The Discovery of Weak Neutral Currents

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Brief chronology

1963 conceived as large
2nd generation bubble chamber
geometry $R=1\text{m}$ $L=4.8\text{m}$
heavy liquid ($CF_3\text{Br}$ and $C_3H_8$)
good identification of final state
1970 installed at CERN
1971 first run in $WB$ $\nu$ and $\bar{\nu}$-beams
1973 discovery of NC
1978 break down (crack)
A Historic Moment

End of 1971: M.K. Gaillard, B. Zumino, J. Prentki, C. Bouchiat,
M. Veltman approach Gargamelle and Weinberg HPW

1. Weinberg: There is a model combining leptonic weak and
   electromagnetic interactions based on the
gauge symmetry $\text{SU}(2) \times \text{U}(1)$
2. 't Hooft: this model is renormalizable
3. The key element: weak neutral currents

Request: look for $\nu + e \rightarrow \bar{\nu} + e$ and $\nu + N \rightarrow \nu + X$!
Two Detectors

Gargamelle at CERN PS

- Heavy Liquid Bubble Chamber
- Magnet Coil and iron yoke
- Thick iron Shielding

E-1A at NAL PS

- Liquid Scintillation Calorimeter
- Magnetic Iron Spectrometer
GARGAMELLE

- Approved 1970
  priority: nucleon structure
- Data taking 1971/2
- Heavy liquid bubble chamber
  strong magnet coils, shielding
- CERN PS Booster 24 GeV
- WB hornfocussed ν and ¯ν
  beams 1-10 GeV
- Record everything

E-1A  HPW

- Approved 1970
  priority: W search
- Data taking end 1972+spring 73
- Target calorimeter + muon
  spectrometer
- NAL PS 200/300 GeV
- WB beam mixed ν and ¯ν
  10-200 GeV
- Set trigger to select interesting
  events

Note: Excellent research topics – but not Neutral Currents!
Sudden change of priority to NC search in 1972
Searching for a new effect

1. Define signature of candidates for the new effect
2. Investigate all processes simulating this signature
   *all* means in practice *all known*

Claim a discovery if

# signal $\gg$ # background
E-1A

Signal

Need two independent triggers: energy deposition and no muon

Background

CC events with wide angle muon escaping
No worry about punch through
Scanning rules were setup before experiment started

- **Class A**: events with muon candidate
- **Class B**: events with identified hadrons
- **Class C**: one or more protons
- **Class D**: only electrons and positrons

\( \nu \)-induced events are in class A.
\n\( n \)-induced events are in class A, if a charged final state hadron fakes a muon
\n\( n \)-induced events are in class B, if final state particles are identified as hadrons

- Class B serves to estimate the unavoidable neutron background in class A

**The challenge**: Are there \( \nu \)-induced events **without** muon in the final state?  
**If so**, they are already in **class B**: start NC search without delay
An exciting leptonic NC candidate

360000 pictures scanned
Isolated forward e found at Aachen in Dec 1972.

Interpretation:

\[ \overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e \]

Properties of electron:

- **Identification**: unique by bremsstrahlung and curling
- **Energy**: 385±100 MeV
- **Angle**: 1.4 ± 1.4 degree

**Background**: 0.03 ±0.02

\[ \nu_e n \rightarrow e + p \]
*(proton invisible)*
An early NC candidate

- 3-prong event
- very clean
- no muon
- total visible energy about 6 GeV
The March 1973 Meeting
Euphory and Doubts

**Euphory**

- The unique $\bar{\nu}e$-candidate
- Many candidates without $\mu$
- Subsample of CC events ignoring the $\mu$ and imposing the same criteria on hadrons

**Expected** shape of distribution along chamber axis:

1. If NC candidates $n$-induced, then exponential falloff
2. If NC candidates $\nu$-induced, then flat distribution
3. The CC-subsample flat

**Distinctive features:**

- $n$: exponential falloff ($\lambda \ll L$)
- $\nu$: everywhere flat ($\lambda \gg L$)
The Data

- Compare hadron final state of NC with CC (no $\mu$) and form NC/CC
  $X=\text{along beam direction}$
  $R=\text{radial}$
- **NC = $\nu$- or n-induced?**
- 3 arguments favour $\nu$-origin
  - NC/CC is flat and big
  - NC look $\nu$-like
  - NC do not look n-like
- Oversimplified ORSAY Monte Carlo disfavours neutrons

*A discovery at hand?*
Damped Euphory

Two critical arguments
• Neutrons make cascades
  → n-background ~ cascade length
  ORSAY MC underestimates neutrons
• Broad neutrino beam generates neutrons from sides → appearing as flat distribution (sensitive to energy and angular distribution of neutrons)

Conclusion
• No distinctive feature left
• n-background may be dangerously big
• Dilemma: HPW may publish first
  ↔ n-background underestimated
• Decide for absolute prediction of neutron background including cascade and detailed geometry

The setup in terms of interaction lengths
• The chamber is embedded in heavy material
• #ν events ~ λ
• Huge number of ν-interactions outside the chamber
Neutron Background Calculation

**Ingredients**

- Matter distribution
- Neutrino flux
- Dynamics of final hadron state
- Evolution of hadrons in matter
- Complicated, but known
- Measured
- From v-events
- Need cascade model

**Cascade Model**: start March – ready beginning of July 1973

- At first hopeless: short time and complexity
- Breakthrough: cascade only transported by nucleon (>1 GeV)
- Linear problem: need only the energy loss per collision
- Elasticity distribution has been extracted from pp-data

**Conclusion**: Absolute prediction of neutron background

*no free parameter*
Appearance of neutron interactions

**B-event:**
ν-interaction upstream in shielding
Observe in chamber the **end** of the neutron-cascade

**AS-event:**
ν-interaction inside chamber
Observe in chamber the **beginning** of the neutron-cascade

**Predict B/AS:**
optimal use of data
model dependence reduced (except for cascade effect)
The Proof

Beginning of July 1973: 102 NC candidates in $\nu$-film and 15 AS

Worst case hypothesis: All NC are background

\[
\frac{B}{AS} = \frac{NC}{AS} = \frac{102}{15}
\]

Cascade program predicts:

\[
\frac{B}{AS} = 1 \pm 0.3
\]

Similarly for antineutrino data

Hypothesis must be rejected: a new effect exists

Internal Method

**Idea:** Reconstruct for each event the flight direction from vector sum of final state hadrons
Then apply classical Bartlett method to obtain the apparent interaction length

<table>
<thead>
<tr>
<th>Beam</th>
<th>$1/\lambda$ for NC</th>
<th>$1/\lambda$ for CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$</td>
<td>$0.16 \pm 0.10 \text{ m}^{-1}$</td>
<td>$0.15 \pm 0.10 \text{ m}^{-1}$</td>
</tr>
<tr>
<td>$\bar{\nu}$</td>
<td>$0.27 \pm 0.13 \text{ m}^{-1}$</td>
<td>$0.10 \pm 0.10 \text{ m}^{-1}$</td>
</tr>
</tbody>
</table>

Probability distribution:

$$\varphi(x)dx = \frac{e^{-x/\lambda}}{1 - e^{-L/\lambda}} \frac{dx}{\lambda}$$

Measure: flight and potential paths $x$ and $L$
for each event
Max Likelihood-fit to NC and CC samples

**Conclusion:** $1/\lambda(\text{NC}) \ll 1/\lambda(n)$
The Authors of the Discovery Papers

Deceased: Lagarrigue, Rousset, Musset, Rollier, Faissner, Schultze, Lanske, Nguyen-Khac, Camerini, Fry, Wachtshmu, Natali, Bullock, Violette Brisson
For the first time high energy neutrino physics included → from now on Lepton-Photon Conference

GGM presentation of results on weak neutral currents
1. The published Gargamelle analysis
2. Include last minute contribution from HPW
   (based on analysis submitted to PRL in May 1973)
3. Contribution from Argonne 12 ft BC: exclusive 1-pion channel
4. First attempt to compare with theory: \( \sin^2 \theta \approx 0.3 \)

C.N.Yang announces at the end of the conference: NC exist
The Hot Fall

- Prominent physicists disbelieve the Gargamelle analysis: "You have rediscovered the neutron!"
- GGM had anticipated all their arguments and rejected them firmly
- Bad stroke: HPW runs with modified detector: NC effect disappeared
- The CERN Directorate got worried
- Instead of doubting HPW Gargamelle was blamed to be wrong!
- General suspicion: GGM is wrong because of error in treating neutrons
- Way out: YES or NO by special exposure of Gargamelle with proton pulses to test explicitly the neutron cascade

Modified HPW-detector

Introduce 13’ iron plate (red): increase muon acceptance
fatal consequence: punchthrough NC misidentified as CC
thus: loose NC effect
HPW Publication History

- July 17, 1973
  Rubbia informs Lagarrigue: 100 NC events
- August 3, 1973
  Submitted to PRL
  Also submitted to Bonn Conference
- September 14, 1973
  Slightly revised
- Collaboration decides to postpone and wait for more data with modified detector
- November 13, 1973
  HPW informs Lagarrigue about absence of NC
- February 25, 1974
  New paper submitted to PRL
- April 1974
  Published in PRL 32 (1974) 800
  Existence of neutral currents confirmed
Cascades really exist

- Event from the special exposure of Gargamelle in Nov/Dec 1973
- A proton of 7 GeV is entering and generating (event 3241 671 view2)
- A neutron cascade
- The measurement of the first interaction gives the apparent interaction length of the chamber liquid
- Similarly the last interaction with energy deposition exceeding 1 GeV gives the effective cascade length
Check the Background Calculation

- Special runs in Nov+Dec 1973 anticipate what should be observed
- Gargamelle exposed to fast extracted proton pulses of 4, 7, 12 and 19 GeV
- Measure apparent interaction length in chamber
- Measure cascade length
- Compare with prediction of neutron program (dotted lines)
- Reported to APS Meeting Washington (April 1974)

All aspects of the cascade program are confirmed
Spring 1974 : The Happy End

1. Gargamelle
   - Double statistics – good consistency
   - Neutron background accounts for only 10% of the candidates
     proven by absolute calculation and backed up by internal method
     cascade effect is experimentally confirmed

2. HPW confirms finally muonless events (the alternating currents)

3. ANL : 12’ BC exclusive \( n \pi^+ \) and \( p \pi^0 \) production

4. CITF : new experiment at NAL in narrow band \( \nu \) and \( \bar{\nu} \)
   - new method: event length

The existence of weak neutral currents is finally accepted
The Impact of the Discovery

- All major laboratories define a long range research program to explore the new force
- Two immediate applications
  1. Gravitational collapse
     \[ W \rightarrow e\nu \text{ also } Z \rightarrow \nu\nu \ (e, \mu, \tau) \]
  2. Predict W- and Z-masses
     \[ M_W = \frac{\sqrt{\frac{\pi \alpha}{\sqrt{2} G}}}{\sin \theta} = \frac{37.3 \text{ GeV}}{\sin \theta} \approx 70 \text{ GeV} \]
     Propose \( \bar{p}p \) experiment
     CERN collider

- Start the electroweak way: weak and electromagnetic forces are on equal footing
- Breakthrough to gauge theories
  radiative effects
  nonabelian nature
- Develop and test models
- Push frontiers in energy \( \rightarrow \) new colliders
  precision \( \rightarrow \) large calorimeters
- Large collaborations
- Computing
Epilog

• Gargamelle was an excellent collaboration with an excellent pioneering spirit
• It was an exciting time seeing the huge progress of electroweak physics and QCD
• It was my first *large collaboration*, though small in today’s standard
• It was a life without email, without ready-to-use computer codes, without laptop, but punching cards, handwritten slides,…

It was an honour for me to have been a member of Gargamelle and to feel the responsibility in a discovery situation