Neutron Emission after μ Capture

A Study of Neutron Emission in AlCap

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AlCap
Experimental Goals

1) Measure the rate and energy spectrum of charged particle emission with 5% precision for energies greater than ~2.5 MeV.

Proton emission dominates the single hit rates in the tracking chambers.

2) Measure the rate and spectrum of neutron emission for neutrons between a few MeV and ~15MeV.

Neutrons cause significant backgrounds in all detector systems

3) Measuer muonic x-rays after μ capture

Atomic x-ray emission is a proposed technique to determine the number of muon stops in order to normalize the Mu2e branching ratio

Relevance to the Mu2E Experimental Measurement

Neutron SEU

An estimate of the SEU in various FPGA’s using information of the test in the **iRoC report**

1 Neutron Background at the standard NYC latitude 40.7^0 N (Sea-Level)→ 14 n/hr/cm^2 → 3.9 x10^{-3} n/s/cm^2

2 1 FIT = 1 failure in 10^9 hrs → 2.4 x 10^{-8} failure/day

3 Neutron Rate in the Tracker → 5 x 10^4 n/s/cm^2

4 Neutron Rate/Sea-Level Rate → 1.3 x 10^{-7}

The above assumes no error correction, but this may take a number of clock cycles. Also note that the iRoC report does not include functional interrupts and transients due to ionizations or radiation damage.

FPGA	Measured FIT Sea Level	Scaled FIT Tracker	Failure/Day	Failure/day 300 FPGA	Failure/hr 300 FPGA
Actel	<0.04	<5.2x10^5	<0.01	<3.6	--
Xilinx XC 351000	320	4.2x10^9	100	3.0x10^4	1300
Altera	460	6.0x10^9	144	4.3x10^4	1800

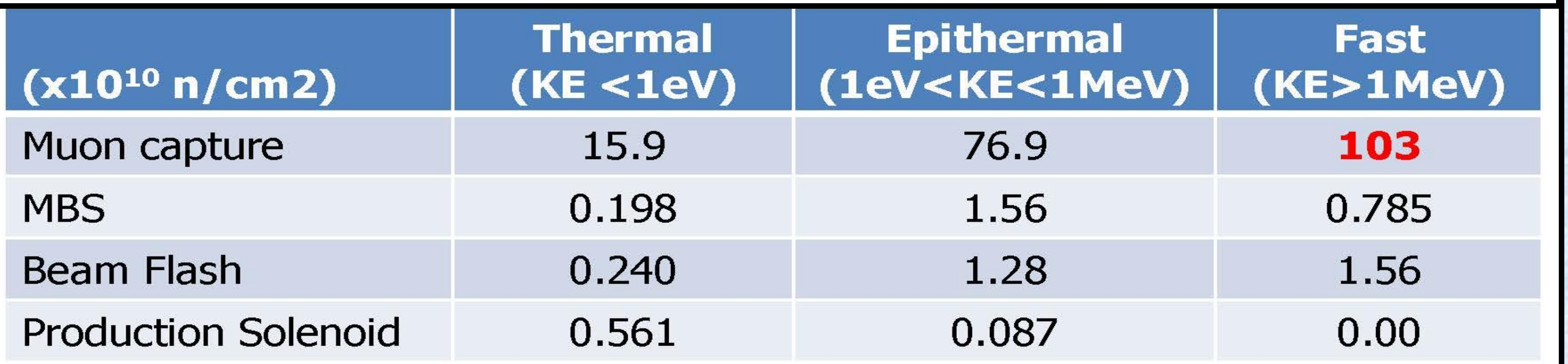
MyeongJae Lee
(LBNL) Mu2e Soft/Sim meeting, Jan 10, 2012

- Estimating Neutron flux is important to the Tracker electronics radiation hardness.
  - Fast neutron is an important source of Single Electron Upset (and subsequent failure) in the real time operation of electronics system.
- Target Tolerance level

  = 1 [reset of all electronics] / day

  = 64 / 21600 reset/day/chip = 3×10^{-8} reset/sec/chip

  - This means we can endure DAQ recycling once a day. Channel/chip ratio not decided yet.
- Lifetime of exp (including duty rate) = 4×10^{7} sec
- Life time neutron dose (all energy) = 2×10^{12} n/cm^2
  - Obtained from Mu2eG4. Muon capture neutrons are dominant.



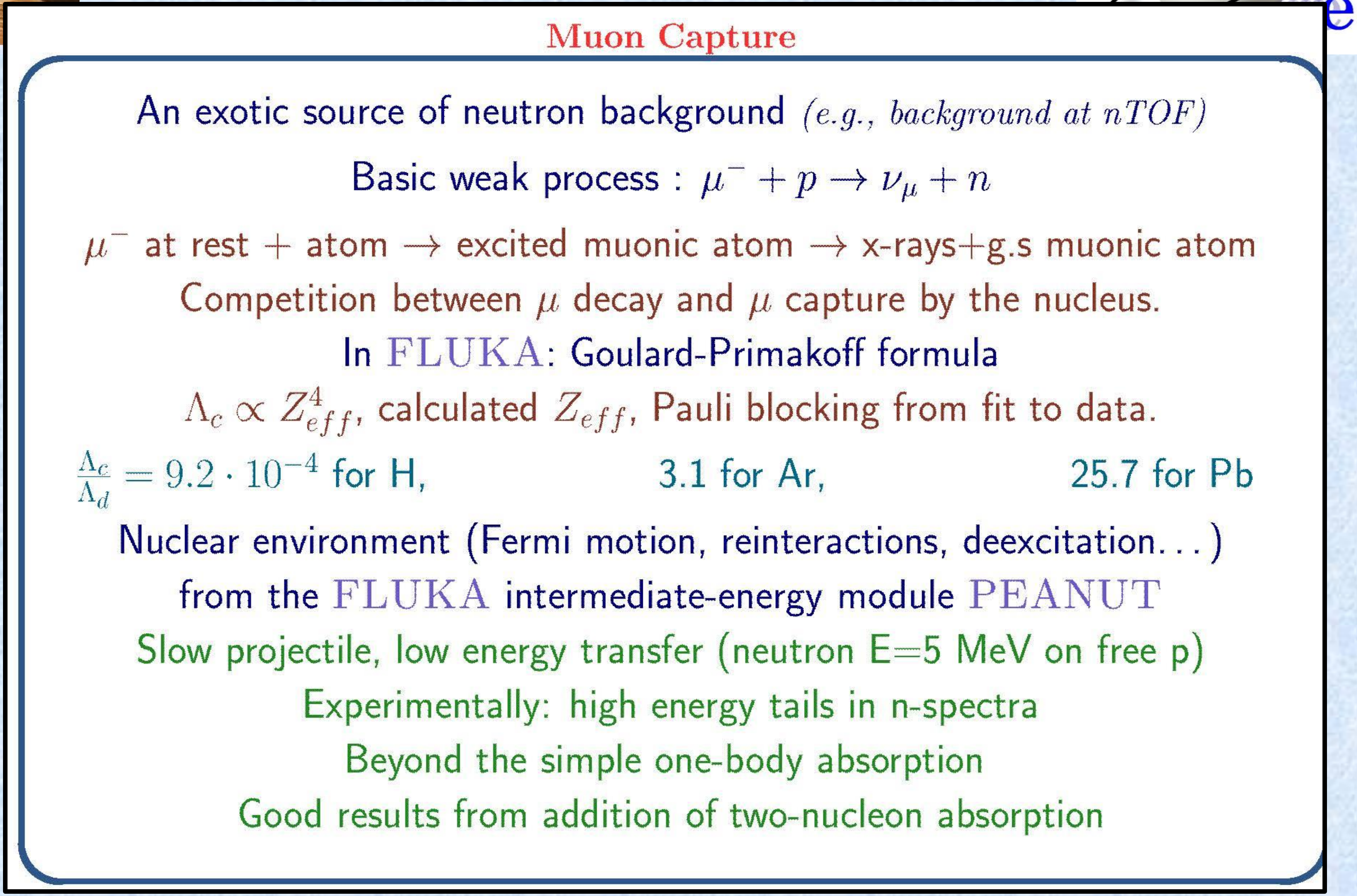
($\times10^{10}$ n/cm2)	Thermal (KE <1eV)	Epithermal (1eV<KE<1MeV)	Fast (KE>1MeV)
Muon capture	15.9	76.9	**103**
MBS	0.198	1.56	0.785
Beam Flash	0.240	1.28	1.56
Production Solenoid	0.561	0.087	0.00

SiPM Radiation Damage
Mu2e-doc-db 3213

After 10^{13} thermal n/cm^2 the SiPM QE drop is small but an increase of the SiPM's dark count rate is significant.

At room temperature individual PEs will be difficult to resolve after 10^{13} thermal n/cm^2 (which is equivalent to 10^{10}-10^{11} of 1 MeV neutrons/cm^2). The SiPM's dark count increase is expected to be around 10-100 MHz/mm^2 at room temperature. The SiPM's dark count rate drops ~2 times per 10 C.

FLUKA MC Simulations



Muon Capture

An exotic source of neutron background *(e.g., background at nTOF)*

Basic weak process : $\mu^- + p \to \nu_\mu + n$

μ^- at rest + atom → excited muonic atom → x-rays+g.s muonic atom

Competition between μ decay and μ capture by the nucleus.

In FLUKA: Goulard-Primakoff formula

$\Lambda_c \propto Z_{eff}^4$, calculated Z_{eff}, Pauli blocking from fit to data.

$\frac{\Lambda_c}{\Lambda_d} = 9.2 \cdot 10^{-4}$ for H, 3.1 for Ar, 25.7 for Pb

Nuclear environment (Fermi motion, reinteractions, deexcitation. . .)

from the FLUKA intermediate-energy module PEANUT

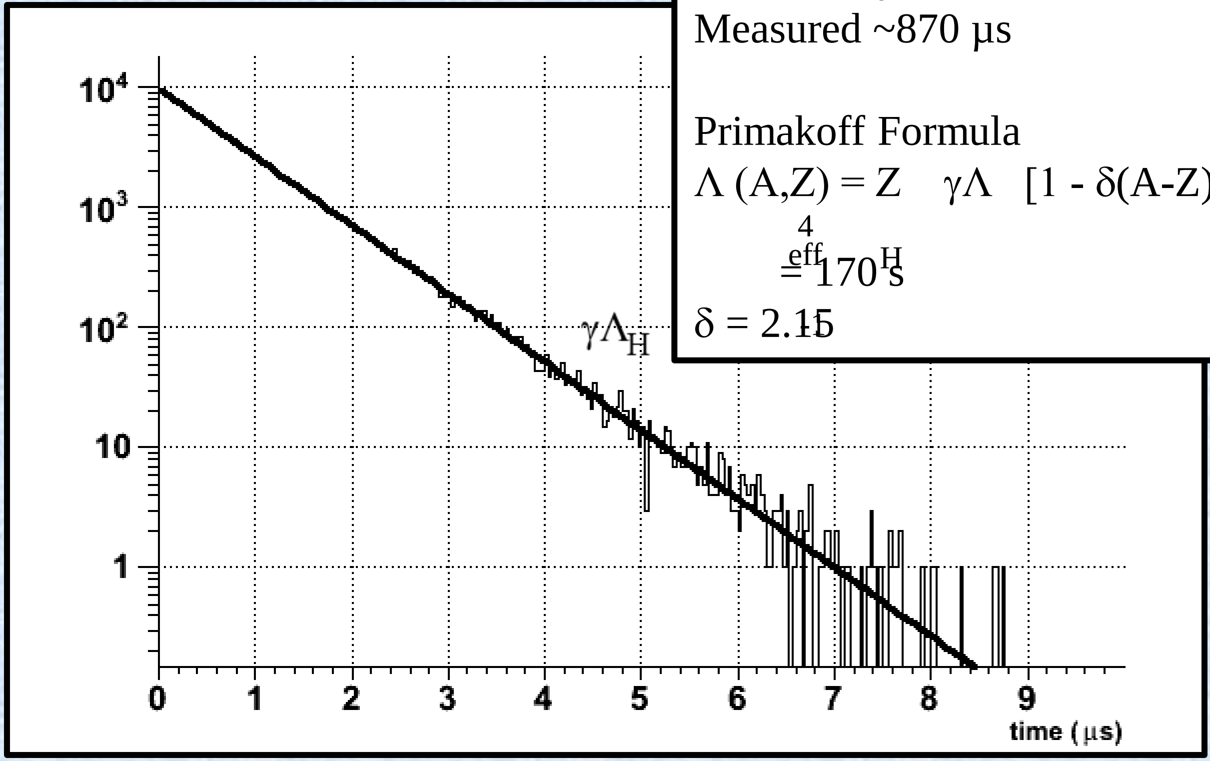
Slow projectile, low energy transfer (neutron E=5 MeV on free p)

Experimentally: high energy tails in n-spectra

Beyond the simple one-body absorption

Good results from addition of two-nucleon absorption

MC Lifetime Al



Fluka 756 μs
Measured ~870 μs

Primakoff Formula

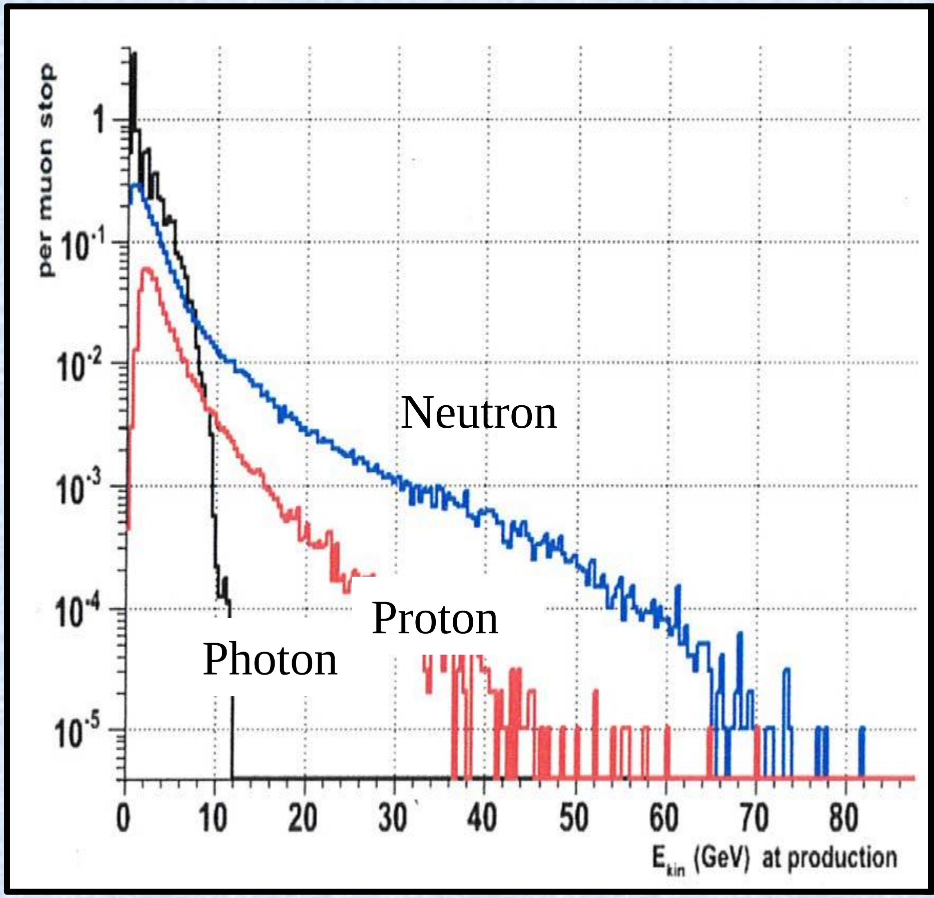
$\Lambda(A,Z) = Z_{eff}^4 \gamma\Lambda_H [1 - \delta(A-Z)/2A]$

$\gamma\Lambda_H = 170\ s$

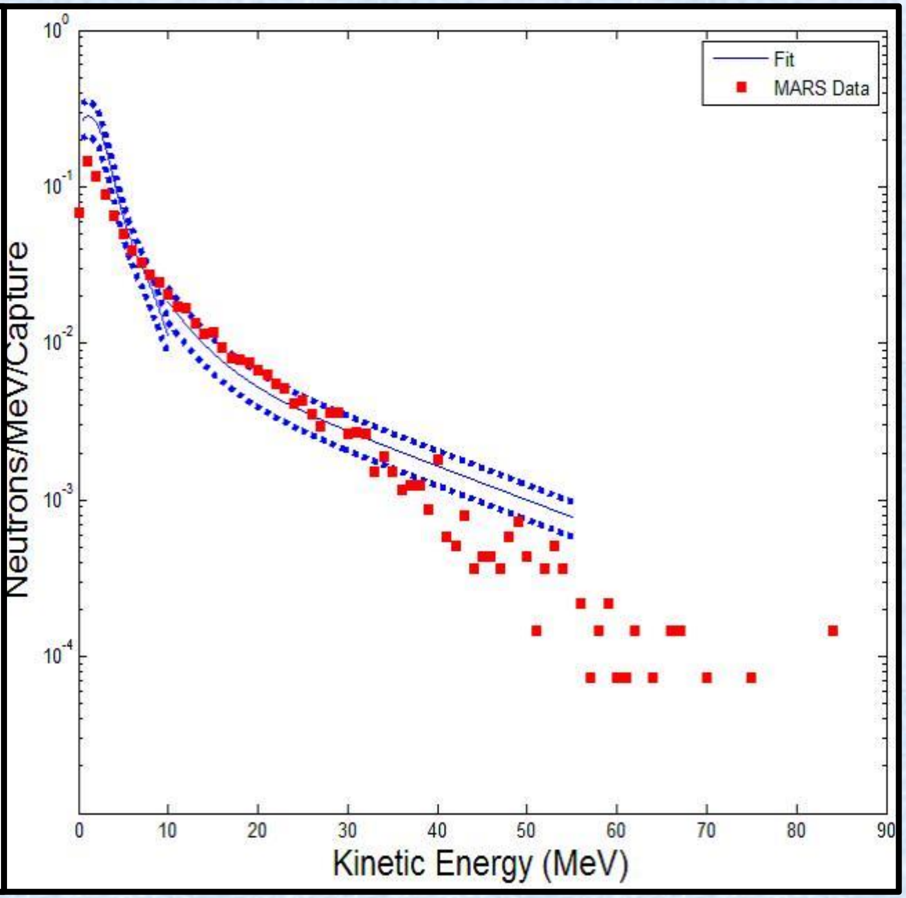
$\delta = 2.15$

MC Simulations

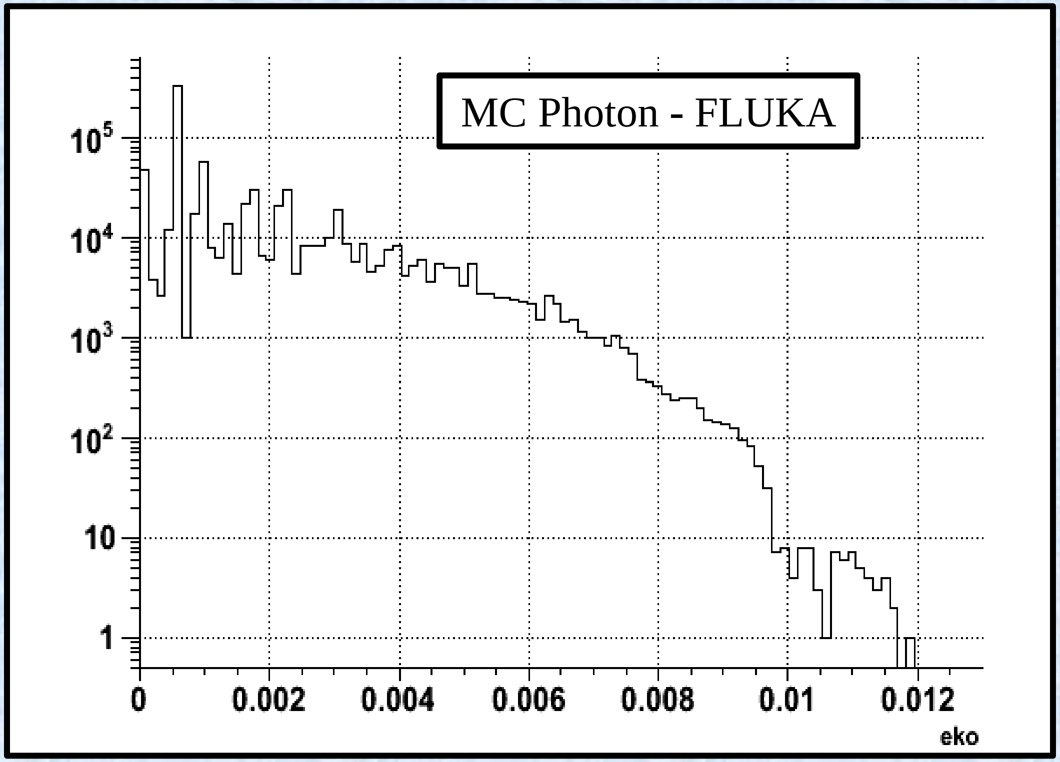
MC Neutron, Proton, Photon - FLUKA



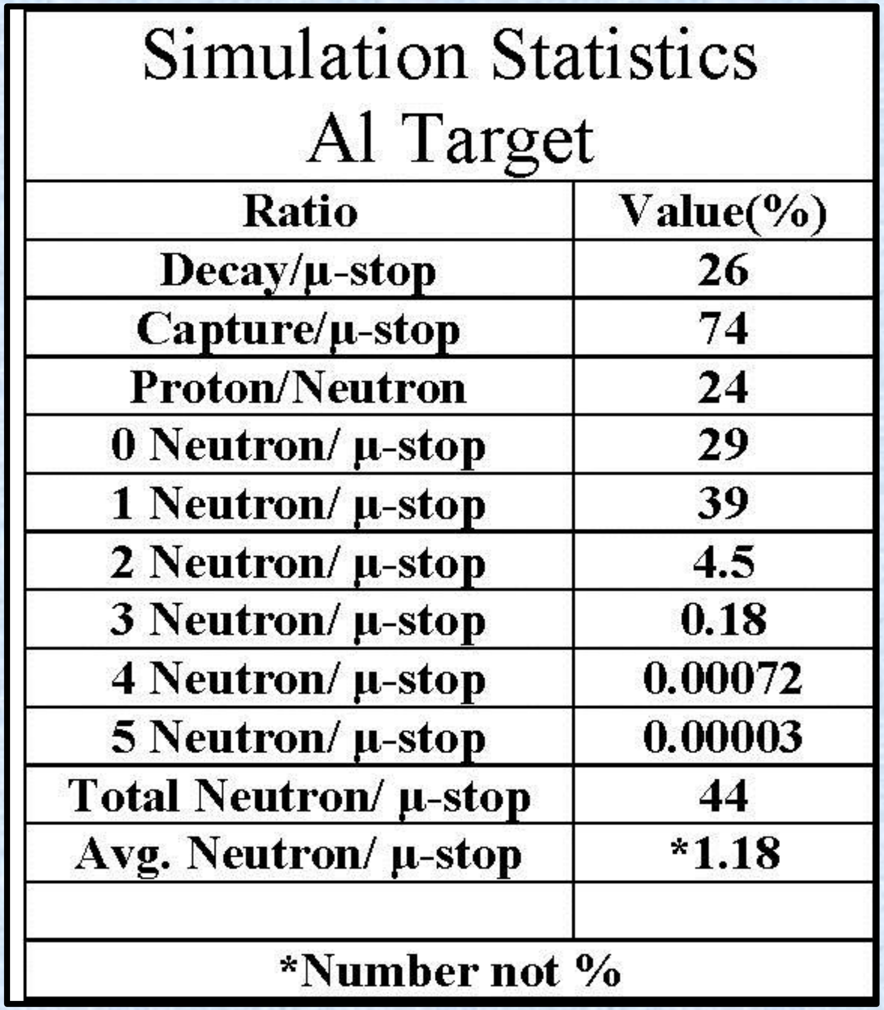
MC Neutron - MARS



Photon Spectrum
Al



Fluka MC
Al



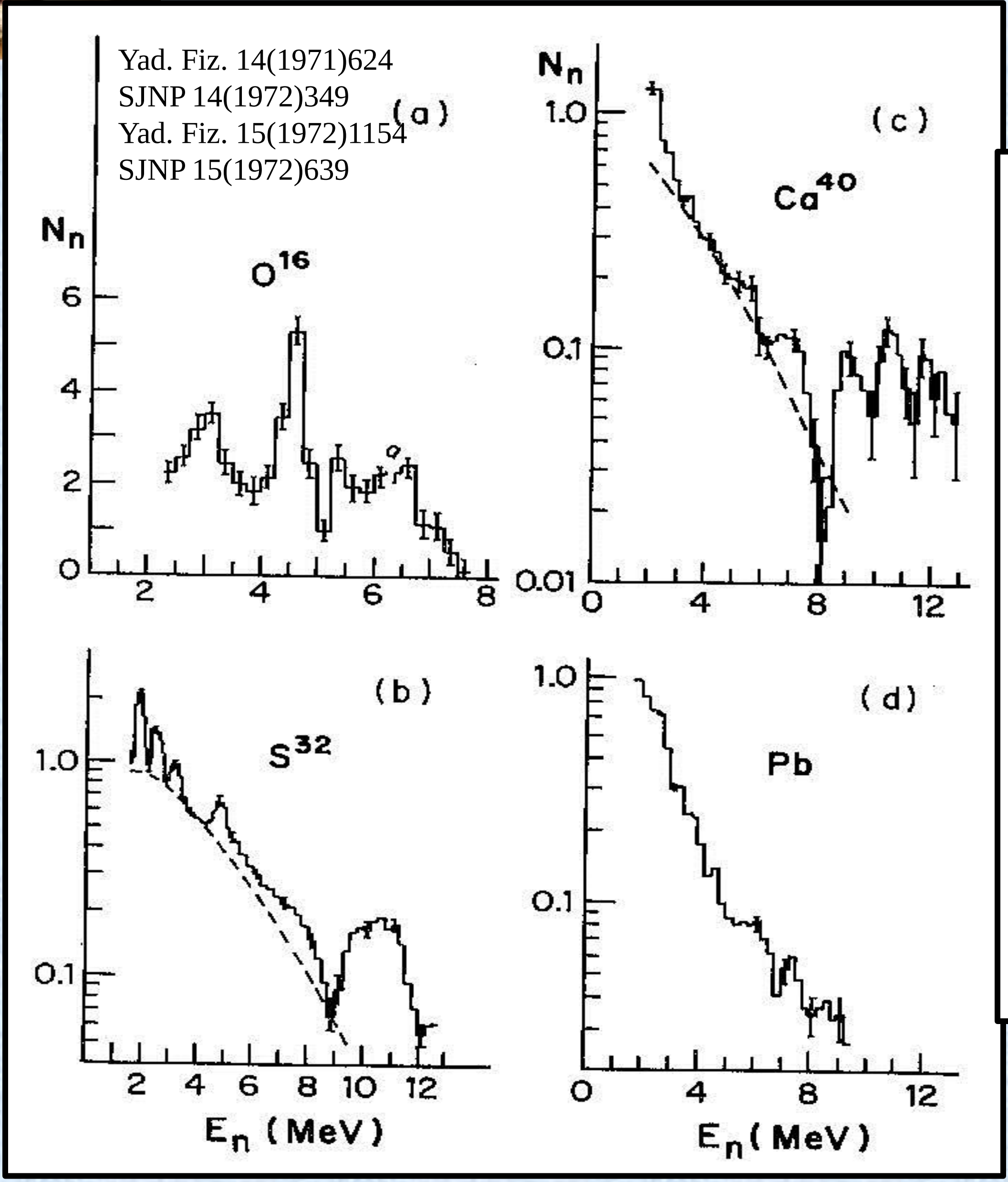
Simulation Statistics
Al Target

Ratio	Value(%)
Decay/μ-stop	26
Capture/μ-stop	74
Proton/Neutron	24
0 Neutron/ μ-stop	29
1 Neutron/ μ-stop	39
2 Neutron/ μ-stop	4.5
3 Neutron/ μ-stop	0.18
4 Neutron/ μ-stop	0.00072
5 Neutron/ μ-stop	0.00003
Total Neutron/ μ-stop	44
Avg. Neutron/ μ-stop	*1.18

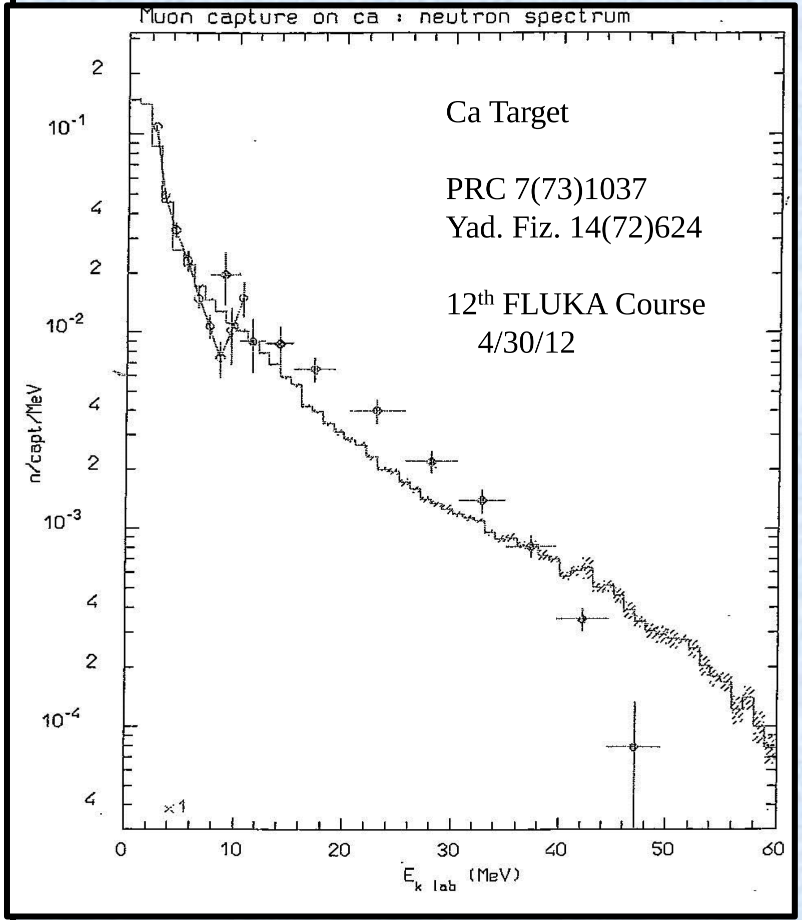
*Number not %

Previous Experimental Measurements

Measured Neutron Emission



Yad. Fiz. 14(1971)624
SJNP 14(1972)349
Yad. Fiz. 15(1972)1154
SJNP 15(1972)639

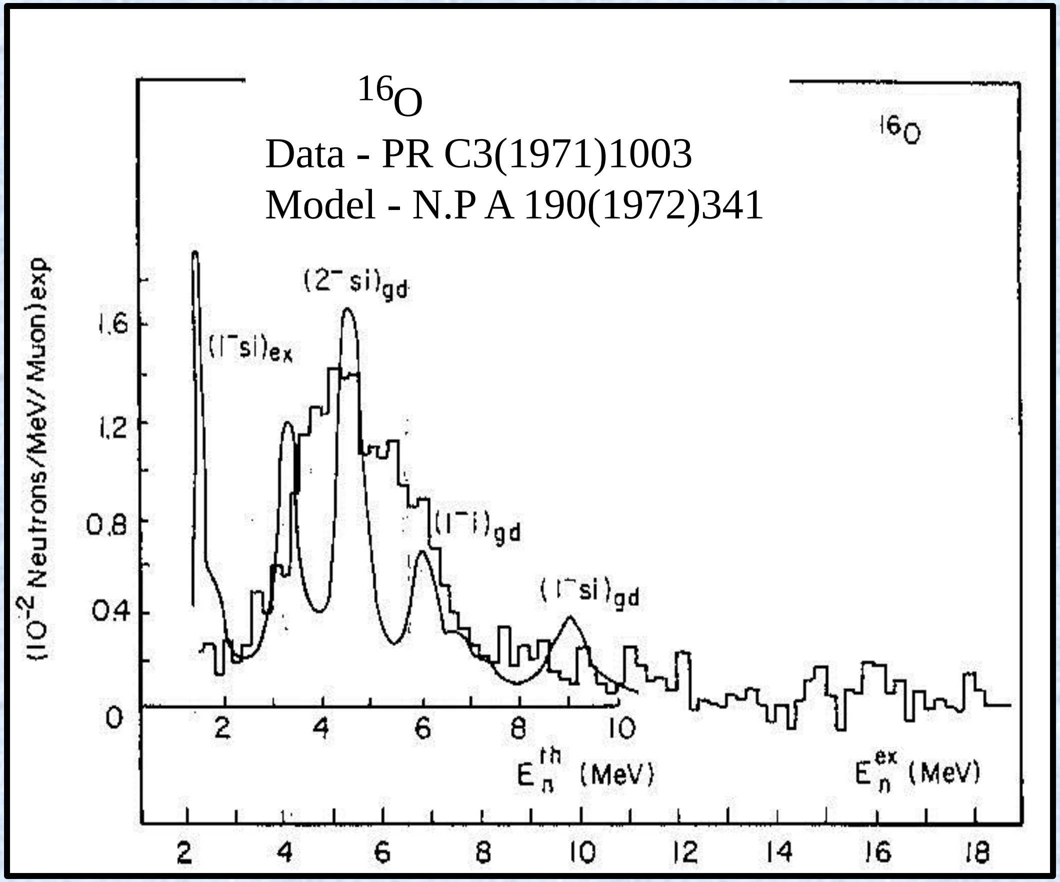


Ca Target

PRC 7(73)1037
Yad. Fiz. 14(72)624

12th FLUKA Course
4/30/12

Neutron Emission from μ-Capture on ^{16}O leading to Giant Resonance Excitation Data and Model comparison

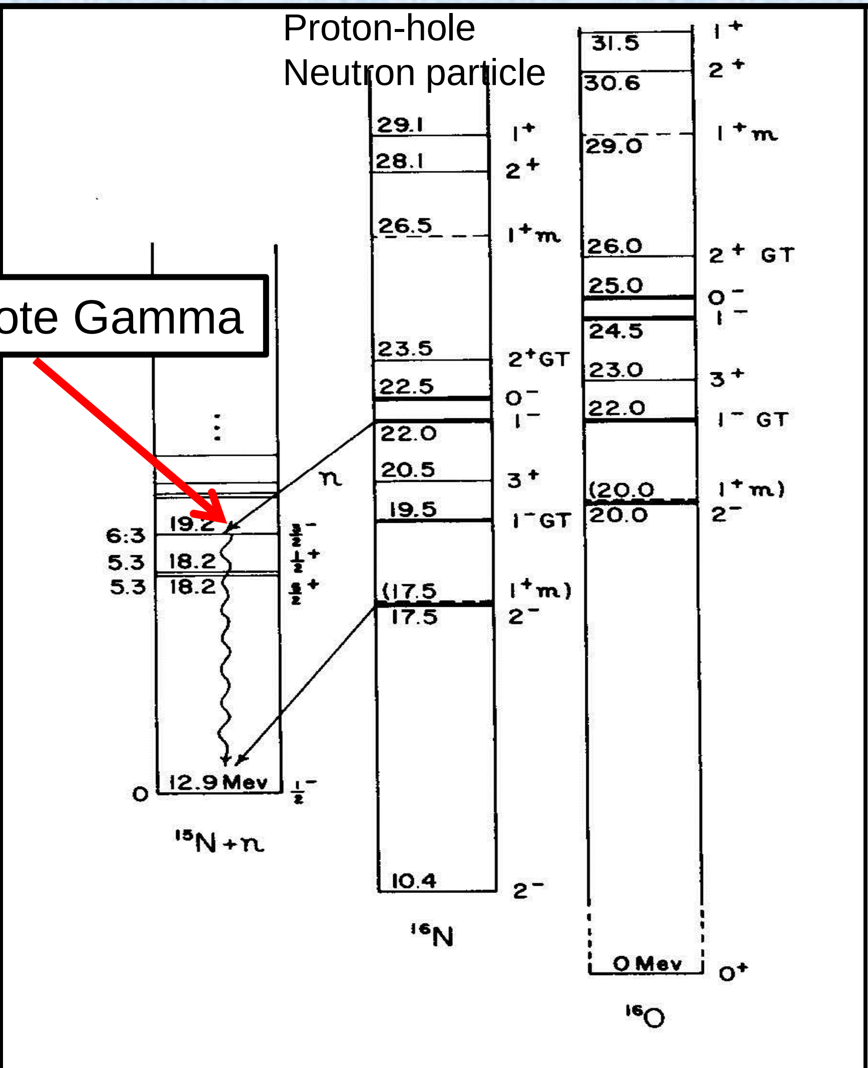


^{16}O

Data - PR C3(1971)1003

Model - N.P A 190(1972)341

Giant Resonance Excitation In Neutron Emission



Proton-hole
Neutron particle

Note Gamma

Fig. 1. Spectra of giant multipole resonance states in ^{16}O and ^{16}N, and neutron decay channels to ^{15}N.

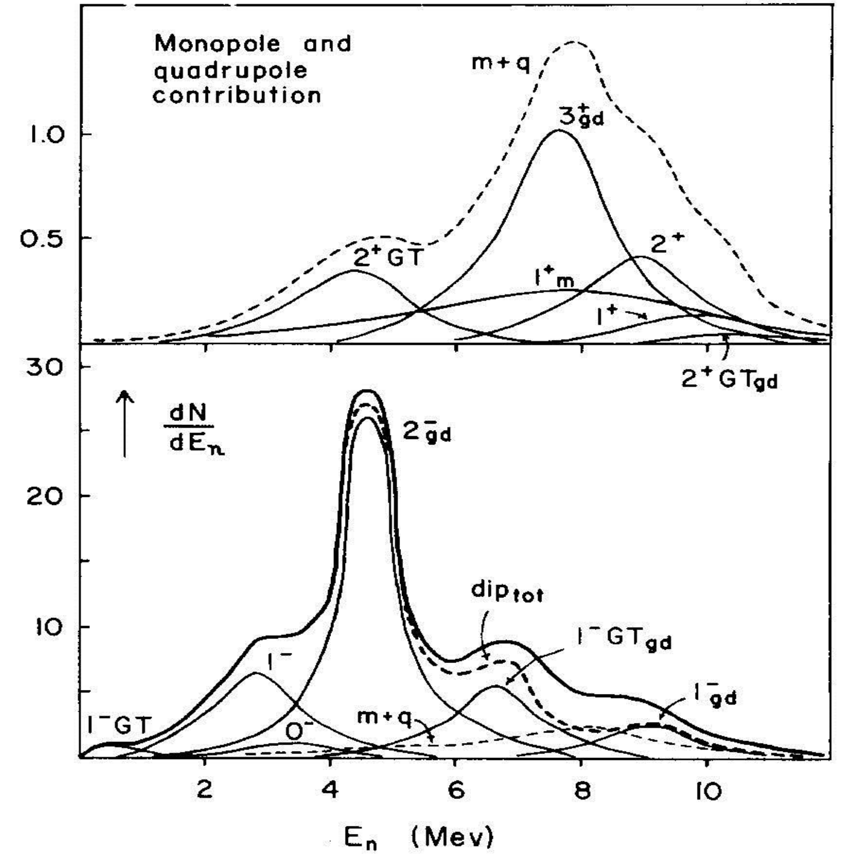
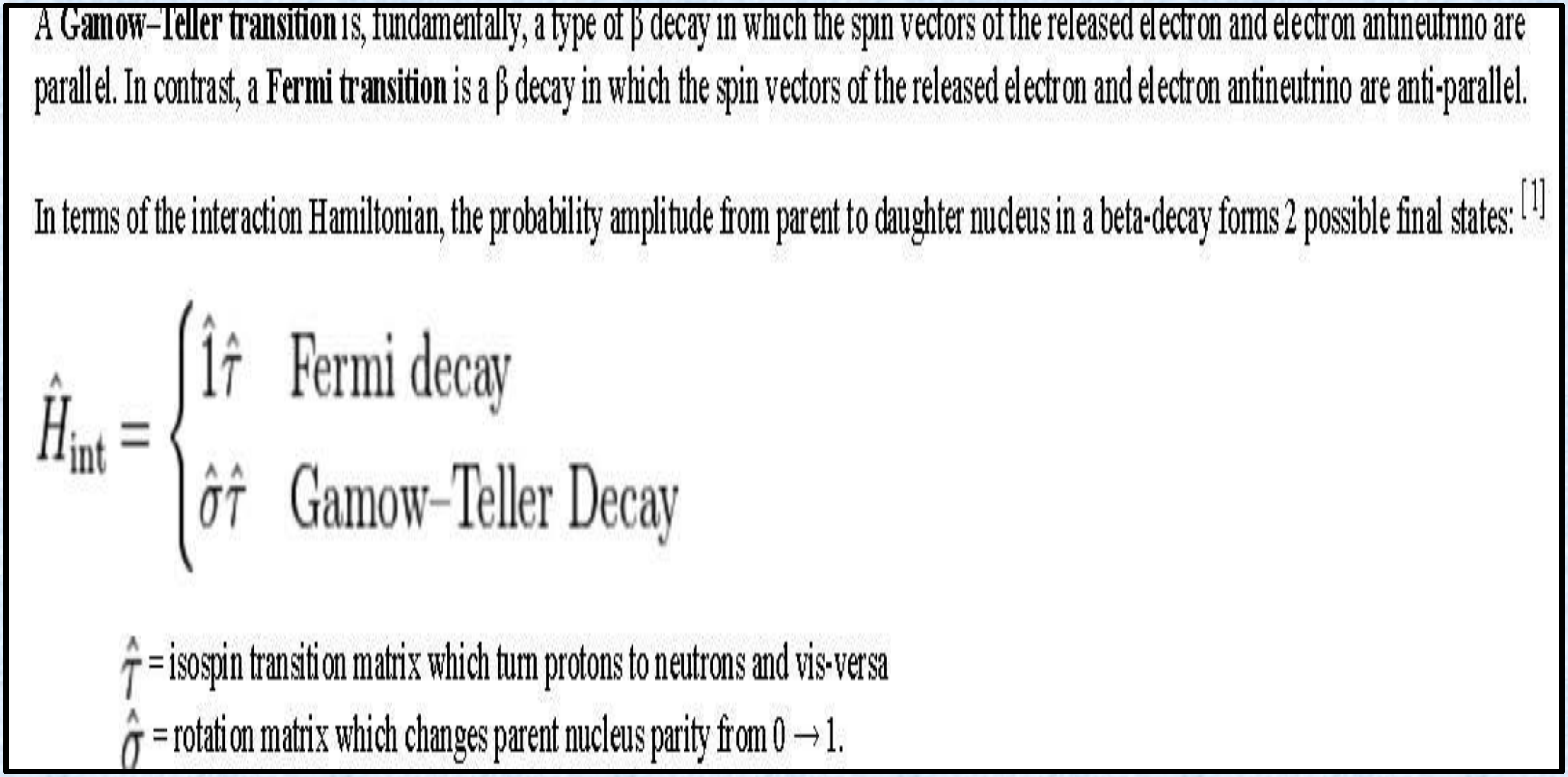


Fig. 2. Neutron spectra from the decay of giant resonance states in ^{16}N excited by muon capture in ^{16}O (arbitrary units). Top: monopole and quadrupole states. Bottom: individual dipole states; their total, and total from top of figure (broken curves); total neutron spectrum (heavy curve).

Gamow-Teller Transitions



A **Gamow–Teller transition** is, fundamentally, a type of β decay in which the spin vectors of the released electron and electron antineutrino are parallel. In contrast, a **Fermi transition** is a β decay in which the spin vectors of the released electron and electron antineutrino are anti-parallel.

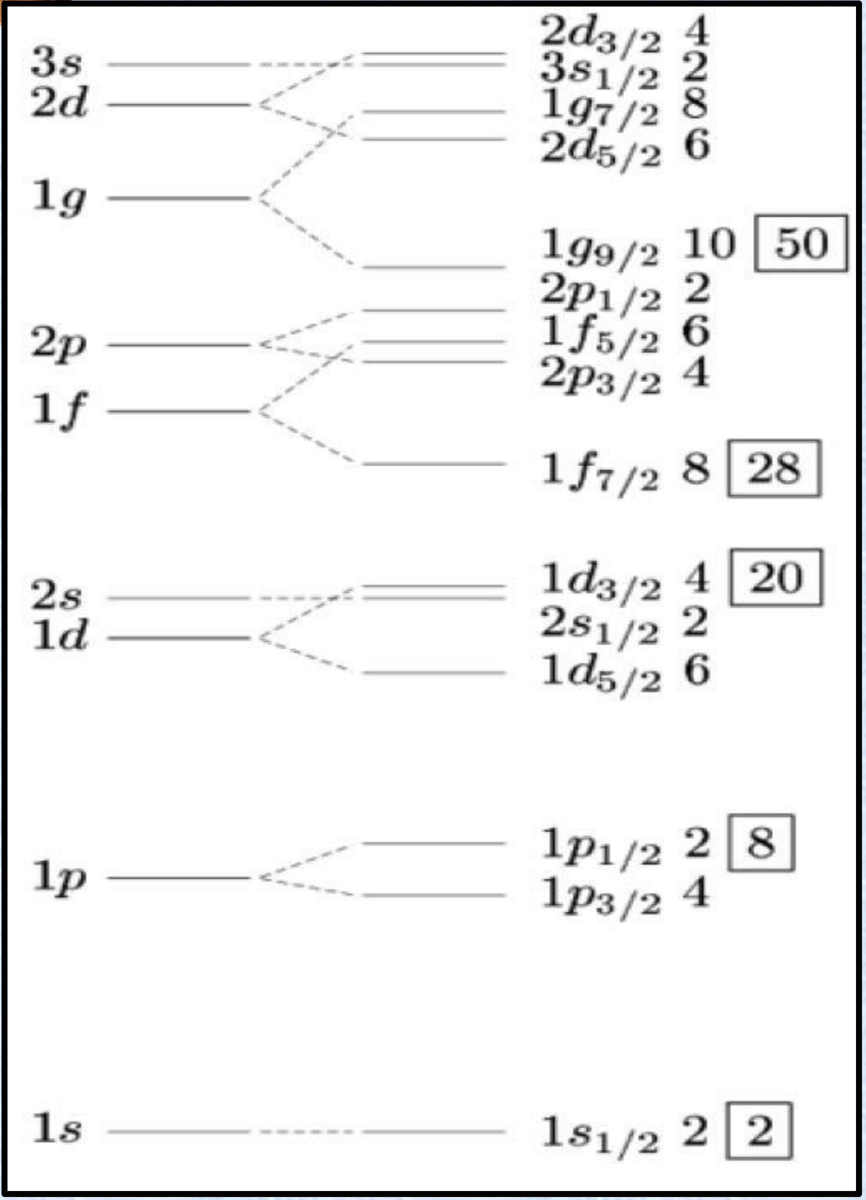
In terms of the interaction Hamiltonian, the probability amplitude from parent to daughter nucleus in a beta-decay forms 2 possible final states: [1]

$$\hat{H}_{\text{int}} = \begin{cases} \hat{1}\hat{\tau} & \text{Fermi decay} \\ \hat{\sigma}\hat{\tau} & \text{Gamow–Teller Decay} \end{cases}$$

$\hat{\tau}$ = isospin transition matrix which turn protons to neutrons and vis-versa

$\hat{\sigma}$ = rotation matrix which changes parent nucleus parity from $0 \rightarrow 1$.

Shell Model States



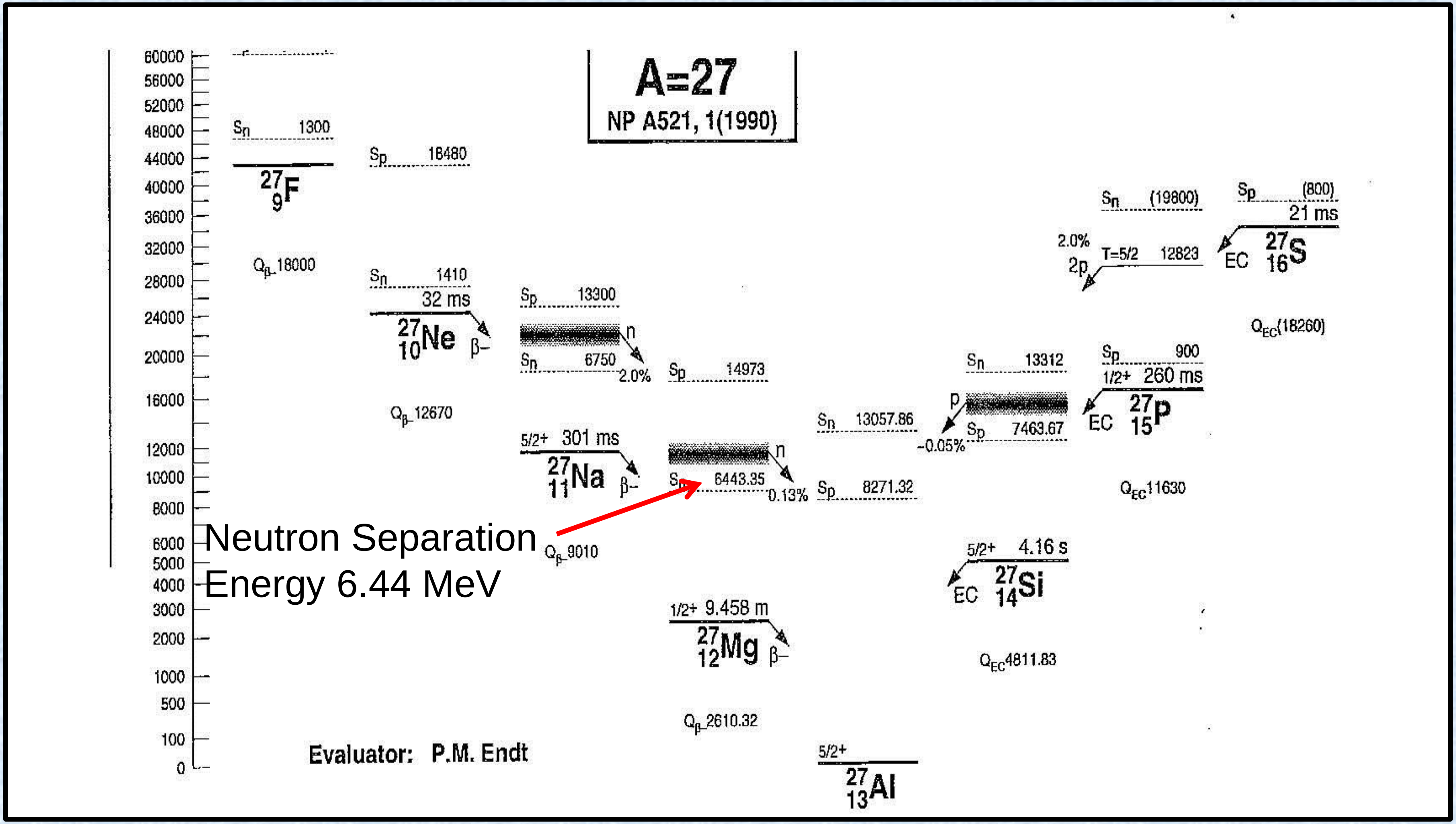
$_{13}^{27}\mathrm{Al}_{14}$

GS Spin $5/2^{+}$
Not a good single particle
Shell model nucleus

13 – protons
14 – neutrons
μ-capture is a GT transition
ΔI = 0,1, spin flip

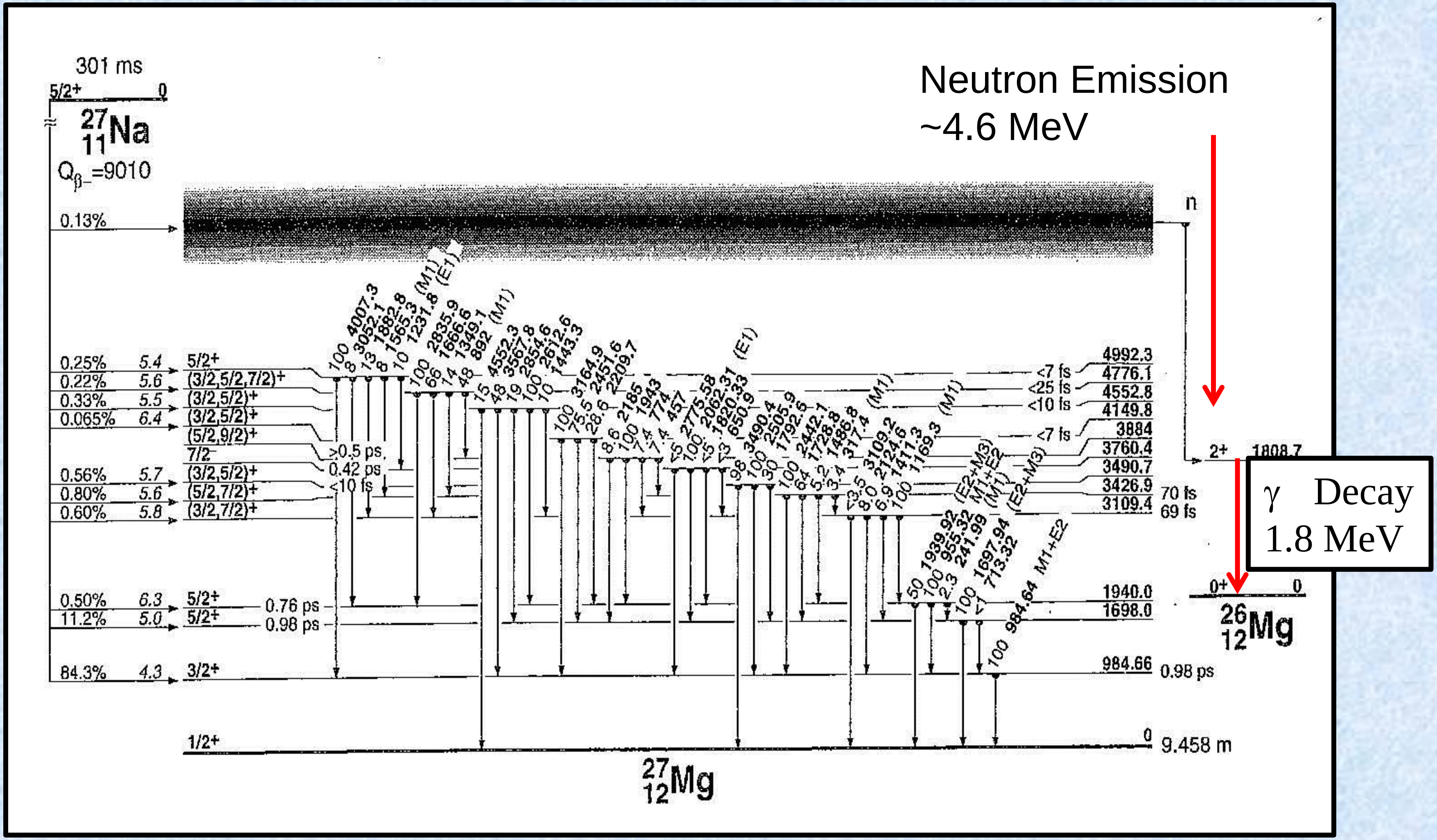
GT States J = $3/2^{-}, 5/2^{-}, 7/2^{-}$
GS Spin $_{12}^{27}\mathrm{Mg}_{15}$
J = $1/2^{+}$

^{27}A Nuclides



Neutron Separation Energy 6.44 MeV

^{26}Mg Level Diagram



Neutron Emission
~4.6 MeV

γ Decay
1.8 MeV

Count Rates

Contribution	Rate or ratio
Mu-beam/s	10^4
Mu-stop/s Thick Target	$\sim 10^4$
Capture/Mu-stop	0.74
# single n/Mu-stop	0.39
Detector $\Delta\Omega$	0.016
Detector Efficiency	0.25
Neutron Attenuation	0.4
# Detectors	2
Single Neutron/s	92
Ratio (N/peak)/Total N	0.03
Counts in Peak/s	0.3