - i24$ | 2.3 |
| Cu | $4.7 - i$ | $104 - i22$ | 2.2 |
| Zr | $5.3 - i$ | $59 - i11$ | 1.8 |
| Mo | $5.3 - i$ | $89 - i16$ | 2.3 |
| W | $6.5 - i$ | $106 - i16$ | 3.0 |
| Pb | $6.7 - i$ | $57 - i8.6$ | 2.3 |
| Bi | $6.7 - i$ | $49 - i7$ | 2.1 |

- $a_{nbar}$ = 4.23 fm, $a_n$ =4.37 fm → 1% difference

V. V. Nesvizhevsky et al. *Phys. Rev. Lett.*, **122**, 221802 (2019)
K. V. Protasovet al. *Phys. Rev. D*, **102**, 075025 (2020)
V. Gudkov et al.," *Phys. Lett. B* **808**, 135636 (2020).

# Other proposals for the n-nbar oscillation search

- Other proposals:
  - V. V. Nesvizhevsky et al. 2019: to use (anti)neutron mirrors for the beam experiment:

    10-20% error on nbar-A scattering length is acceptable

  - V. Gudkov et al., 2020: Pre-select the spin state of a neutron beam, fill the neutron path with gas s.t. the magnetic potential is canceled to zero (loosen the magnetic field requirement)

$$S = (2\vec{\mu}_n \cdot \vec{B} - V_n + V_{\overline{n}})$$

→ **Key: <u>the scattering length of antineutrons with nucleus</u>**

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K. V. Protasovet al. *Phys. Rev. D*, **102**, 075025 (2020)
V. Gudkov et al.," *Phys. Lett. B* **808**, 135636 (2020).

# Antineutron/antiproton-nucleus interaction: available data

- pbar-nuclear scattering/annihilation:
  - pbar elastic scattering: PS184 (D, C, Ca, Pb)
  - ASACUSA : pbar elastic scattering/annihilation at 100 MeV/c (C) and 15.3 MeV/c (125 keV)
  - KEK-E-074: pbar elastic scattering/annihilation at 470-880 MeV/c (C, Al, Cu)
  - ..
- nbar-nuclear annihilation:
  - OBELIX (PS201): nbar annihilation at 100-400 MeV/c
- pbar atom spectroscopy: PS209

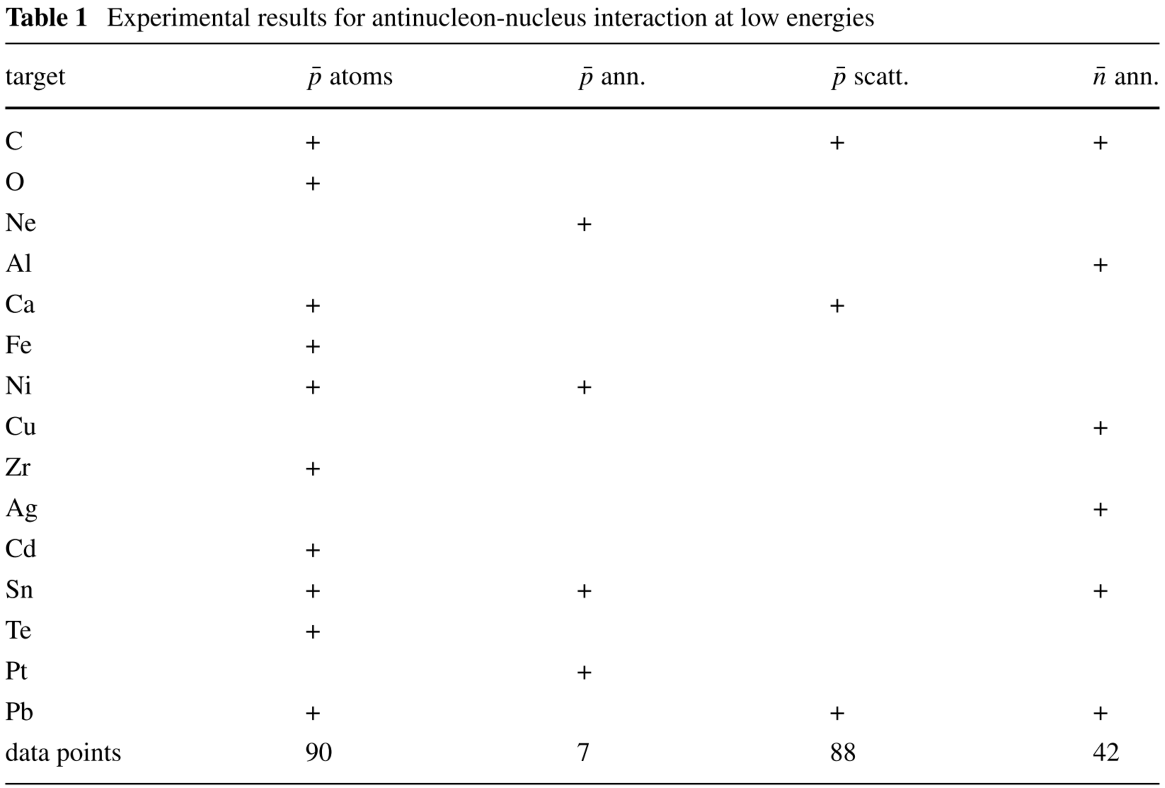


**Table 1** Experimental results for antinucleon-nucleus interaction at low energies

| target | $\bar{p}$ atoms | $\bar{p}$ ann. | $\bar{p}$ scatt. | $\bar{n}$ ann. |
|---|---|---|---|---|
| C | + | | + | + |
| O | + | | | |
| Ne | | + | | |
| Al | | | | + |
| Ca | + | | + | |
| Fe | + | | | |
| Ni | + | + | | |
| Cu | | | | + |
| Zr | + | | | |
| Ag | | | | + |
| Cd | + | | | |
| Sn | + | + | | + |
| Te | + | | | |
| Pt | | + | | |
| Pb | + | | + | + |
| data points | 90 | 7 | 88 | 42 |

E. Friedman, *Hyperfine Interact.*, **234**, 77–84 (2015).

→ No direct scattering data exists for nbar, but the model can be developed upon pbar data, checked by available nbar annihilation data

# Optical potential model (Batty-Friedman-Gal)

- Scattering wavefunction
  - Only the s-wave amplitude considered: f(θ) → $f_0$

$$\psi = \mathrm{e}^{\mathrm{ikr}} + f(\theta)\frac{e^{ikr}}{r},$$

$$\psi = \mathrm{e}^{\mathrm{ikr}} + \int \rho(\mathbf{r}') f_0 \frac{e^{ikr}}{|\mathbf{r}-\mathbf{r}'|}\psi_{\mathrm{eff}}(\mathbf{r}'),$$

- "tρ model"

$$(\nabla^2 + k^2)\psi(\mathbf{r}) = -4\pi a_0^{\mathrm{eff}}\rho(\mathbf{r})\psi(\mathbf{r}) \qquad \Rightarrow V_{\mathrm{opt}} = -4\pi\frac{\hbar}{2\mu}a_0^{\mathrm{eff}}\rho(\mathbf{r}).$$

μ: reduced mass
ρ: nucleon density

$$2\mu V_{opt}(r) = -4\pi\left(1+\frac{\mu}{M}\frac{A-1}{A}\right)\left[b_0(\rho_n+\rho_p)+b_1(\rho_n-\rho_p)\right]$$

$b_0$: iso-scalar scattering length
$b_1$ : iso-vector scattering length

- Nucleon density distribution parameterization:

$$\rho_{n,p}(r) = \frac{\rho_{0n,0p}}{1+\exp((r-R_{n,p})/a_{n,p})}$$

  - *$b_0$, $b_1$*: scattering lengths, *R*: radius , *a*: diffuseness of the Woods-Saxon potential

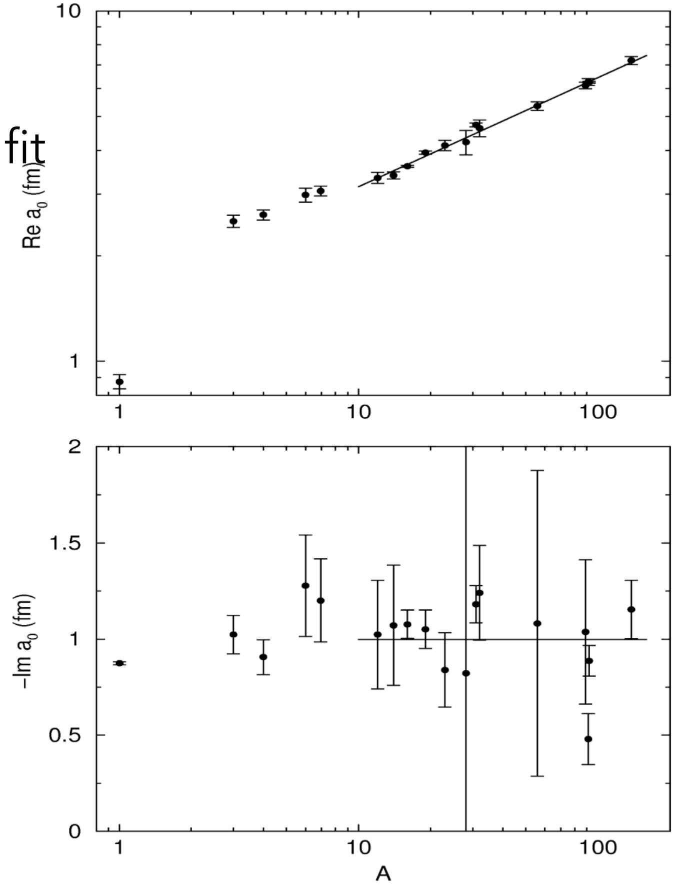
# Unified optical potential model approach applied to pbar-atom data

- Re(a) and Im(a) can be derived by strong-interaction-induced energy shifts and width of pbar atoms
- Used the pbar-atom data to determine the optical potential model parameters by global fit
    - Good agreement for A > 10
- C.J. Batty et al. 2001:
    - Isoscalar model
- E. Friedman et al. 2005: model with different neutron/proton distribution neutron-proton radius fitted by isotope data by PS209
    - Consistent with Im($b_1$)=0

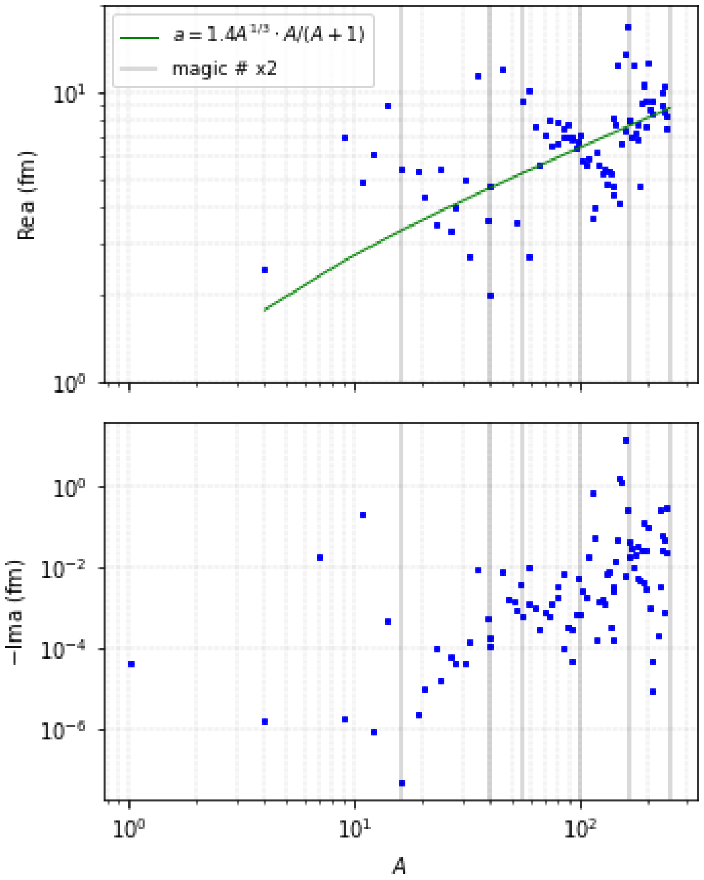
$$
\begin{aligned}
\mathrm{Re}\, a_0 &= (1.54 \pm 0.03) A^{0.311 \pm 0.005}\ \mathrm{fm}, \\
\mathrm{Im}\, a_0 &= -1.00 \pm 0.04\ \mathrm{fm}.
\end{aligned}
$$

Parameter uncertainty at % level

$\bar{p}$ - A



n- A

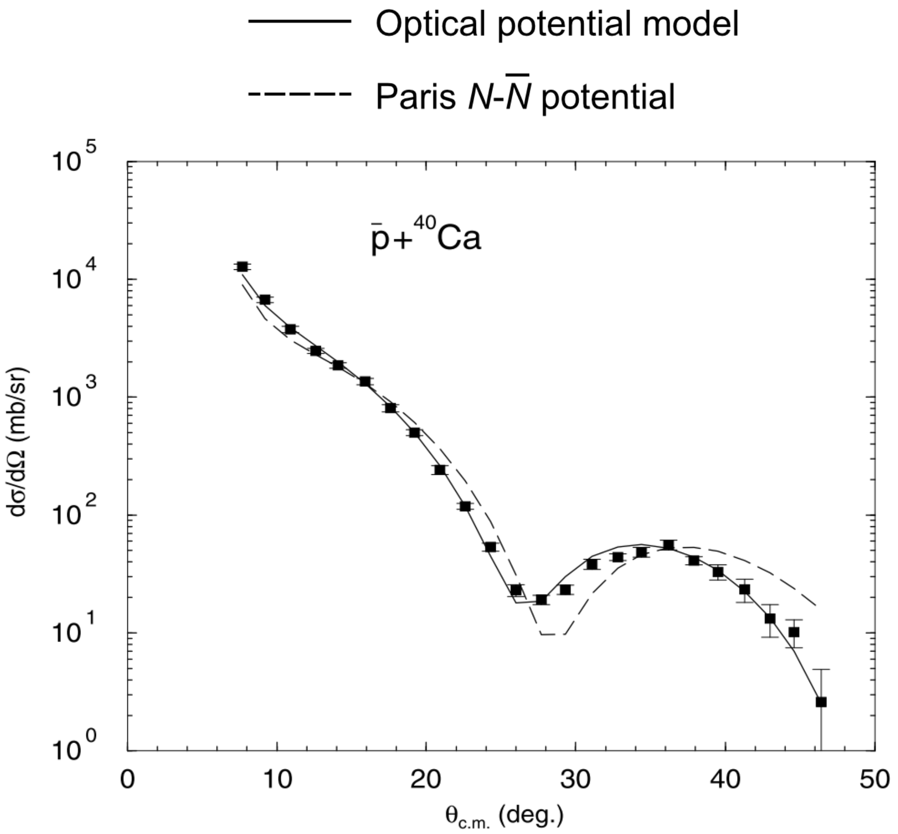


C. J. Batty, E. Friedman, and A. Gal, *Nucl. Phys. A*, **689,** 721–740 (2001).

E. Friedman, A. Gal, and J. Mareš, *Nucl. Phys. A*,.**761**, 283–295 (2005)

# Elastic scattering

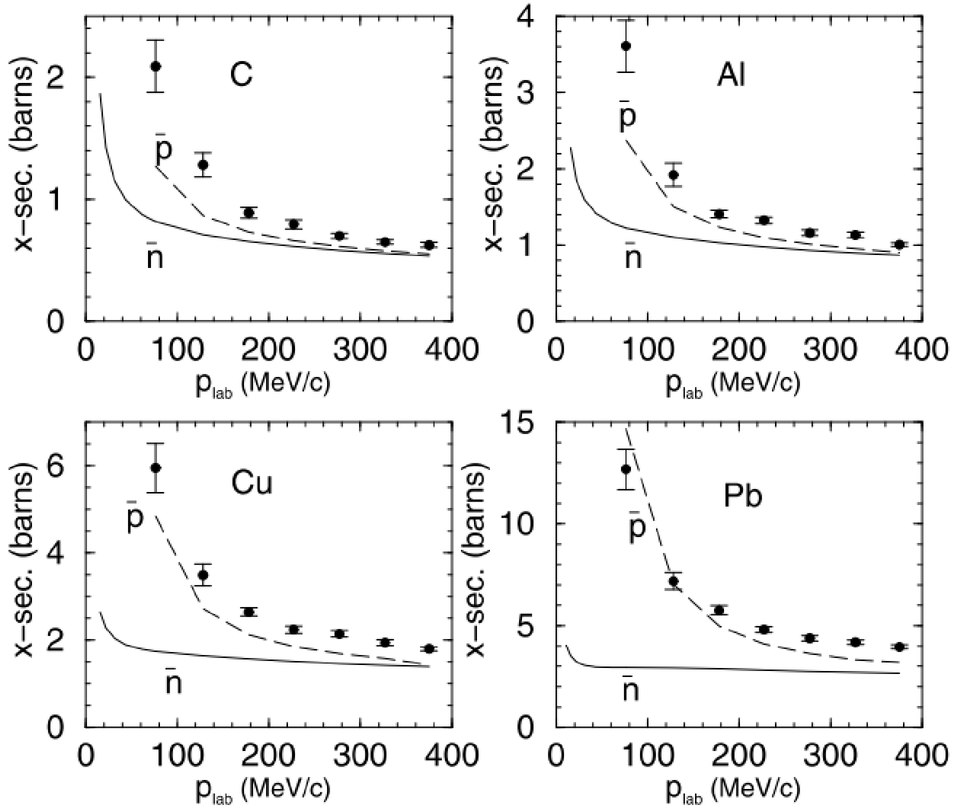
- The simple optical potential reproduces the experimental data better than the Paris N-Nbar potential (at least for this case)
- The same optical potential model works for both the E <0 (bound) and E> 0 (scattering) cases



E. Friedman, A. Gal, B. Loiseau, and S. Wycech, *Nucl. Phys. A* **943**, 101–116 (2015).

# Discrepancy in the annihilation data

- Annihilation cross section calculated by the optical potentia
  severe discrepancy with the OBELIX nbar data
  - Theory underestimates the cross-section
- Scarce data exists for pbar annihilation at the correspondin
  energies (100-400 MeV/c) → Recent works by ASACUSA



Data ● : nbar experiment (not pbar!)

E. Friedman, *Hyperfine Interact.*, **234**, 77–84 (2015).

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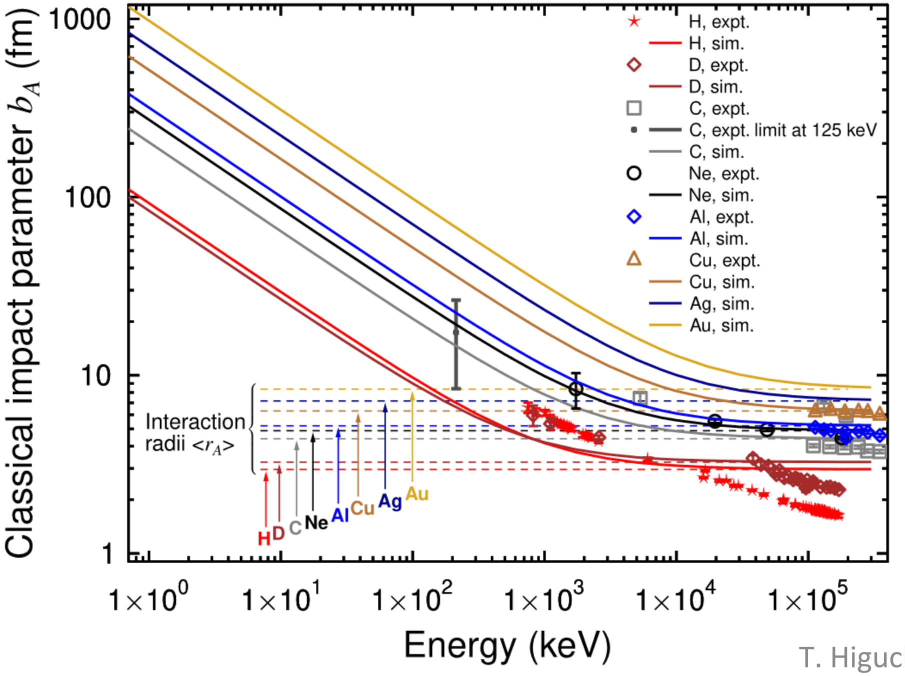
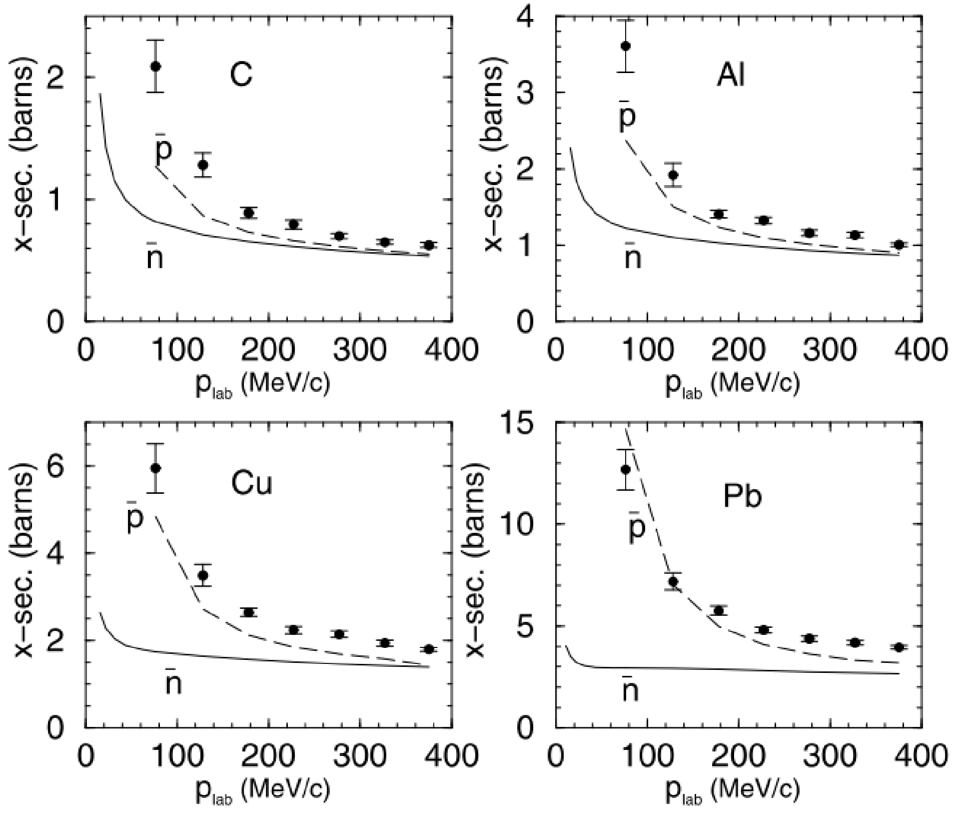
Latest summary in unit of classical impact factor $\sigma_A = \pi b_A^2$





Data ● : nbar experiment (not pbar!)

E. Friedman, *Hyperfine Interact.*, **234**, 77–84 (2015).
K. Nordlund et al., Phys. Rev. A **106**, 012803 (2022)

# Summary of the situations and proposals

- The optical potential model developed upon the pbar-atom spectroscopy data works well to explain elastic scatterings, but lacks full experimental verification

Possible pbar experiments in this context:

- **Annihilation cross-section measurement** in a 100-400 MeV/c momentum range
  - Future facility providing DC beam with variable momentum would be desirable
- **Verification of vanishing of isovector terms**
  - Elastic scattering and pbar-atom spectroscopy with isotopes

❖ Coordination of theoretical and experimental works are essential

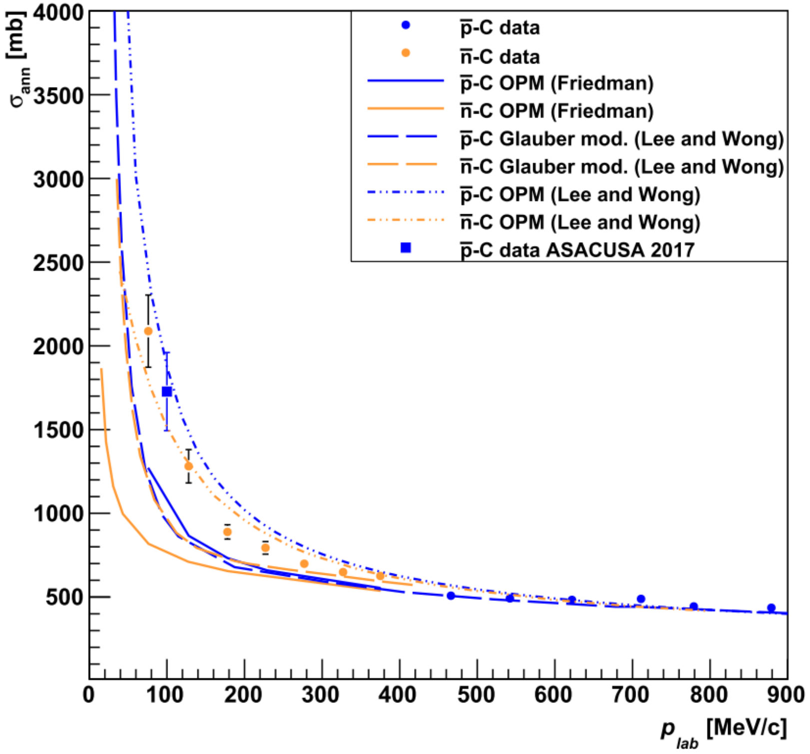
# Annihilation cross-section

- Still not enough pbar annihilation data to judge the nbar discrepancy is due to insufficiency of the theory or some experimental systematics

  →More measurements in 100-400 MeV/c desirable, but preferably done at a DC pbar source

- Recently proposed alternative model (Lee and Wong 2018):
  - Employs more complex model of nucleon density distribution (“double diffuseness”)

  → Possible further theoretical investigation based on *ab-initio* nucleon density distribution

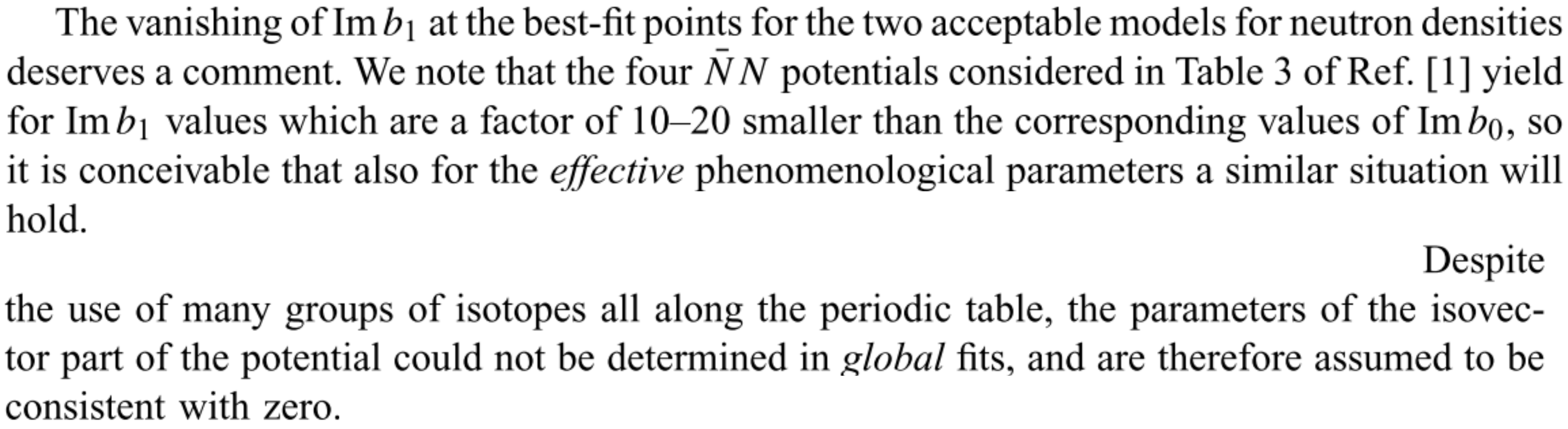


H. Aghai-Khozani et al., Nucl. Phys. A, **970**, 366–378 (2018)

# Isovector term of the scattering length

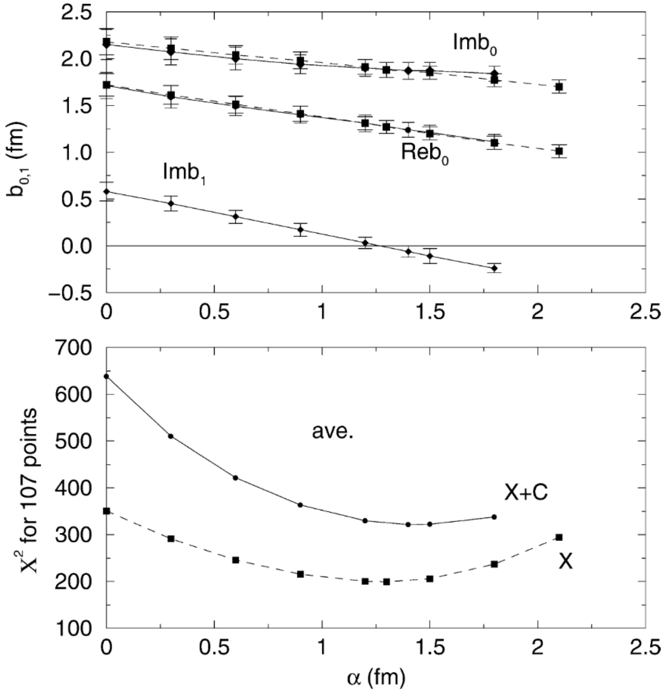
$$2\mu V_{opt}(r) = -4\pi \left(1 + \frac{\mu}{M}\frac{A-1}{A}\right)\left[b_0(\rho_n + \rho_p) + b_1(\rho_n - \rho_p)\right]$$

- The negligible iso-vector term $b_1$=0 in the *tρ* potential model is the basis of applying the pbar scattering length to nbar studies, but in fact there has never been explicit check
  - In the global fits, $b_1$ has correlation with proton/neutron density asymmetry parameters
  - E. Friedman et al. 2005:

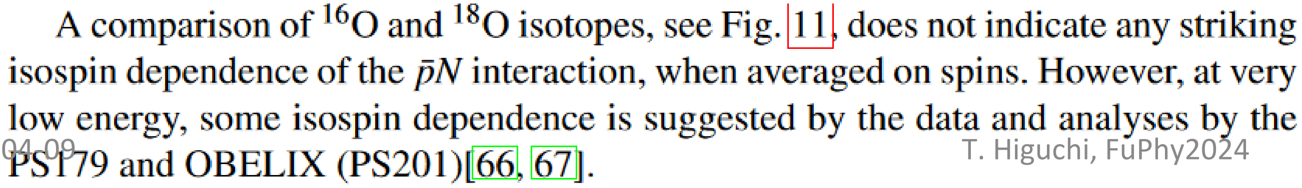


The vanishing of Im $b_1$ at the best-fit points for the two acceptable models for neutron densities deserves a comment. We note that the four $\bar{N}N$ potentials considered in Table 3 of Ref. [1] yield for Im $b_1$ values which are a factor of 10–20 smaller than the corresponding values of Im $b_0$, so it is conceivable that also for the *effective* phenomenological parameters a similar situation will hold.

Despite the use of many groups of isotopes all along the periodic table, the parameters of the isovector part of the potential could not be determined in *global* fits, and are therefore assumed to be consistent with zero.



- However, the charge independence of pbar-n (<-> nbar-p) reaction against pbar-p is not trivial
  - Jean-Marc Richard 2022:



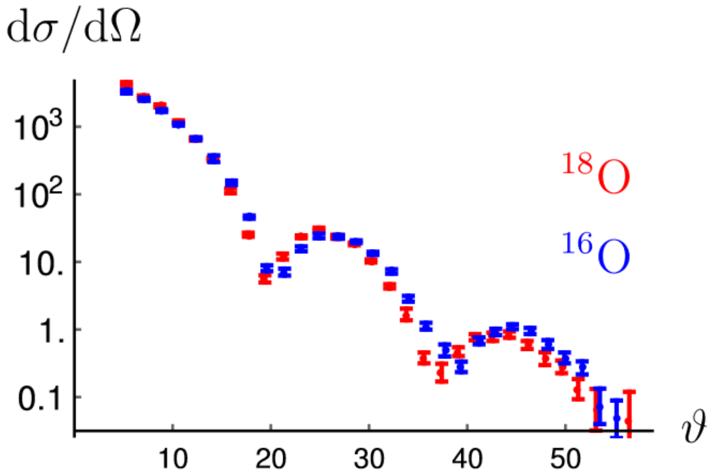
A comparison of $^{16}$O and $^{18}$O isotopes, see Fig. [11], does not indicate any striking isospin dependence of the $\bar{p}N$ interaction, when averaged on spins. However, at very low energy, some isospin dependence is suggested by the data and analyses by the PS179 and OBELIX (PS201)[66, 67].

E. Friedman, A.Gal, & J. Mareš, *Nucl. Phys. A*, **761**, 283(2005).
J-M. Richard, Handbook of Nuclear Physics (2022)

# Isovector term of the scattering length

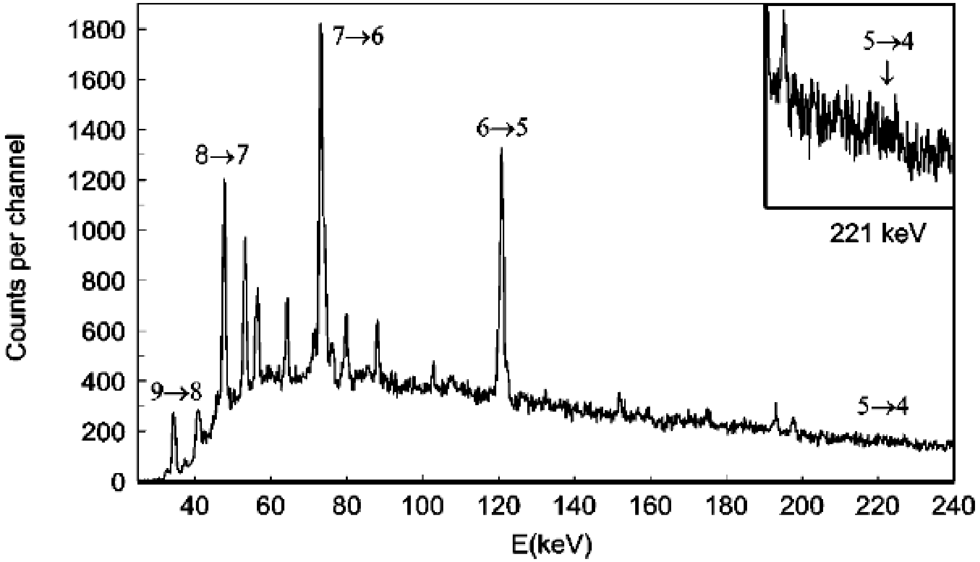
- To explicitly study the isovector term of the scattering length, isotopes with well understood nucleon density distribution are suited, e.g. Ca isotopes

- Scattering (previous study exists for $^{16}O$ &$^{18}O$)



G. Bruge et al. Phys. Lett., **169B,**14 (1986).

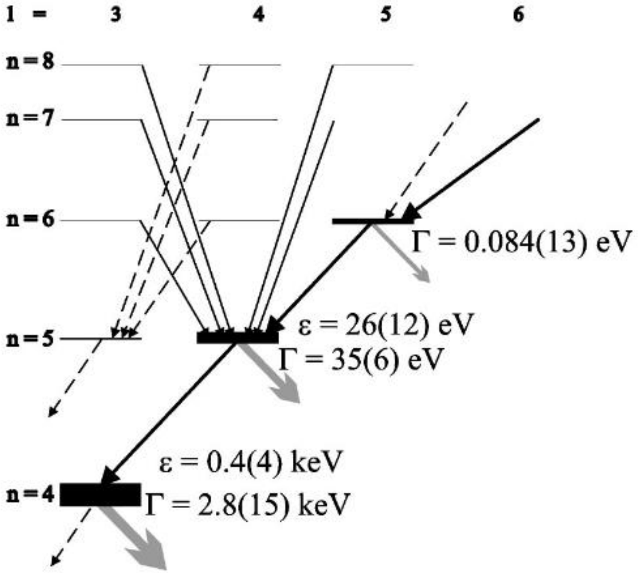
- pbar atom (previous work by PS209, but missing the effectively lowest (n,l) = (5,4) level widths

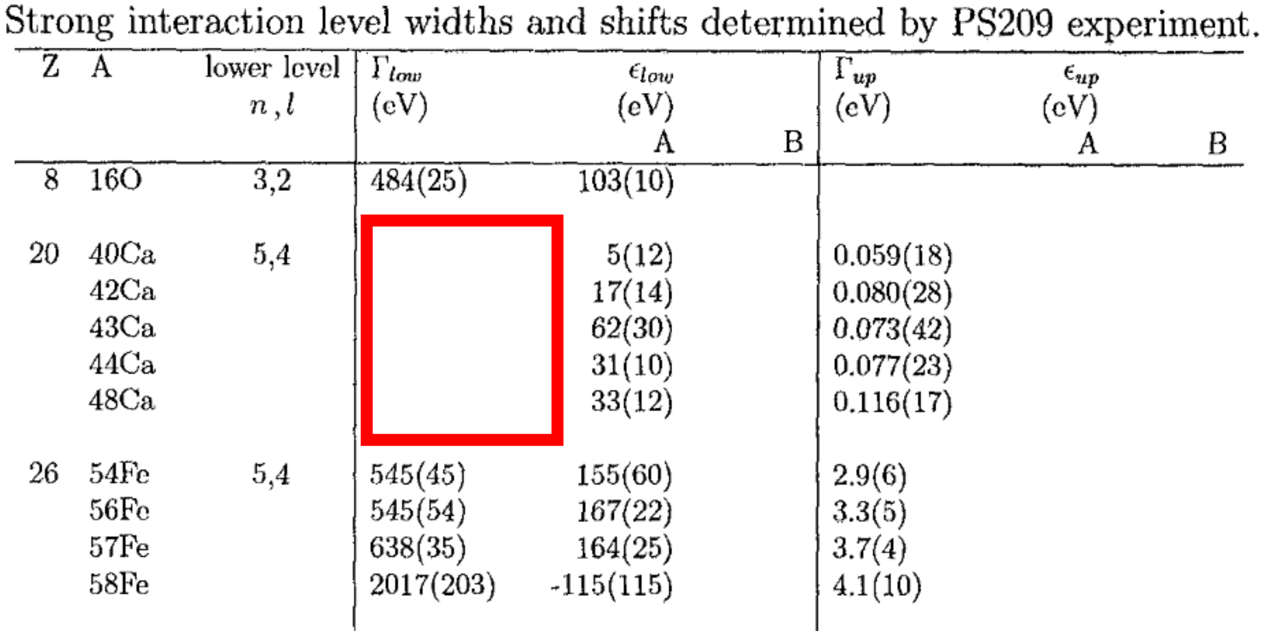


G. Bruge et al. Phys. Lett., **169B,**14 (1986).

# pbar-Ca spectroscopy by PS209

- Ge detector resolution is not sufficient, so used the intensity balance method to indirectly estimate the width of the transitions
  - The broadening by annihilation causes
- Possibility of applying a superconducting transition-edge sensor (TES) (a few eV resolution) to directly determine the width of the (*n*,*l*) = (6,5) → (5,4) around 120 keV (cf. Nancy Paul's talk tomorrow)





Strong interaction level widths and shifts determined by PS209 experiment.

| Z | A | lower level<br>$n\,,l$ | $\Gamma_{low}$<br>(eV) | $\epsilon_{low}$<br>(eV)<br>A | B | $\Gamma_{up}$<br>(eV) | $\epsilon_{up}$<br>(eV)<br>A | B |
|---|---|---|---|---|---|---|---|---|
| 8 | 16O | 3,2 | 484(25) | 103(10) | | | | |
| 20 | 40Ca | 5,4 | | 5(12) | | 0.059(18) | | |
| | 42Ca | | | 17(14) | | 0.080(28) | | |
| | 43Ca | | | 62(30) | | 0.073(42) | | |
| | 44Ca | | | 31(10) | | 0.077(23) | | |
| | 48Ca | | | 33(12) | | 0.116(17) | | |
| 26 | 54Fe | 5,4 | 545(45) | 155(60) | | 2.9(6) | | |
| | 56Fe | | 545(54) | 167(22) | | 3.3(5) | | |
| | 57Fe | | 638(35) | 164(25) | | 3.7(4) | | |
| | 58Fe | | 2017(203) | -115(115) | | 4.1(10) | | |

F. J. Hartmann et al., Phys. Rev. C **65**, 014306 (2001)

A. Trzcinska et al, Nucl. Phys. A **692,** 176-181 (2001)

# Conclusions

- The precise knowledge of antinucleon scattering length has potential of revolutionize the sensitivity of the neutron-antineutron oscillation search
- The optical potential model of antinucleon-nucleus has sufficient precision (~1%) to be applied to the above purpose, but lacks full experimental verification
- Proposed possibilities of experimental/theoretical studies focusing

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***Thank you for your attention!***