NEUTRINO-NUCLEUS INTERACTIONS

By: Deepti Hariharan

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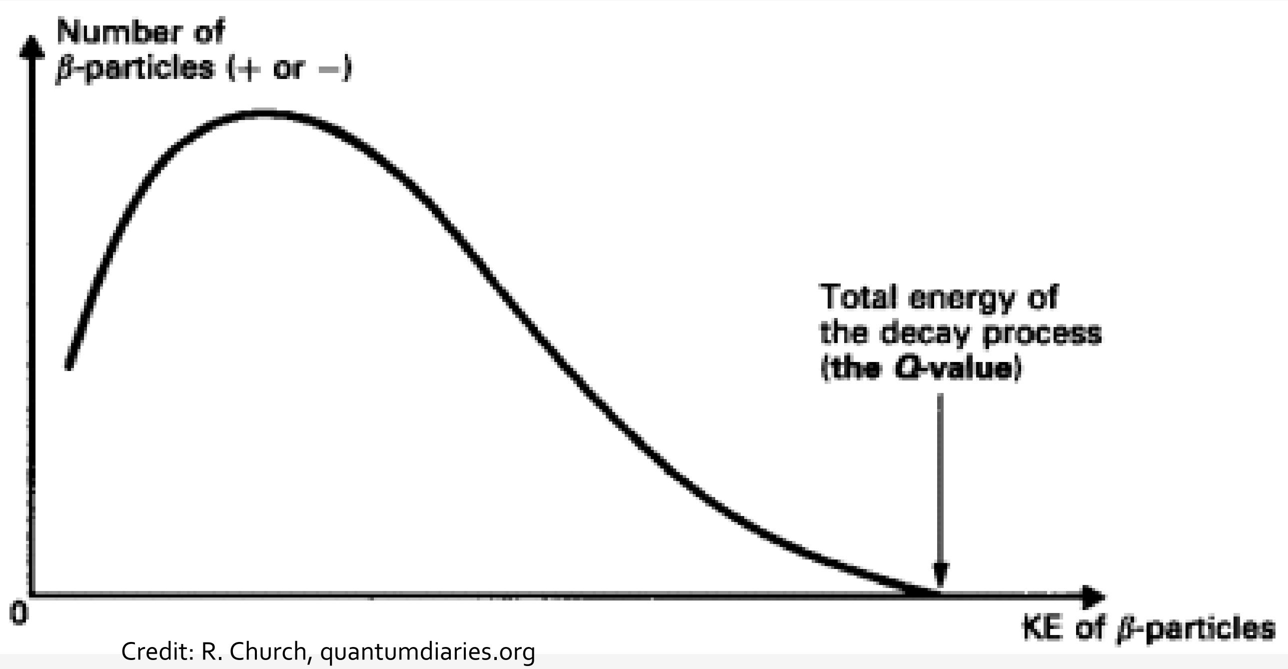
B.Sc. Physics III year

Department of Physics and Nanotechnology

Guide: Dr. Rohit Dhir

A Brief History of Neutrinos

- Hypothesized by Pauli to account for the continuous shape of the β spectrum.



Credit: R. Church, quantumdiaries.org

- Confirmed in the Cowan-Reines neutrino experiment:

$$\bar{\nu}_e + p^+ \rightarrow n^0 + \mathrm{e}^+$$

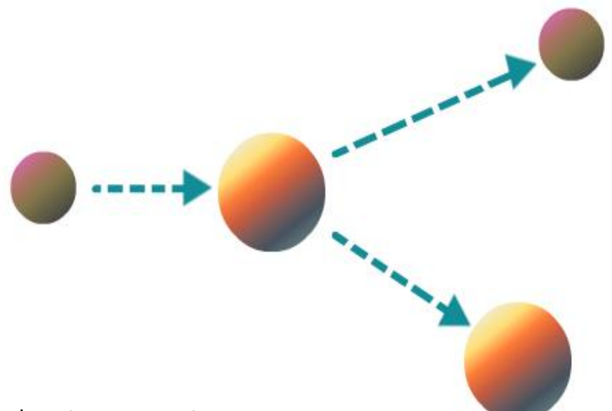
- The μ and τ neutrinos were later discovered.

Types of Scattering

Elastic

Kinetic energy and momentum conserved.

Nucleus acquires momentum and moves.



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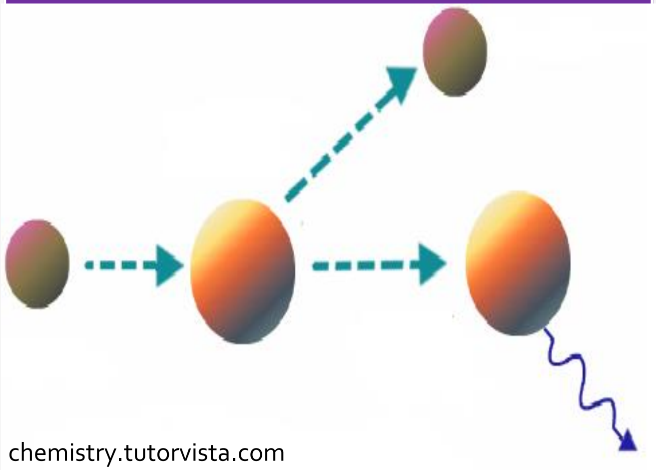
Inelastic

Kinetic energy not conserved, momentum conserved.

Nucleus is excited.



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Quasi-elastic

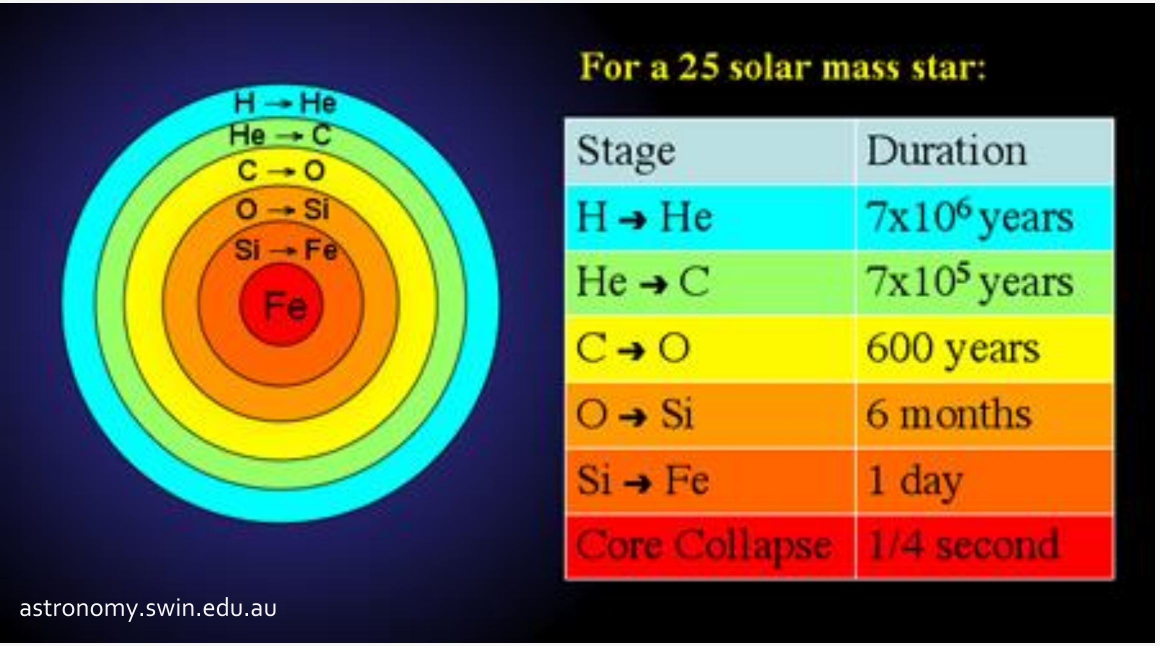
Limiting case of inelastic scattering – transfer of energy from incident particle is very small.

Nucleus is excited.

Supernova Core-Collapse

A supernova is the explosion marking the end of a massive star(>10$M_\odot$).

- Fusion process:
  - Hydrogen burns out and fusion slows down.
  - The star gravitationally collapses.
  - Contraction leads to rise in temperature.
  - Helium fuses into carbon and progressively to higher elements.
  - Iron is a highly stable nucleus and cannot undergo further fusion.
  - Unstable star collapses further.



Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

Neutrino Release

- γ rays are produced which disintegrate iron nucleus to lighter nuclei.
- When M_{star} > Chandrasekhar mass limit (~1.4$M_\odot$):

$$p^{+} + e^{-} \rightarrow n^{0} + \nu_{e}$$

- Further release of energy in the form of energetic neutrinos and antineutrinos.
- Energy of these supernova neutrinos is ~25 MeV.
- The neutrinos escape the core.
- They interact with the nuclei present on the way out – mainly C, O, He, H.

Image Credit: NASA/Maria-Jose Viñas

Area of Work

Study of interactions of low energy neutrinos with light nuclei to help understand the core-collapse event of supernovae.

Scope of Project

- Determining properties like mass and studying neutrino oscillations.
- Solar neutrinos help understand reactions happening in the sun and other stars.
- Understanding the underlying mechanism of supernova core-collapse event.
- The Cosmic Neutrino Background (CνB) gives an insight into the early universe.

References

- Measurement of γ-rays from Giant Resonances of ^{16}O and ^{12}C with Application to Supernova Neutrino Detection, *JPS Conf. Proc. , 010048 (2016)*
- Analysis of γ-ray Production in Neutral-Current Neutrino-Oxygen Interactions at Energies above 200MeV, *PRL 108, 052505 (2012)*
- Signal for Supernova ν_μ and ν_τ Neutrinos in Water Cherenkov Detectors, *0031-9007/96/76(15)/2629(4)*
- Inelastic Neutrino-Nucleus Interactions within the Spectral Function Formalism, *PRL 118, 142502 (2017)*
- Introductory Nuclear Physics – Chapter 9, 11, *K.S. Krane*
- Particle Physics – Chapter 2, *B.R. Martin and G. Shaw*

THANK YOU

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MODES OF DECAY

$$p + {}^{12}C \rightarrow p' + {}^{12}C^*$$

- Electromagnetic (Direct) Decay – decay by emission of radiation (γ-rays):

$$ {}^{12}C^* \rightarrow {}^{12}C + \gamma $$

- Hadronic Decay – decay to a nucleus by release of particle:

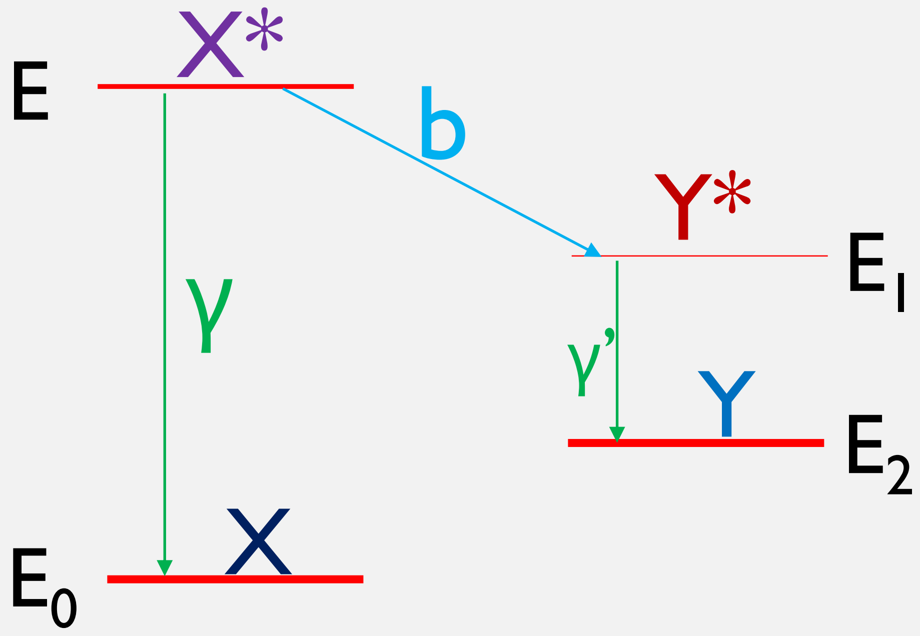
$$ {}^{12}C^* \rightarrow p + {}^{11}B $$

$$ {}^{12}C^* \rightarrow n + {}^{11}C $$

$$ {}^{12}C^* \rightarrow t + {}^{9}B $$

$$ {}^{12}C^* \rightarrow d + {}^{10}B $$

$$ {}^{12}C^* \rightarrow \alpha + {}^{8}Be $$



OPTICAL POTENTIAL MODEL

- Analogous to refraction in optics.
- Real part of potential gives the elastic scattering and the imaginary part takes into account the absorption (inelastic scattering).

$$U = V + i\,W$$

V represents a nuclear shell model potential.

i W gives the absorption effects of the nucleus.

The spin-orbit terms and the Coulombic potentials have to be added for more accuracy:

$$U(r) = U_R(r) + U_{V.A}(r) + U_{S.A}(r) + U_S(r) + U_C(r)$$

- $U_R(r)$ gives the real potential accounting for the elastic scattering:

$$U_R(r) \propto -V\, f(r, R, a)$$

  It represents a potential well of depth V.

- $U_{V.A}(r)$ and $U_{S.A}(r)$ gives the absorption effect in the nucleus.

- $U_S(r)$ is the spin-orbit interaction term which gives the polarization effect:

$$U_S(r) \propto \boldsymbol{s} \cdot \boldsymbol{l}\, V_S \frac{1}{r} \frac{d}{dr} f(r, R_S, a_s)$$

- $U_C(r)$ is the Coulombic potential:

$$U_C(r) \propto \frac{Z_1 Z_2 e^2}{R_C}$$

Here, the form factor, f(r, R, a) is of the form:

$$f(r, R, a) \propto \frac{1}{1 + e^{\frac{r - R}{a}}}$$

The optical model is especially useful for calculating the energy averaged cross section for oscillations with large width and where compound nuclear reactions are significant.

FORM FACTOR

The form factor ‘f(r, R, a)’ can be found in two ways:

- Theoretical calculations
- Experiments

Experiment:

The gamma ray from the reactions are analyzed to obtain the decay width.

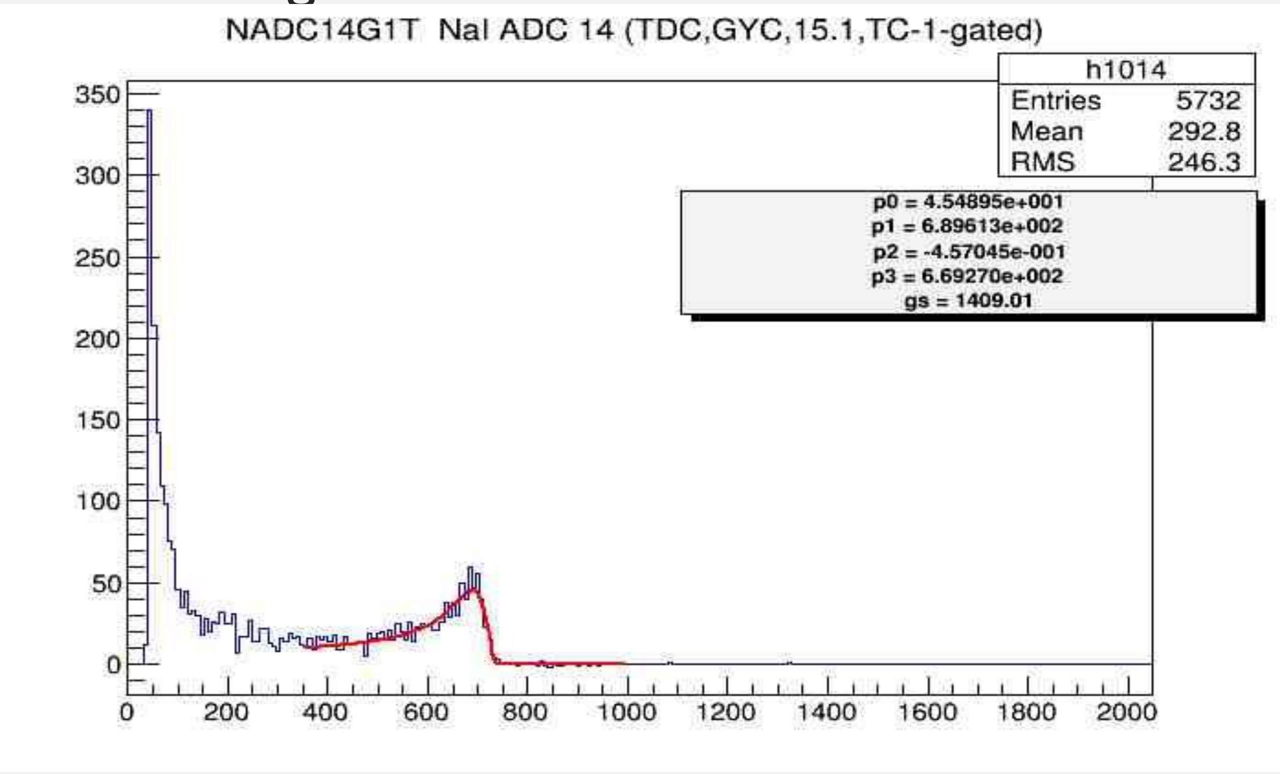
First, the gain must be calibrated and stabilized.

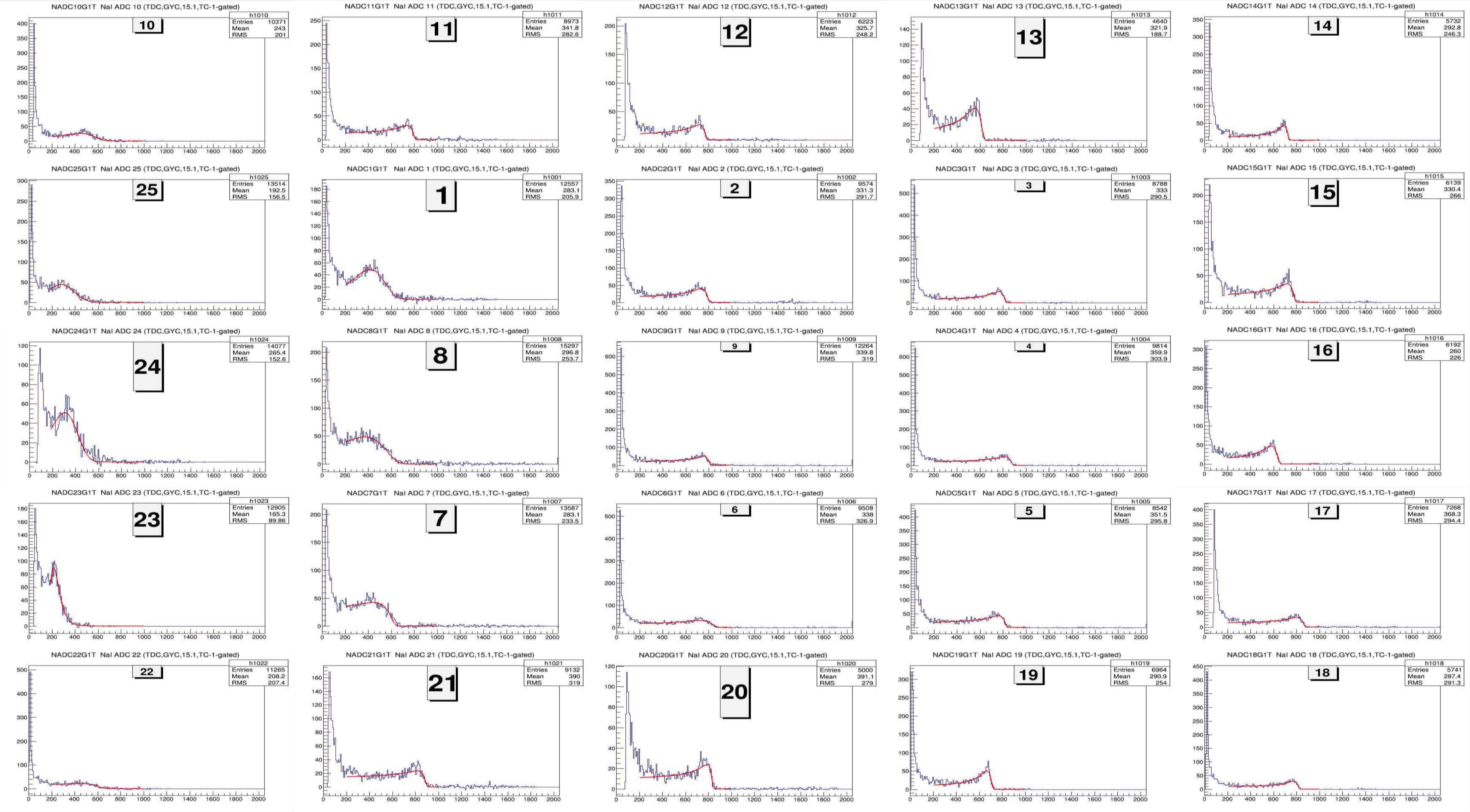
EXPERIMENTAL ANALYSIS OF γ-RAYS

- The γ-ray spectrum from the experiment was fitted using asymmetric gaussian

$$f(x) = p_0 e^{-\frac{(x-p_1)^2}{2\sigma^2}}$$

where $\sigma = p_2(x + p_1) + p_3$

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10
h1010
Entries 10371
Mean 243
RMS 201
NADC11G1T NaI ADC 11 (TDC,GYC,15.1,TC-1-gated)
11
h1011
Entries 8973
Mean 341.8
RMS 282.6
NADC12G1T NaI ADC 12 (TDC,GYC,15.1,TC-1-gated)
12
h1012
Entries 6223
Mean 325.7
RMS 248.2
NADC13G1T NaI ADC 13 (TDC,GYC,15.1,TC-1-gated)
13
h1013
Entries 4640
Mean 321.9
RMS 188.7
NADC14G1T NaI ADC 14 (TDC,GYC,15.1,TC-1-gated)
14
h1014
Entries 5732
Mean 292.8
RMS 246.3
NADC25G1T NaI ADC 25 (TDC,GYC,15.1,TC-1-gated)
25
h1025
Entries 13514
Mean 192.5
RMS 156.5
NADC1G1T NaI ADC 1 (TDC,GYC,15.1,TC-1-gated)
1
h1001
Entries 12557
Mean 283.1
RMS 205.9
NADC2G1T NaI ADC 2 (TDC,GYC,15.1,TC-1-gated)
2
h1002
Entries 9574
Mean 331.3
RMS 291.7
NADC3G1T NaI ADC 3 (TDC,GYC,15.1,TC-1-gated)
3
h1003
Entries 8788
Mean 333
RMS 290.5
NADC15G1T NaI ADC 15 (TDC,GYC,15.1,TC-1-gated)
15
h1015
Entries 6139
Mean 330.4
RMS 266
NADC24G1T NaI ADC 24 (TDC,GYC,15.1,TC-1-gated)
24
h1024
Entries 14077
Mean 265.4
RMS 152.6
NADC8G1T NaI ADC 8 (TDC,GYC,15.1,TC-1-gated)
8
h1008
Entries 15297
Mean 296.8
RMS 253.7
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9
h1009
Entries 12264
Mean 339.8
RMS 319
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4
h1004
Entries 9814
Mean 359.9
RMS 303.9
NADC16G1T NaI ADC 16 (TDC,GYC,15.1,TC-1-gated)
16
h1016
Entries 6192
Mean 260
RMS 226
NADC23G1T NaI ADC 23 (TDC,GYC,15.1,TC-1-gated)
23
h1023
Entries 12905
Mean 165.3
RMS 89.86
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7
h1007
Entries 13587
Mean 283.1
RMS 233.5
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h1006
Entries 9508
Mean 338
RMS 326.9
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h1005
Entries 8542
Mean 351.5
RMS 295.8
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h1017
Entries 7268
Mean 368.3
RMS 294.4
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h1022
Entries 11265
Mean 208.2
RMS 207.4
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21
h1021
Entries 9132
Mean 390
RMS 319
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h1020
Entries 5000
Mean 391.1
RMS 279
NADC19G1T NaI ADC 19 (TDC,GYC,15.1,TC-1-gated)
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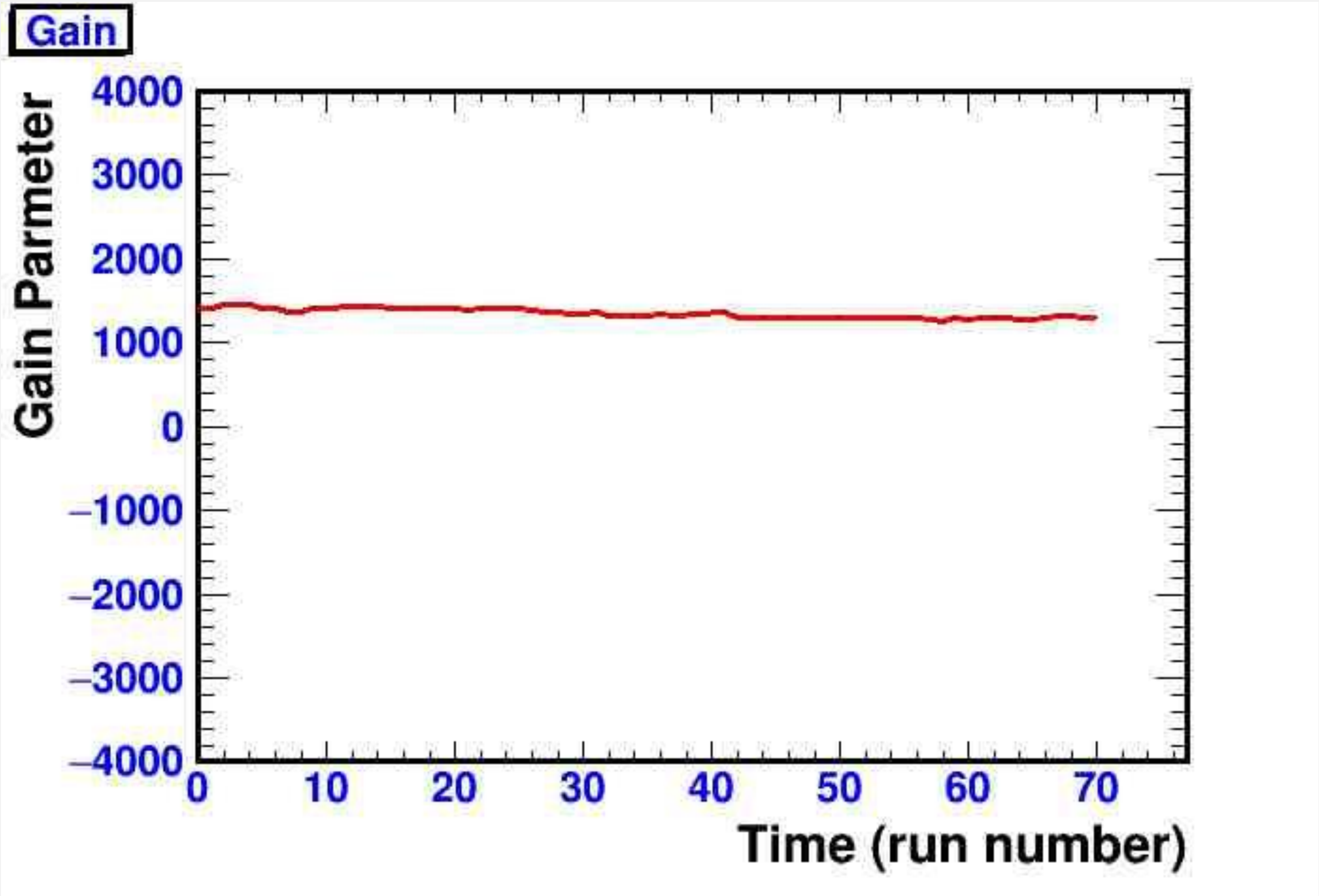
h1019
Entries 6964
Mean 290.9
RMS 254
NADC18G1T NaI ADC 18 (TDC,GYC,15.1,TC-1-gated)
18
h1018
Entries 5741
Mean 287.4
RMS 291.3

- Full width at half maximum gives the gain shift parameter defined as

$$g_s = p_1 + \sigma$$



CONCLUSION

- The gain calibration has been found.
- Next, energy calibration must be done and compared with the theoretical values.

THANK YOU

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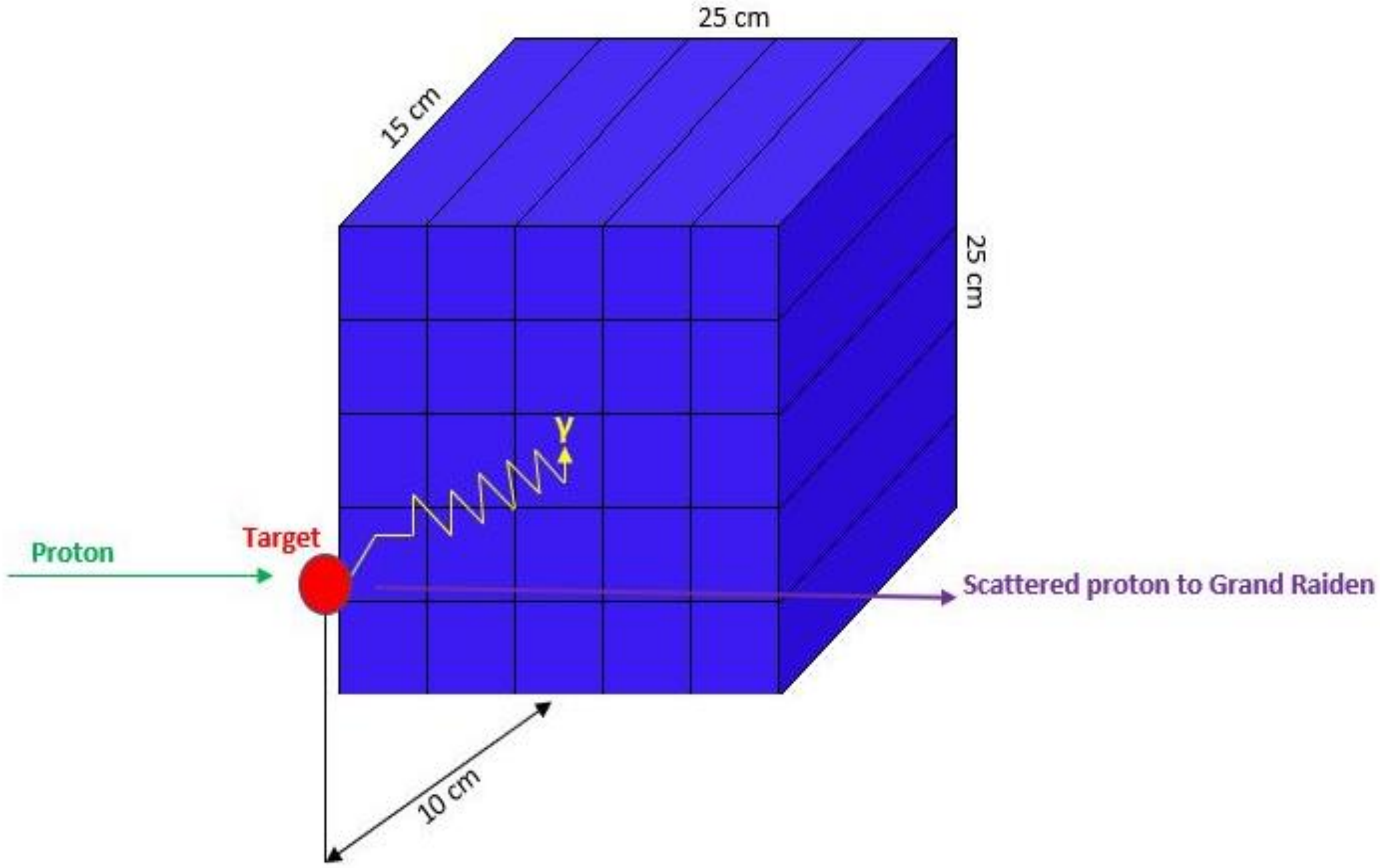
Experiment

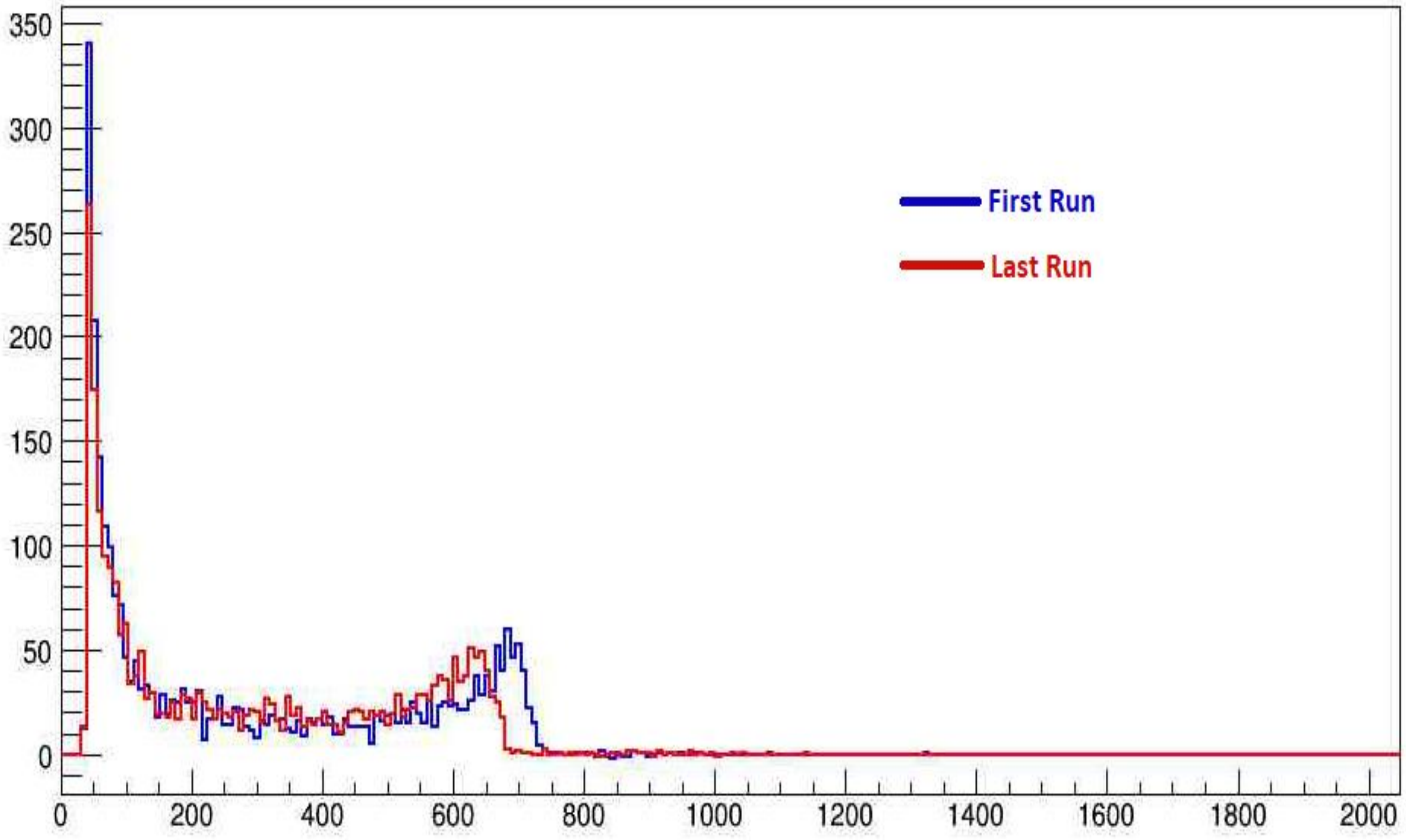
392 MeV proton beam is scattered off pure carbon and cellulose and measured by 25 NaI(Tl) counters to obtain systematic experimental data.

Proton beam excites ^{12}C and ^{16}O to giant resonant states.

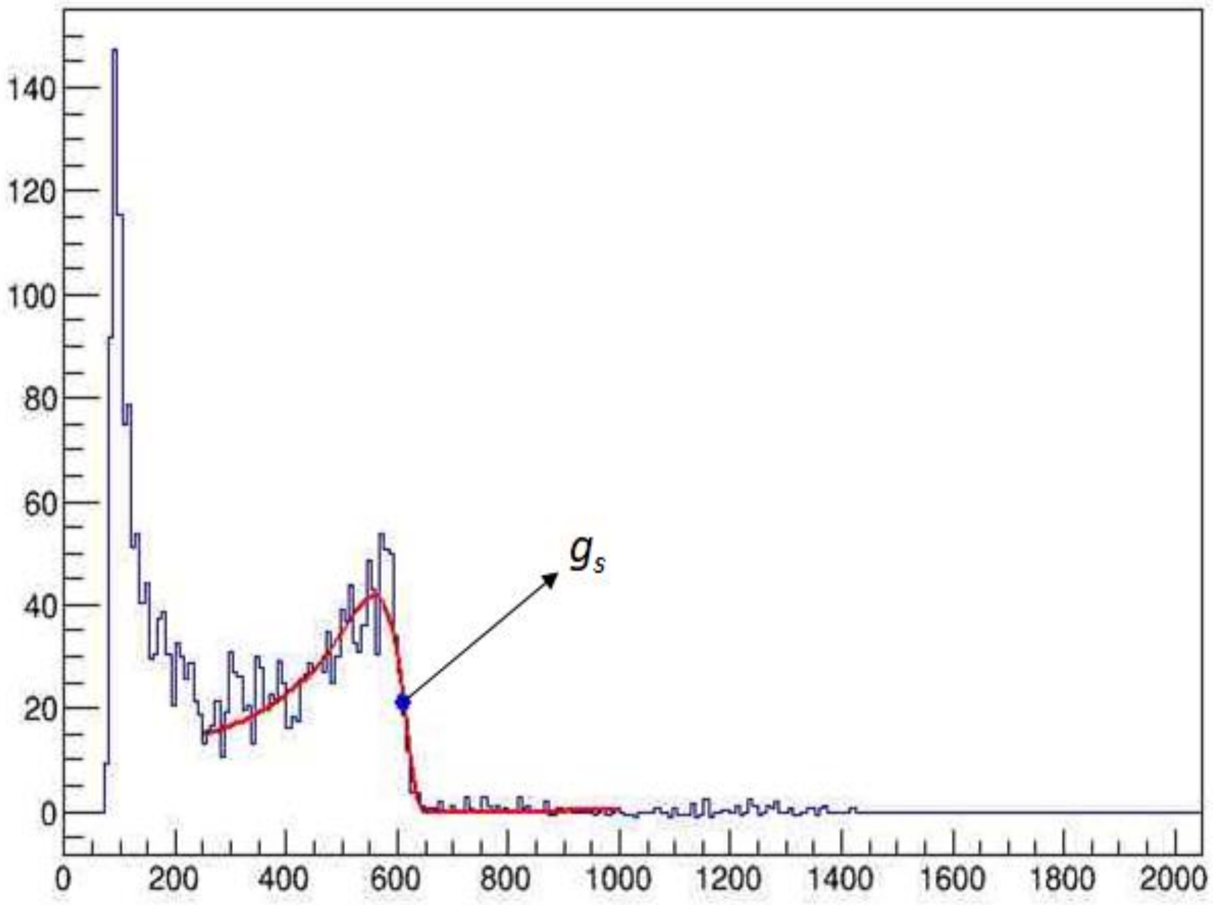


Gain Calibration

Gain calibration is done to correct the shift in gain value due to continuous radio-activation of counters.

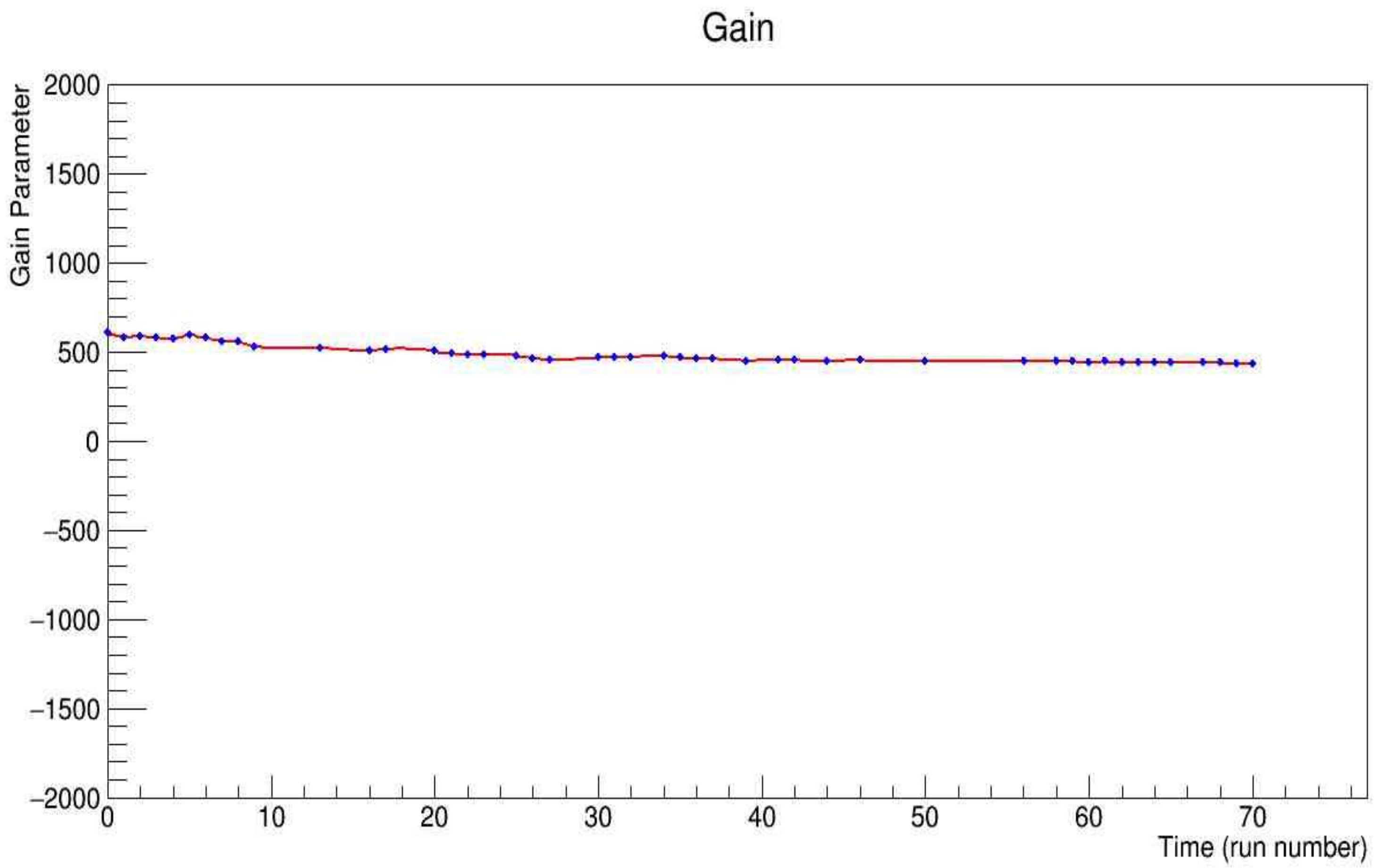


Gain parameter, g_s is defined as the half value:



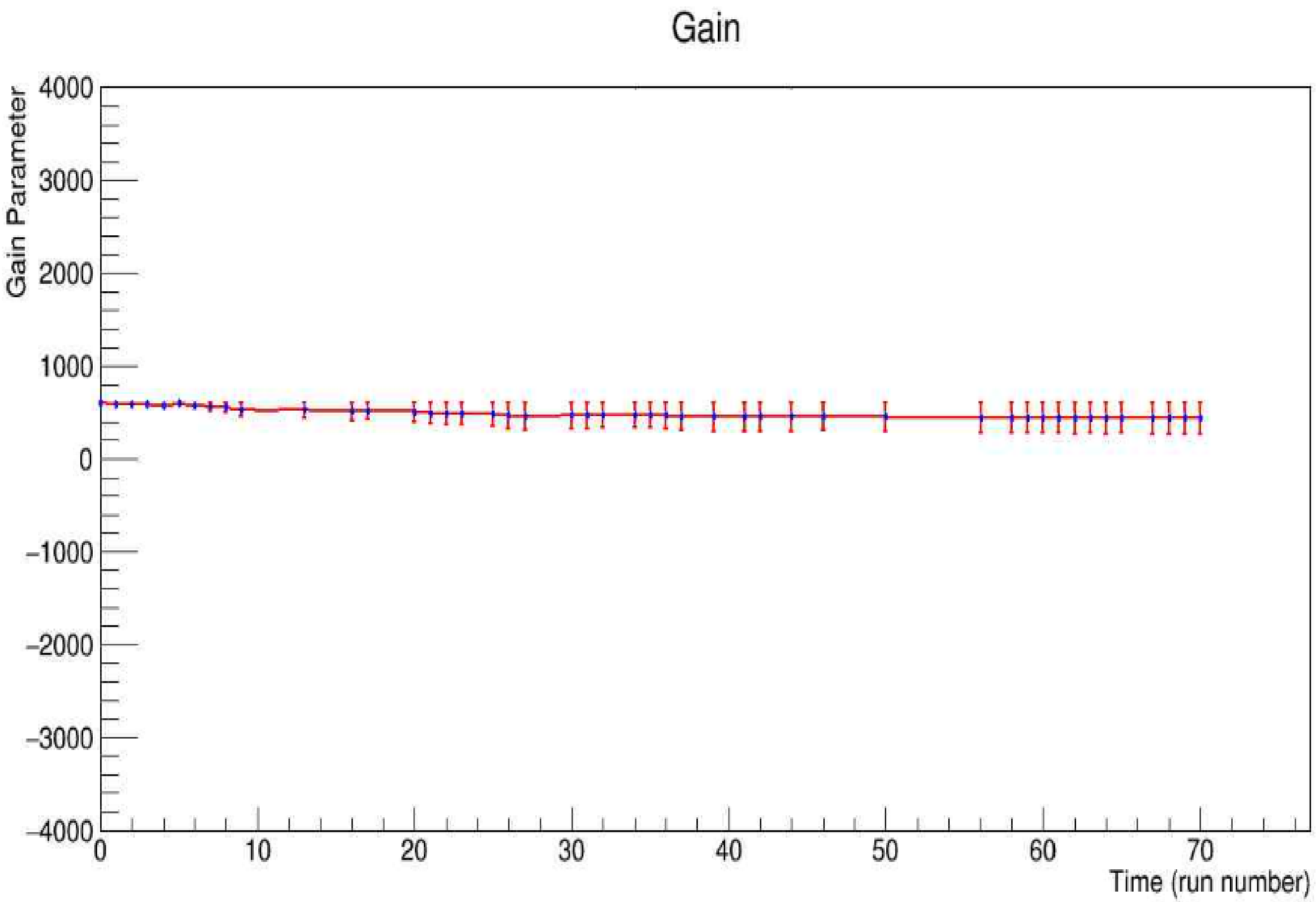
For all runs, the gain shift parameter is obtained:

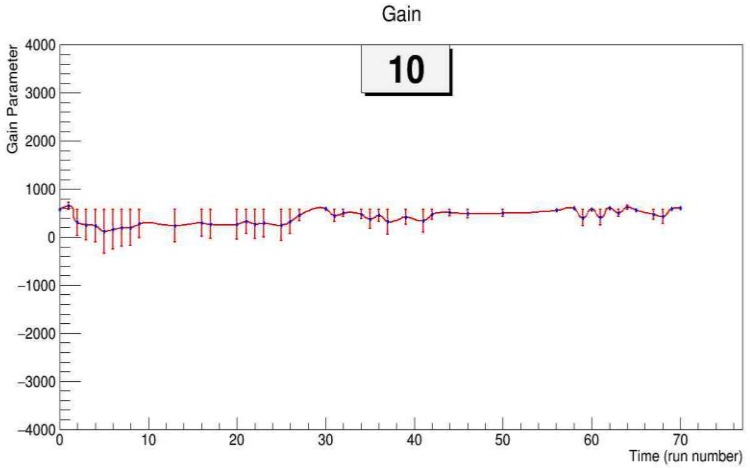
It was done for the 15.1 MeV giant resonance state of ^{12}C.



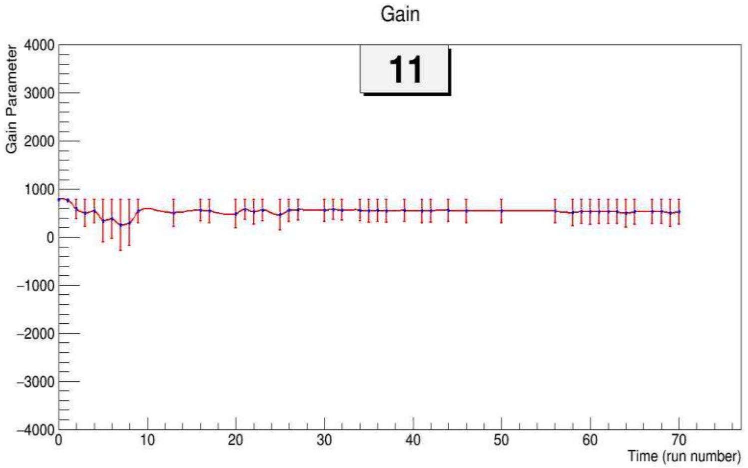
Gain Correction

Gain shift correction is done with respect to the first run.





Gain
10
Gain Parameter
Time (run number)



Gain
11
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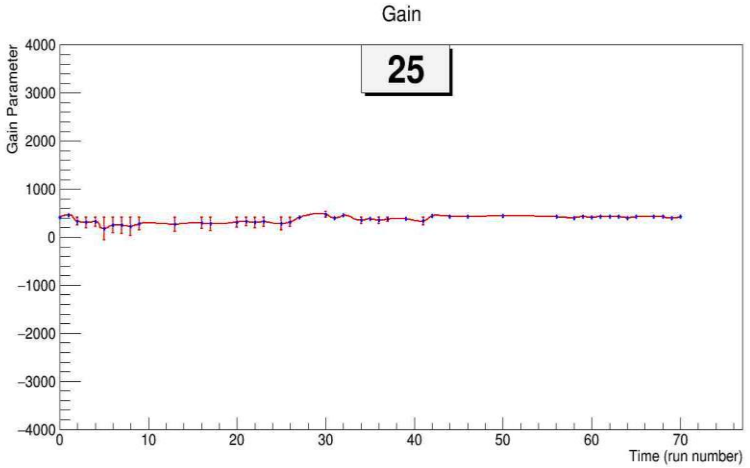
Time (run number)



Gain
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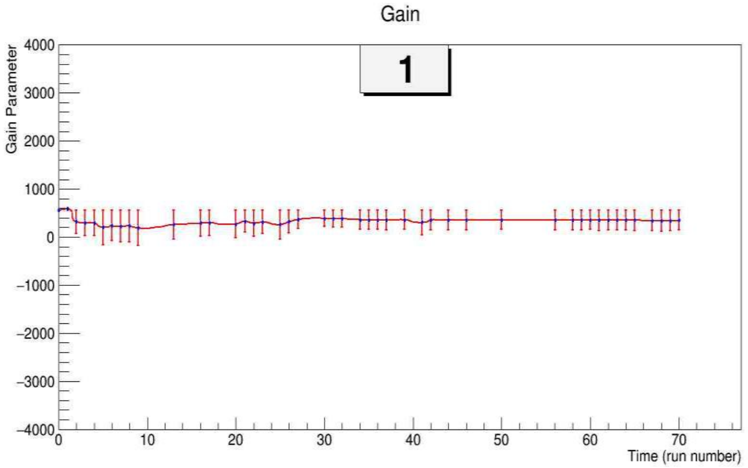
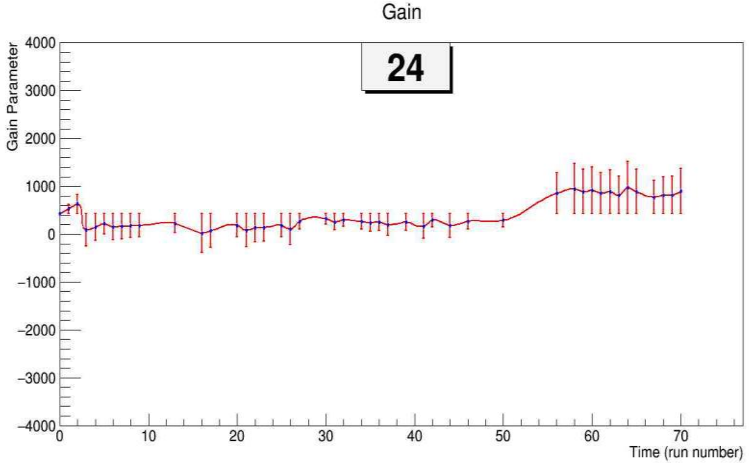
Time (run number)



Gain
1
Gain Parameter
Time (run number)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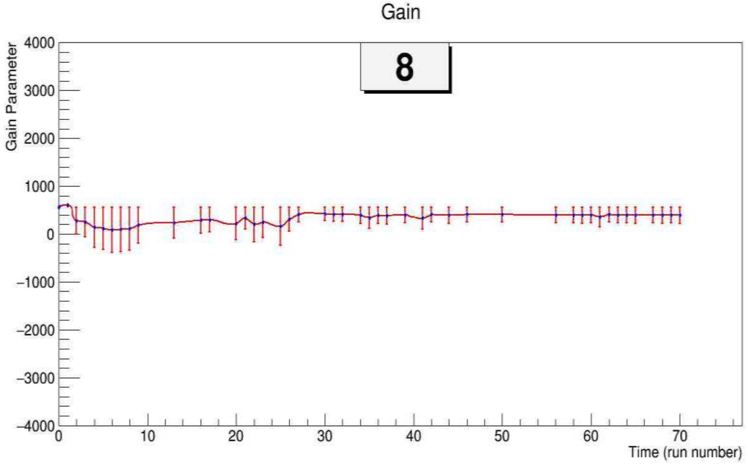
Time (run number)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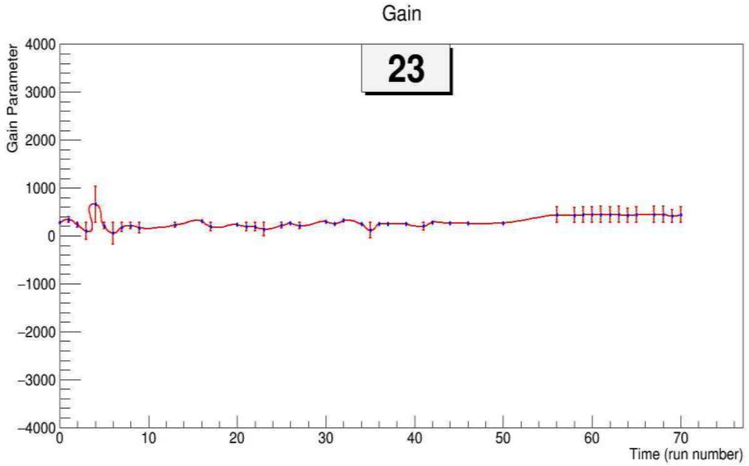
Time (run number)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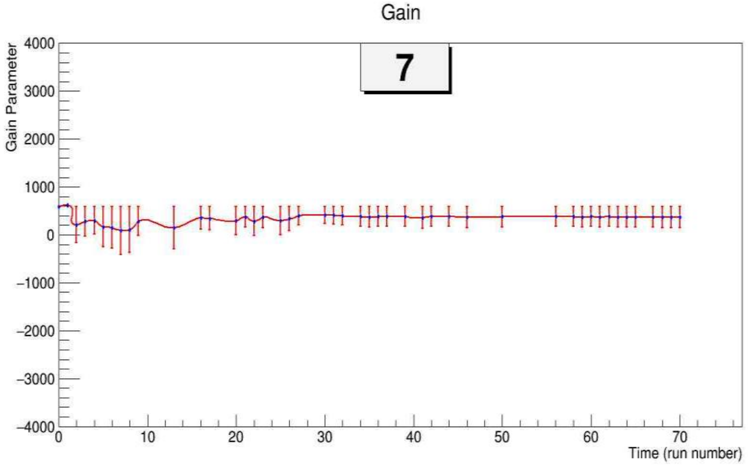
Time (run number)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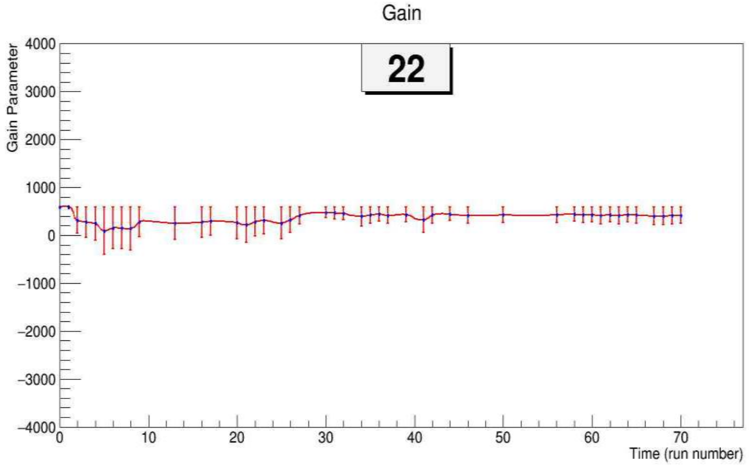
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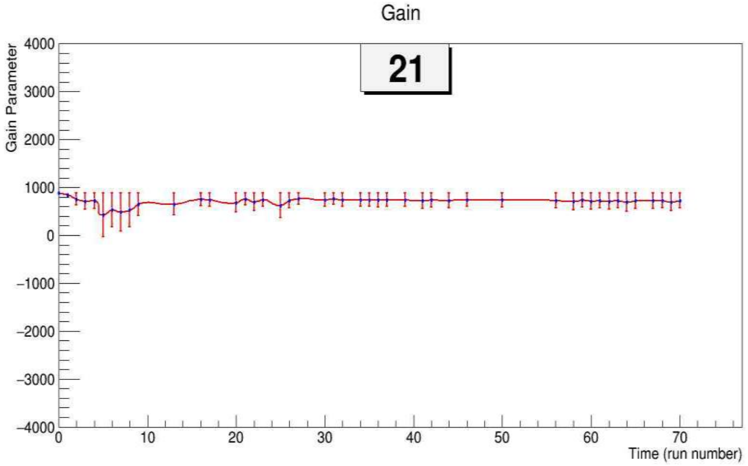
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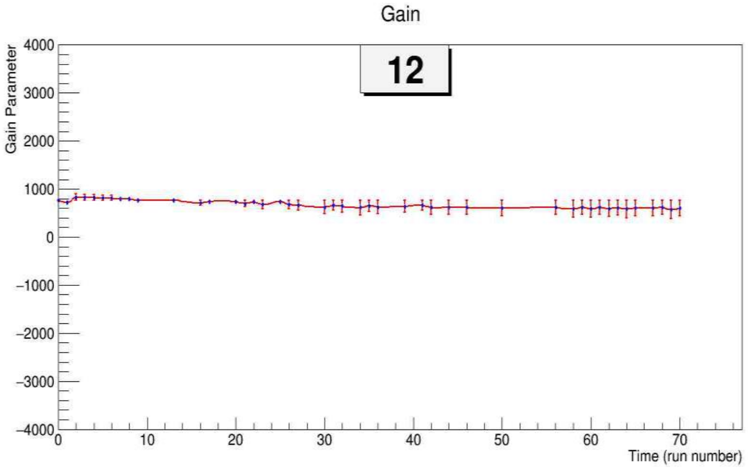
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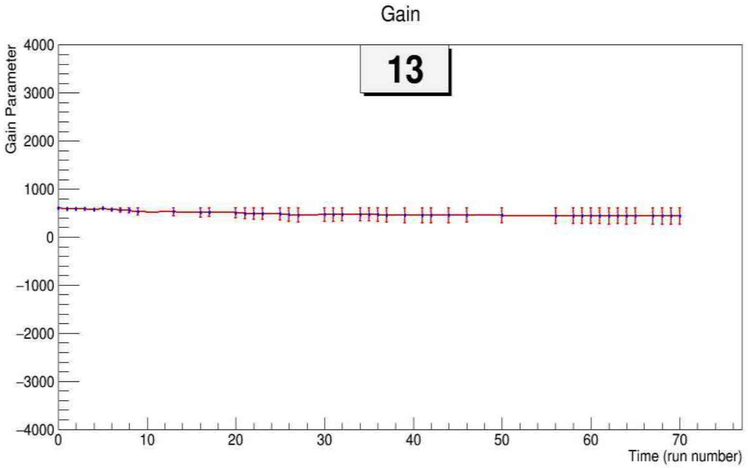
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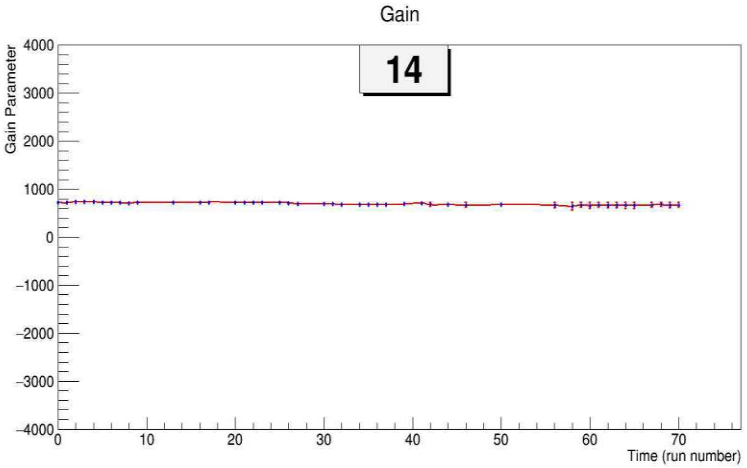
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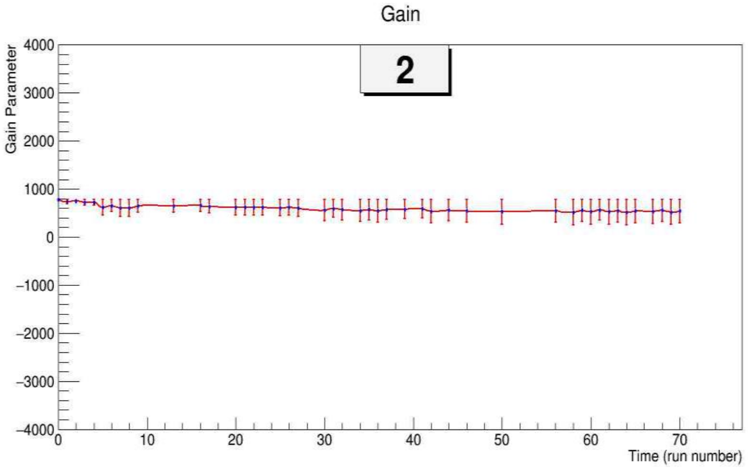
Time (run number)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Gain Parameter
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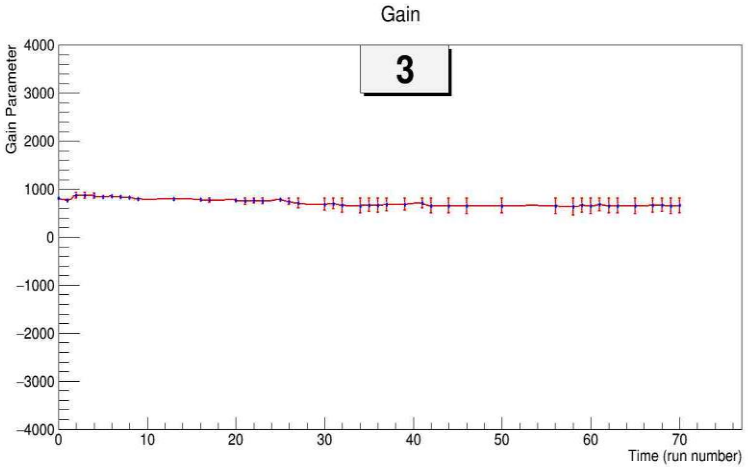
Time (run number)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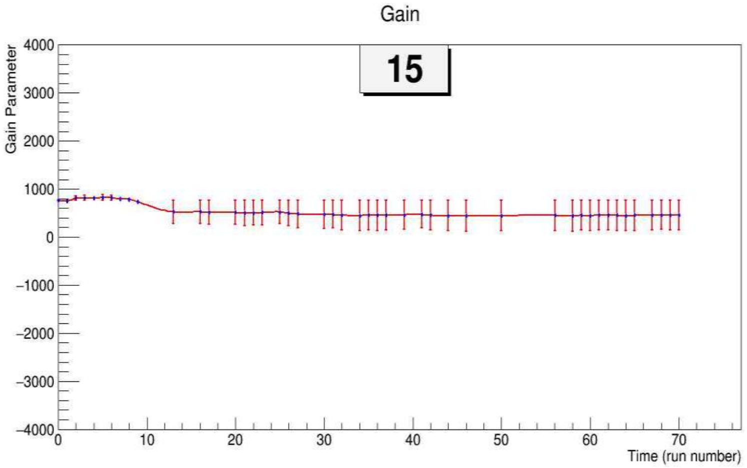
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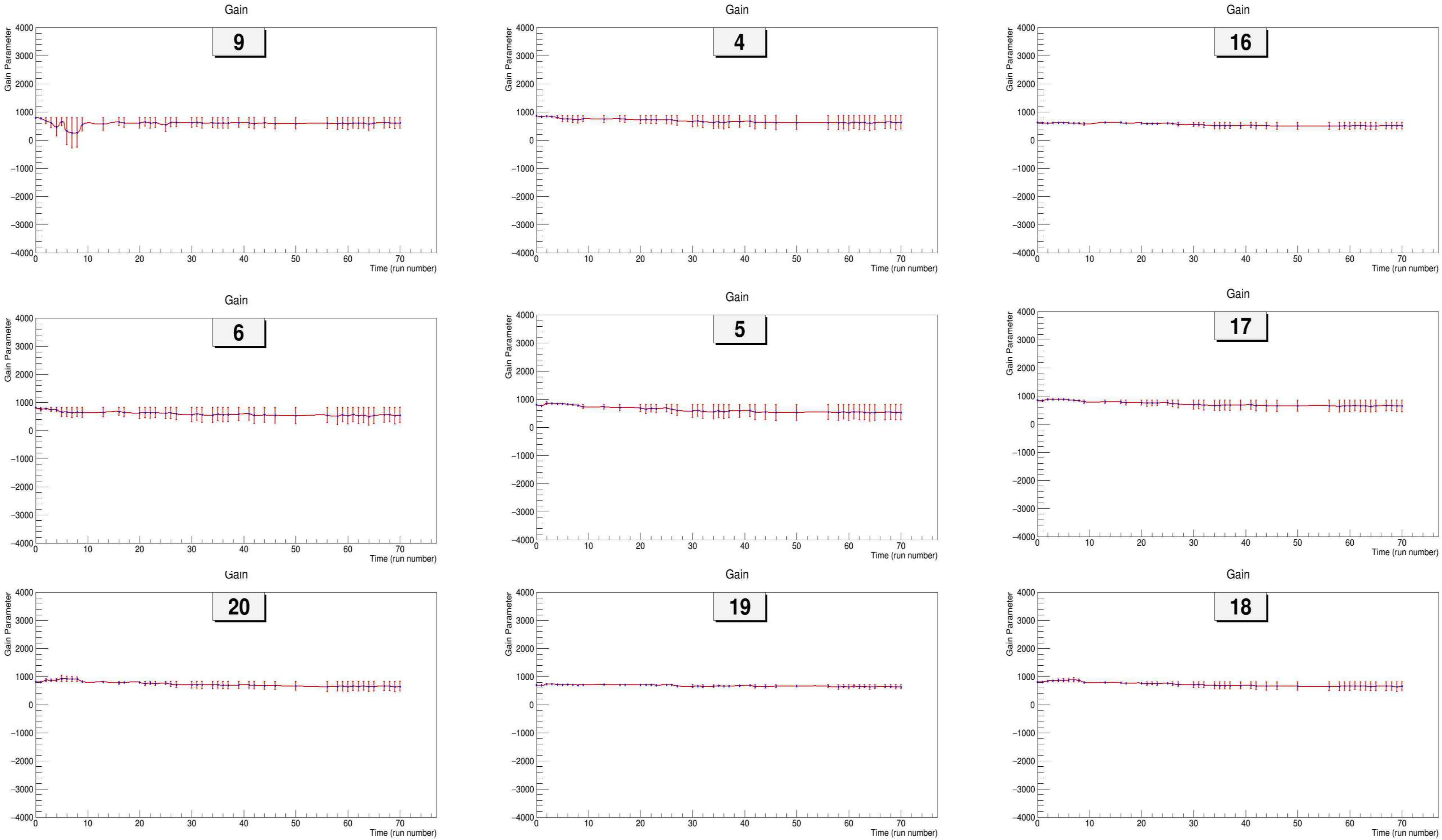
Gain
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Gain Parameter
Time (run number)
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−4000
0
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20
30
40
50
60
70

Conclusion

The relative length of the error bar and the stability of the curve shows how good and reliable a counter is and how much calibration is required.

THANK YOU

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Introduction

- First hypothesized by Pauli, developed by Fermi and later confirmed in the Cowan-Reines experiment.
- Neutrinos are charge-less, leptonic particles that interact only via the weak forces.

Importance in Supernovae

- Core-collapse supernovae emit large number of neutrinos and anti-neutrinos of all flavors.
- Second largest signal is expected to come from neutral-current inelastic scattering of neutrinos (ν_μ / ν_τ) with ^{12}C, ^{16}O and protons.
- ^{12}C and ^{16}O are excited to giant resonances which emit gamma rays during de-excitation.

- No systematic data exists for gamma ray production for giant resonances of ^{12}C and ^{16}O.

Optical Potential Model

Theoretical framework for understanding the interaction potential.

Given by sum of central and spin-orbit potentials:

$$U(r) = U_C(r) + \ U_S(r)\boldsymbol{\sigma} \cdot \boldsymbol{l}$$

where $U_C(r) = V_C - V f_o(r) - iW f_v(r) + 4iW_s \frac{d}{dr} f_s(r)$

and $U_S(r) = (\frac{\hbar^2}{mc})^2 \frac{1}{r}\ [V_s \frac{d}{dr} f_{vs}(r)\ + iW_s \frac{d}{dr} f_{ss}(r)]$

The form factor is of the Woods – Saxon form:

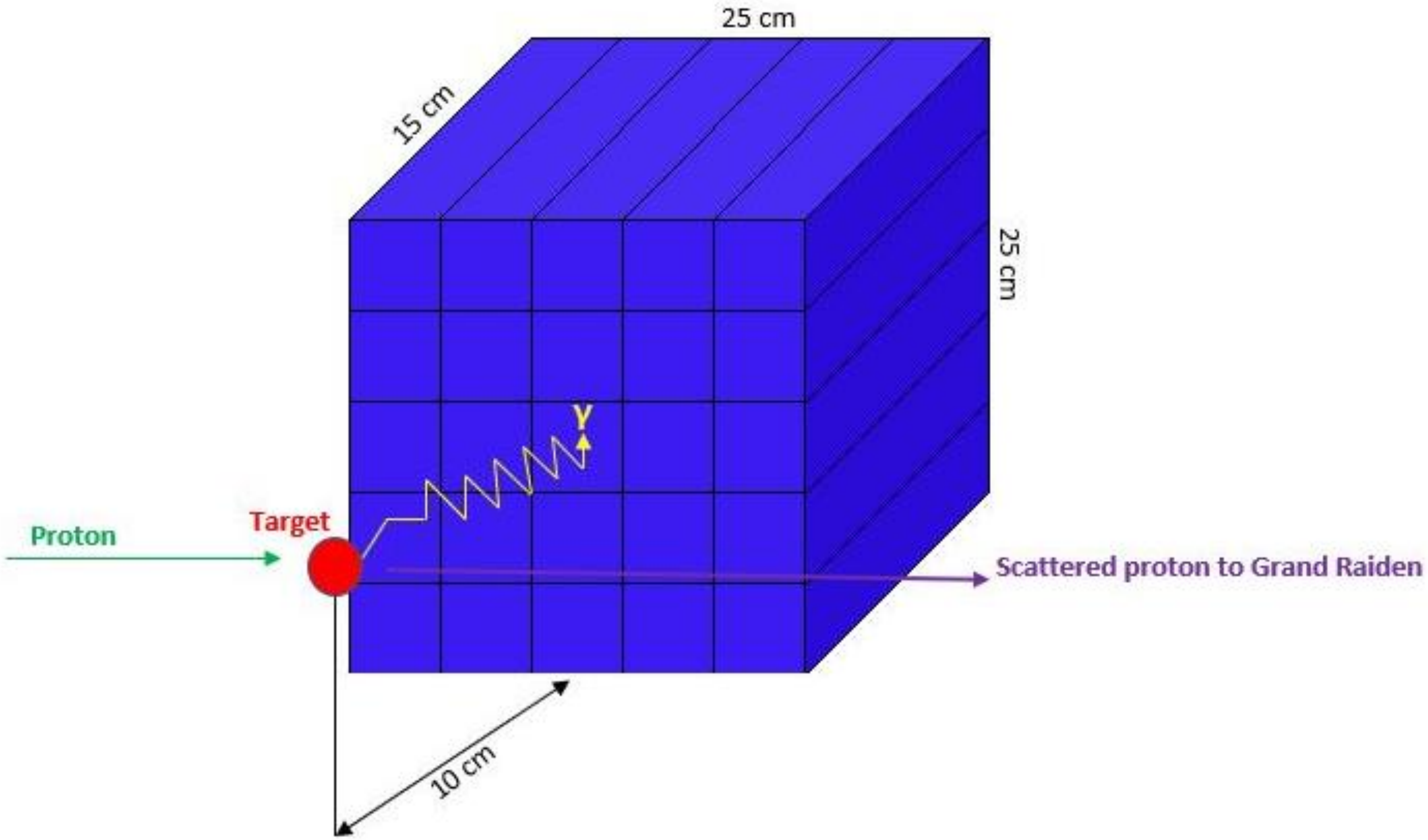
$$f(r) = \frac{1}{1 + e^{\frac{r-R}{a}}}$$

It give the scattering amplitude.

Experiment

392 MeV proton beam is scattered off pure carbon and cellulose.

Proton beam excites ^{12}C and ^{16}O to giant resonant states which decay by release of gamma rays and measured by 25 NaI(Tl) counters.



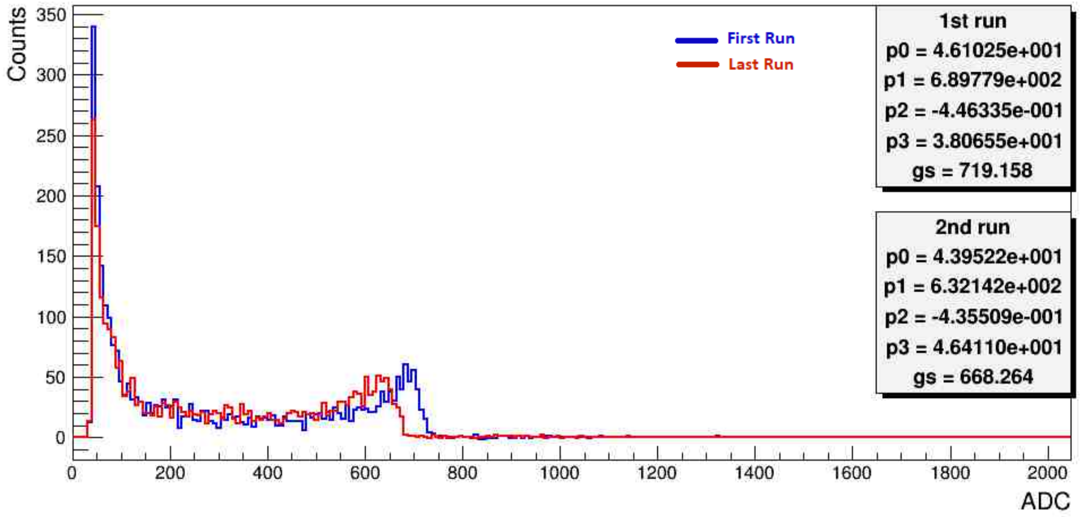
Experimental Analysis of γ-rays

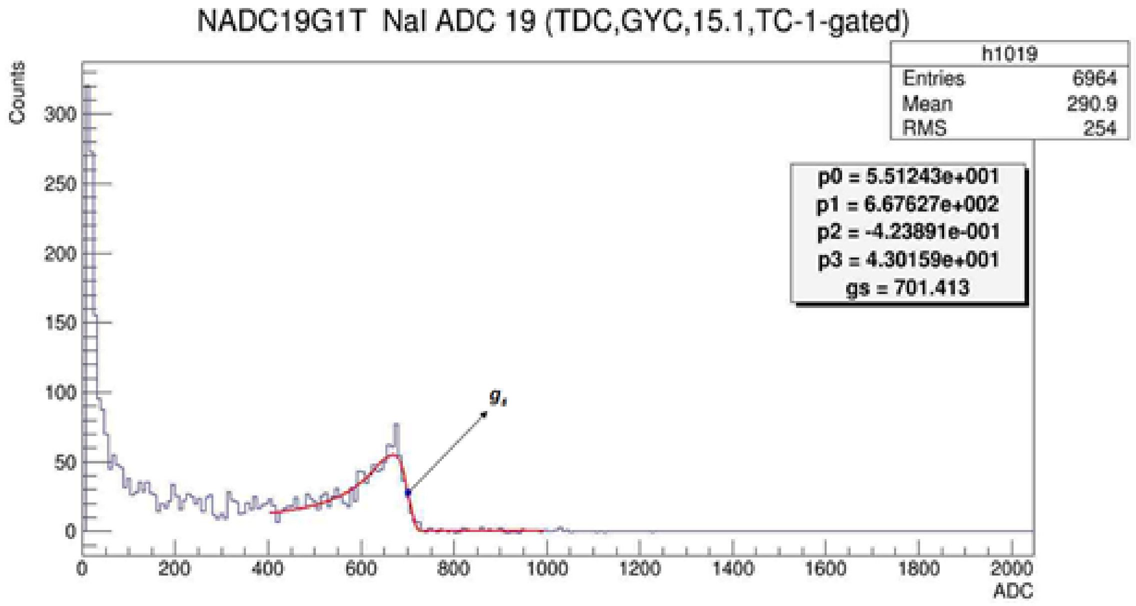
- Shift in gain is observed due to radio-activation of PMTs – leads to decrease in energy resolution.
- Peak region was fitted with asymmetric gaussian:

$$f(ADC) = p_0 e^{-\frac{(ADC-p_1)^2}{2\sigma^2}}$$

$$\sigma = p_2(ADC + p_1) + p_3.$$

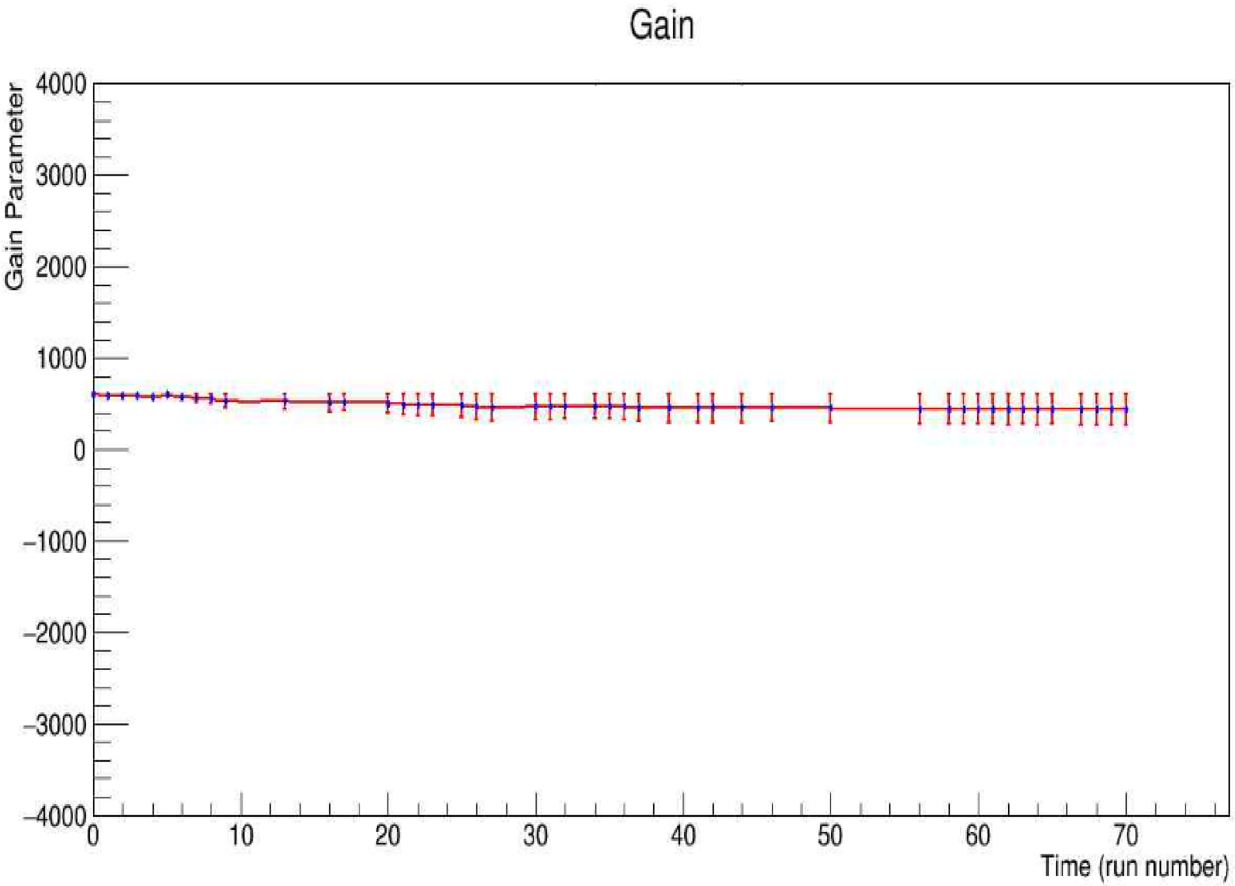
- Gain parameter is the half value.

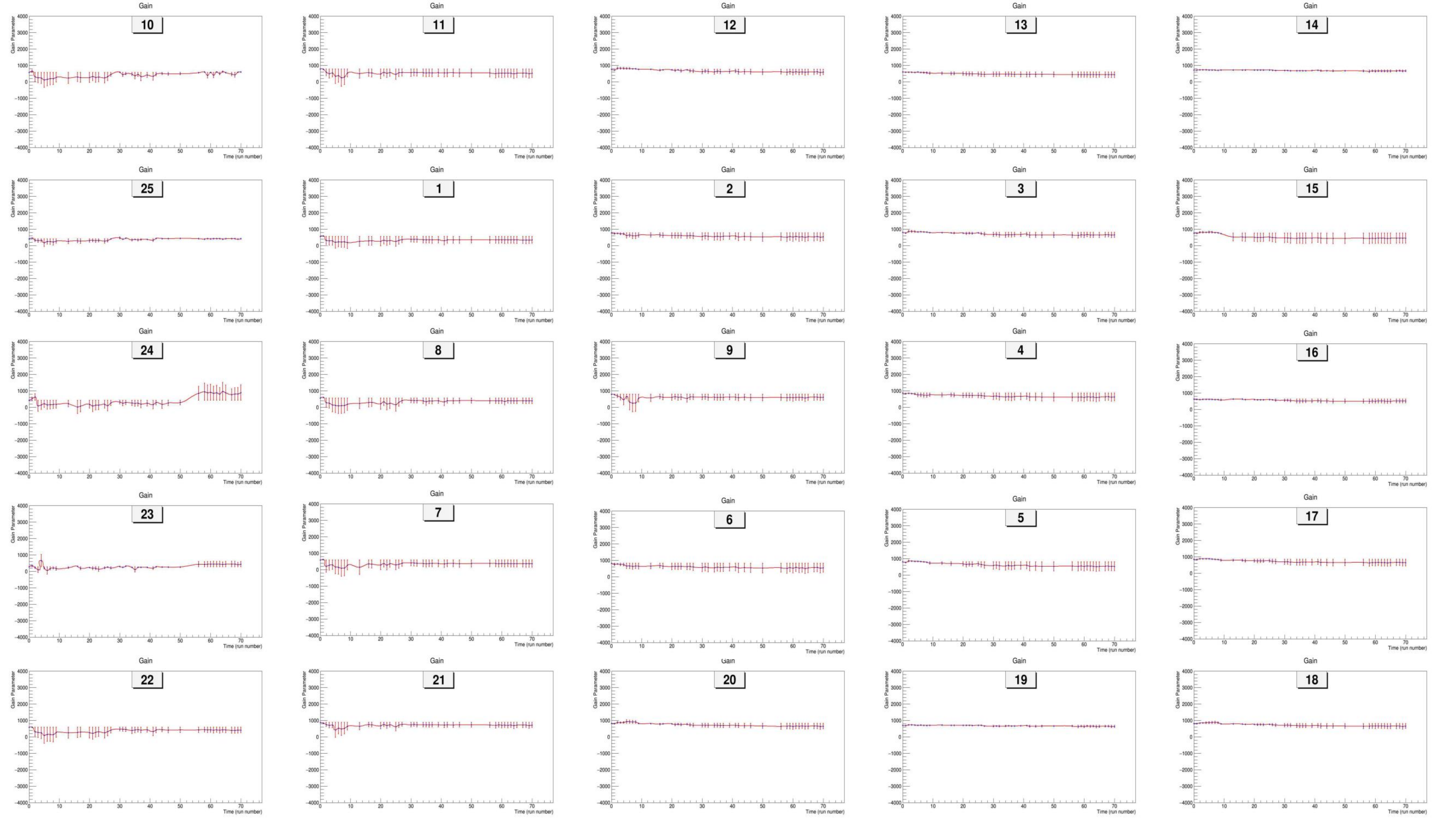




Gain Shift Correction

- It is corrected with respect to first run.
- This has been done for all counters for the 15.1 MeV giant resonance state of ^{12}C.




Gain
10
11
12
13
14
25
1
2
3
15
24
8
9
4
16
23
7
6
5
17
22
21
20
19
18
Gain Parameter
Time (run number)

Conclusion

- The first three columns are unstable and unreliable – they receive the forward angle radiation.
- The last two rows are reliable for accurate measurements.

Gives systematic data for background comparison during neutrino experiments in large-scale detectors.

Scope

- Helps understand the supernova core-collapse event.
- Can also help understand the neutrino mass hierarchy problem and give and insight into physics beyond the Standard Model.

THANK YOU