Experimental Investigation of Pontecorvo Reactions in $^3$He Using a Simplified Apparatus

Luca Venturelli
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On behalf of the ASACUSA Collaboration

FuPhy 2024
Future Nuclear and Hadronic Physics at the CERN-AD
SMI Vienna, Apr. 8-10, 2024
Pontecorvo reactions

*Their existence was suggested by Pontecorvo in 1956 (only a few months after the antiproton discovery at Bevatron)*

Pontecorvo reactions are (rare): antinucleon annihilations forbidden on a free nucleon but allowed on nucleons bound in nuclei

For antiproton annihilations at rest:

<table>
<thead>
<tr>
<th>TARGET</th>
<th>USUAL ANNIHILATIONS</th>
<th>B.R. ≈ 100%</th>
<th>PONTECORVO REACTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>H&lt;sub&gt;2&lt;/sub&gt;</td>
<td>$\bar{p} \rightarrow p$, mesons</td>
<td>meson number ≥ 2</td>
<td>$\bar{p} \rightarrow p$, mesons (π&lt;sup&gt;−&lt;/sup&gt;, π&lt;sup&gt;0&lt;/sup&gt;, K&lt;sup&gt;0&lt;/sup&gt;, ω, ρ, φ,...)</td>
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<td>$\bar{p} \rightarrow ^3$He, meson number = 0</td>
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L.Venturelli – Pontecorvo reactions - FuPhy2024
Interest on Pontecorvo reactions

- Pontecorvo reactions are **sensitive to the small internucleon separations** in nuclei, can provide info on **dynamics between nucleons** in nuclei

2 main theoretical approaches

- **Rescattering model**
  - Example of rearrangement
    - $\bar{p}^3\text{He} \rightarrow n \ p$
    - $\bar{p} d \rightarrow \pi^- p$
  - 2-step model: antiproton annihilates on proton and the (virtual) $\pi^+$ is absorbed by neutron

- **Fireball model**
  - Compound system ('fireball') formed by the 3 antiquarks and 6 quarks decaying statistically
  - Different predictions between the 2 models

B.R. $10^{-8}$ - $10^{-7}$

B.R. $10^{-6}$

Example of rearrangement
Existing data

- First measurements (6 events) in bubble chambers in the 1960s
- Preliminary measurements at LEAR by Asterix

**Pontecorvo reactions were systematically measured at rest in deuterium at LEAR(CERN)**

by Crystal Barrel and OBELIX in 1990s

B.R. \(\approx 10^{-6} - 10^{-5}\)

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- also data from KEK (Chiba et al., PRD 1997)

\[B(\bar{p}d \rightarrow \pi^0 n) = (1.03 \pm 0.41) \times 10^{-5}\],
\[B(\bar{p}d \rightarrow \pi^0 \Delta^0) = (4.67 \pm 1.66) \times 10^{-5}\],
\[B(\bar{p}d \rightarrow \eta n) < 8.94 \times 10^{-6}\] (95% C.L.), and
\[B(\bar{p}d \rightarrow \eta \Delta^0) < 6.40 \times 10^{-5}\] (95% C.L.)
More in-depth on existing data

The data from Crystal Barrel and OBELIX are in agreement (when they can be compared)

Pontecorvo reactions measured at LEAR in liquid deuterium and in gas

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- **good agreement**, assuming charge independence
- **good agreement**, assuming isospin invariance
More in-depth on existing data

Theoretical models are not always in agreement

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The 2 theoretical models agree well with the ratio of these B.R.s

The rescattering model agrees well with the ratio of these B.R.s

These B.R.s are in good agreement with the fireball model and in disagreement with the rescattering model.
More in-depth on existing data

The data from Crystal Barrel and OBELIX are in agreement

(when they can be compared)

Theoretical models are not always in agreement

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More experimental data could help...

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(Non-)existing data

- Pontecorvo annihilations on three nucleons have never been measured

\[ \bar{p} \, ^3\text{He} \rightarrow n \, p \quad \text{or} \quad \bar{p} \, ^3\text{H} \rightarrow n \, n \]

Interest: different models predict different rates (by 1-2 orders of magnitude)

- Rescattering model
  - B.R. $10^{-8} - 10^{-7}$

- Fireball model
  - B.R. $10^{-6}$
\[ \overline{p} \, ^3\text{He} \rightarrow n \, p \] measurement in ASACUSA

ASACUSA is studying the possibility of measuring \[ \overline{p} \, ^3\text{He} \rightarrow n \, p \]

Difficulties:
- Need of a DC antiproton beam
- Pontecorvo reactions are rare processes (B.R. = \(10^{-5} - 10^{-8}\))
- Background

Measurement at rest in \(^3\text{He}\) can be performed by the ASACUSA collaboration

2 options:

1) using the DC slow antiprotons from the new **secondary line in ASACUSA**

or

2) using the antiprotons from **ELENA modified** to deliver a DC beam

ASACUSA at CERN-AD
- antiprotonic helium atoms with laser spectroscopy to test CPT
- antihydrogen ground-state hyperfine structure to test CPT
- atomic and nuclear collision cross sections of antiprotons at low energies
1) using the DC slow antiprotons from the new secondary line in ASACUSA

The antiproton trap, MUSASHI, can deliver a DC-like beam of antiproton

In MUSASHI: 2 x 10^6 antiprotons captured, cooled and trapped for each ELENA shot (7 x 10^6 antiprotons)

**DC extraction**: (expected in the target) 10^5 antiprotons/100 s cycle @250 eV → 1000 $\bar{p}$/s

1 μm window of the cryogenic $^3$He target requires **re-acceleration** to at least 100 keV

... antiprotons decelerated and then re-accelerated 🤔
2) using the antiprotons from ELENA modified to deliver a DC beam

**AD-ELENA**

The only low-energy $\bar{p}$ source

AD: 5.3 MeV **pulsed** beam: $3 \times 10^7 \bar{p}$ every ~ 100 s

ELENA: 5.3 MeV $\rightarrow$ 100 keV
4 experiments run in parallel (24h/day)

ELENA could be modified to have a **slow extracted** (DC) antiproton beam at 100 keV

(expected in the target) $4-6 \times 10^4 \bar{p}/s$ x 10-100 better than with MUSASHI

... and no need to re-accelerate

see Davide Gamba’s talk
Typical apparatus for Pontecorvo reactions is a magnetic spectrometer

Made of:
- Magnet
- Tracking detector (drift chambers, ...)
- T.o.F. system
- e.m. calorimeter

Features:
- reconstruct the trajectories of (all) the particles
- Determine their energy-momentum $\rightarrow$ PID
- Determine missing mass

is it possible to use a simpler apparatus?
Goal: Design a “simple” apparatus to measure the B.R. of $\bar{p}^3\text{He} \rightarrow n p$

The idea is to use:

- **an efficient detector for 1 GeV neutron**
  - Thick plastic scintillators

- **a highly efficient veto system** mainly for other neutral particles (especially $\gamma$’s from $\pi^0$’s)
  - Sandwich of Pb layers & plastic scintillators

The design is driven by Monte Carlo simulations with GEANT4
Cube-like geometry with only 4 faces (2/3 $4\pi$ solid angle)

- Neutron detector (plastic scintillators)
- Veto system
- Inner scintillator ($4\pi \Omega$)
- Sandwich of Pb layers & plastic scintillators
- $^3$He target

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Geometry

Neutron detector and veto system are segmented

gaseous $^3$He target (radius = 5 cm)
Target Al vessel thickness = 0.32 mm
Inner cube length = 10 cm

Veto system: sandwich of scintillators & Pb layres

- # of scintillator layers = 12
- scintillator layer thickness = 6 mm
- # of Pb layers = 10
- Pb layer thickness = 6 mm

Neutron scintillator detector

- # of layers = 3
- layer thickness = 15 cm

# of electronic readout channels = 9762
Topology-based event selection

Applied selection to acquire $\bar{p}^3\text{He} \rightarrow n + p$
and to reject BKG

- Only 1 hit on the first scintillator layer of veto
  ("proton" signal)

- A signal in the neutron detector behind the red hit
  $\theta_1 < 10^\circ$ ("fast proton" signal)
  to reject the spectator proton

AND

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Topology-based event selection

Applied selection to acquire $\bar{p}^3\text{He} \rightarrow n + p$

and to reject BKG

- Only 1 hit on the first scintillator layer of veto

  (“proton” signal)

  AND

- A signal in the neutron detector behind the red hit

  $\phi_1 < 10^\circ$ ("fast proton" signal)

  to reject the spectator proton

  AND

- A signal in the neutron detector in the opposite direction

  $\phi_2 < 10^\circ$ ("neutron" signal)

  AND

- No signal in the veto system far from the

  “proton” $\phi_3 < 300^\circ$ (no other particle)
Monte Carlo results

**SIGNAL**

\[ \bar{p} \ ^3\text{He} \rightarrow n + p \]

Detection efficiency for Pontecorvo reaction is 11%.

**BACKGROUND**

Selected Geant4 Physics list: FTFP_BERT_HP + STD + HP. It uses quark gluon string model for high energy interactions.

For annihilations at rest B.R. values expected to be not very realistic.

\[ \# \text{ of generated } \bar{p} ^3\text{He} \text{ annihilations} = 1.8 \times 10^8 \]

\[ \# \text{ of fake Pontecorvo events} = 2 \]

no BKG events for other reactions (not in GEANT4):

- Another Pontecorvo reaction: \( \bar{p} ^3\text{He} \rightarrow d \, \pi^0 \)

- Semi-Pontecorvo reactions (antiproton annihilates on a correlated (pn) pair in \(^3\text{He})):

  e.g. \( \bar{p} ^3\text{He} \rightarrow \pi^- \, p \, p \) \( \bar{p} \ll d \gg \rightarrow \pi^- \, p \) \( \ll d \gg \) quasi-deuteron.
Monte Carlo results

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\[ \bar{p}^3\text{He} \rightarrow \pi \]

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**Validation of the GEANT4 simulations**

Experimental data are needed to validate the GEANT4 simulations of high-energy neutrons
Detection efficiency of a plastic scintillator for 1 GeV neutron can be measured at the n_TOF facility at CERN
Rate estimate in ASACUSA

To measure in ASACUSA: antiproton acceleration (100 keV?)

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<th>similar results in (^3)H</th>
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<td>Antiprotons (from MUSASHI)</td>
<td>(10^5/\text{spill} = 10^5 / 115\text{s})</td>
<td>(but safety issues)</td>
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<td># of ELENA spills for 1 Pontecorvo event</td>
<td>90 spills = 3 h</td>
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N.B. also acquire data of antiproton annihilations in hydrogen → useful to study the BKG

\[\text{x } 10-100 \text{ better with a DC beam from ELENA}\]
Other options

Consider the following options:

• Reduce the material

Present configuration:
Cube-like geometry with 4 faces (2/3 $4\pi$ solid angle)
Inner cube length = 10 cm  Outer cube length = 136 cm

Stuff:
165 kg of Pb
20 kg of veto scintillators
1500 kg of neutron detector scintillators

• Reduce the segmentation/number of electronic readout channels

number of electronic readout channels = 9800

• veto system: use crystals instead of lead and scintillator

(In principle more expensive but it could be possible to recycle a dismissed calorimeter from completed experiments)
Conclusions

On paper, an apparatus with only scintillator detectors seems to work

Pros: the apparatus is relatively cheap, not difficult to build and to maintain

but ...

no PID
not multipurpose: no other measurements can be performed

Consider a totally different scenario: → use a magnetic spectrometer

Pros:
- PID implemented
- multipurpose apparatus → different measurements are possible:
  • In the same data sample other reactions can be studied
    (included the search of the sexaquark $S$)
  • Using a H$_2$ target, the e.m. proton form factor in the time-like region (B.R. $10^{-7}$) could be measured

Cons:
- expensive
- many expert groups should be involved

The apparatus has to be optimized

see the talks by Glennys Farrar and Michael Doser

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Thank you very much for your attention

Short reviews:

C. Amsler, arXiv 1908.08455 (2019)

Credits: