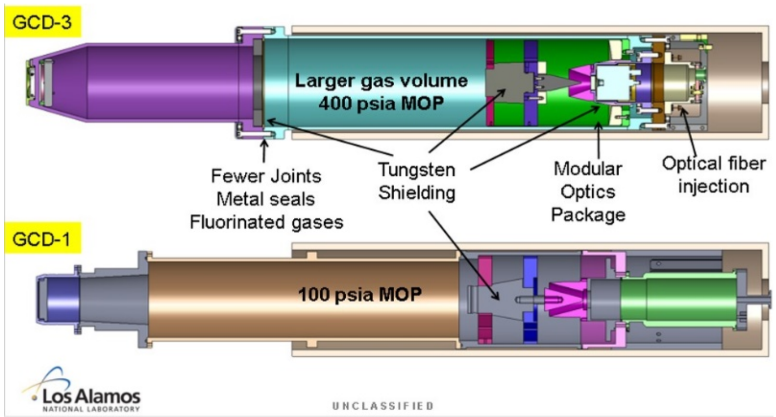
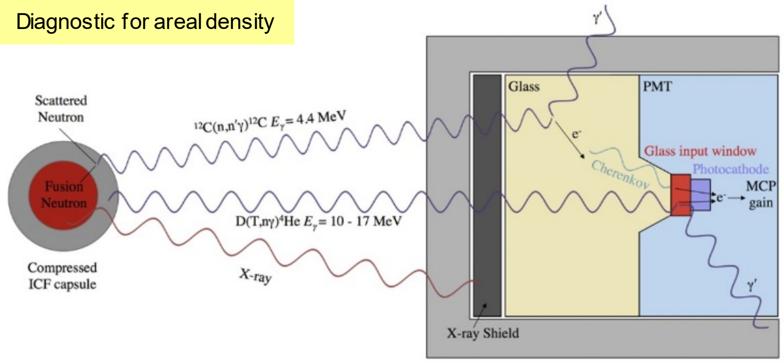
S-Factor Measurements for Gamma-Channel Fusion Reactions



Diagnostic for areal density



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Summary

Temporally resolved Cherenkov detectors were used to study gamma-channel fusion reactions D(T,^{5}He)γ, H(D,^{3}He)γ, and H(T,^{4}He)γ

- **Target and laser parameters were varied on OMEGA implosions to span a wide range of ion temperatures**
- **Branching ratios/S factors were determined over ion temperatures 4-18 keV**

Reaction	γ energy (MeV)	ICF measurement
D(T,^{5}He)γ	10 - 17.5	Branching ratio
H(T,^{4}He)γ	19.8	S factor
H(D,^{3}He)γ	5.5	S factor

Collaborators

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Lawrence Livermore National Laboratory

The S factor is used to determine the rate of fusion reactions as they occur in high-density astrophysical environments

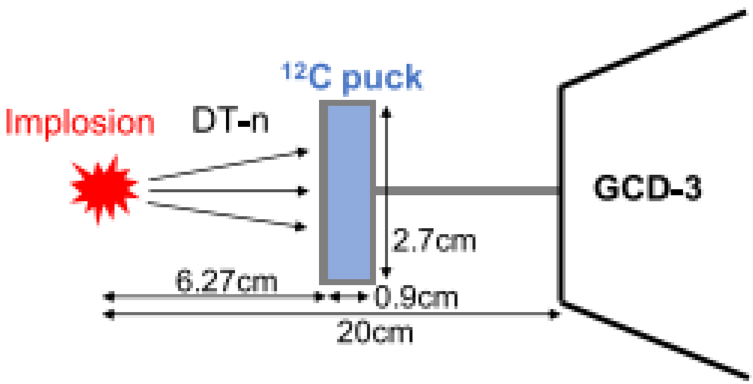
- $S(E) = \dfrac{E}{\exp(-2\pi\eta)}\sigma(E), \quad \eta = \dfrac{Z_1 Z_2 \alpha e^2}{\hbar v}$
  - S factor accounts for Coulomb repulsion between the reactants via Gamow factor $\exp(-2\pi\eta)$
- S factor for gamma branch fusion reactions can be determined in reference to neutron branch

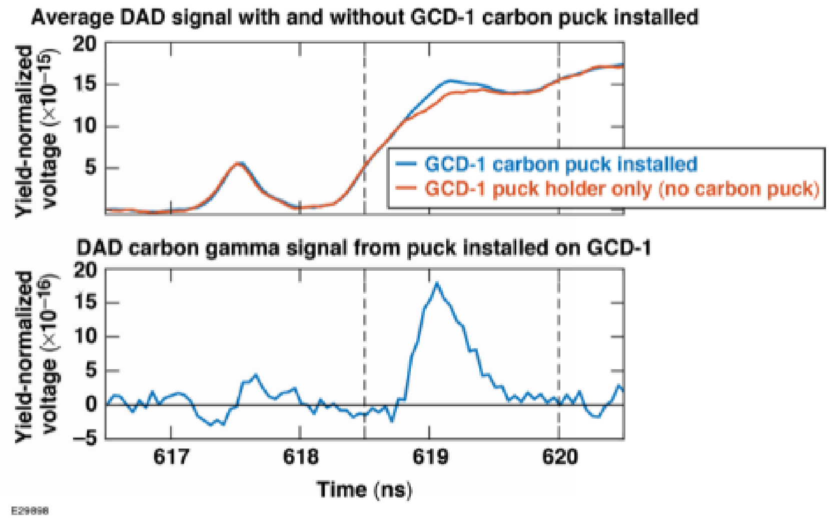
$$S_{HD\gamma} = S_{DDn}\frac{Y_{HD\gamma}}{Y_{DDn}}\left[\frac{n_D A_{HD}}{2n_H A_{DT}}\frac{\xi_{DD}{}^2 e^{-3\xi_{DD}}}{\xi_{HD}{}^2 e^{-3\xi_{HD}}}\right]$$

OMEGA offers a unique opportunity to study these astrophysically-relevant reactions in a plasma environment.

Carbon calibration* is currently the best method of calibrating gamma time-of-flight detectors for use at ICF facilities

- **Implosion-based experiments occur on short time scales**
  - **Calibration methods for traditional pulse-height gamma detectors cannot be used**



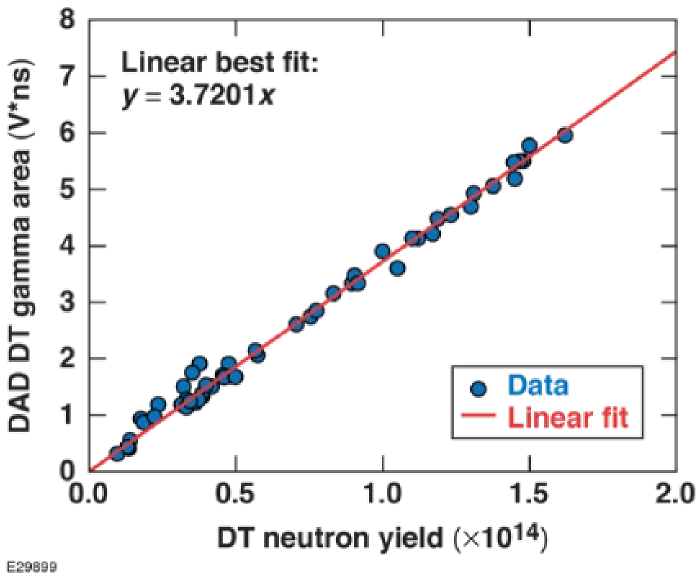


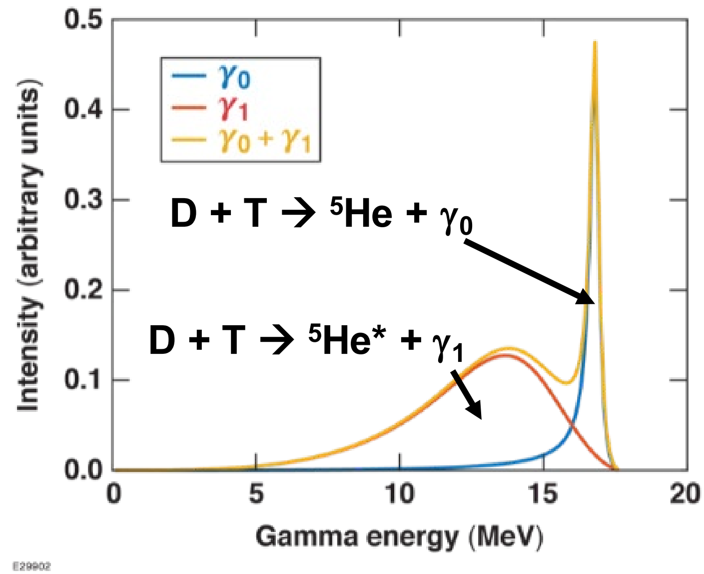
$$\chi = \frac{A}{Y_{DTn}\,\Omega\,R\,e\,QE\,G\,C_{ph}(4.4\ MeV)}\frac{m_C}{f_1\,\sigma}\frac{4\pi D^2}{M_{puck}}$$

- *Zylstra *et al.*, “Improved calibration of the OMEGA gas Cherenkov detector.” *RSI 90* (2019): 123504.

DT γ-to-n branching ratio was determined based on DAD data with carbon calibration

- Data set included 52 *cryogenic* DT shots with ion temperatures 2.7- 6.4 keV (E_{CM} = 14-26 keV)
- Branching ratio = $\frac{Y_{DT\gamma}}{Y_{DTn}}$, with $Y_\gamma = \frac{A_\gamma}{\Omega\, R\, e\, QE\, G} \frac{1}{C_{ph}(E_\gamma)\,\chi} \longrightarrow \frac{Y_{DT\gamma}}{Y_{DTn}} = \frac{A_{DT\gamma}}{Y_{DTn}} \frac{1}{\Omega\, R\, e\, QE\, G} \frac{1}{C_{ph}(E_\gamma)\,\chi}$
- Response must be weighted by characteristic DT γ energy spectrum*

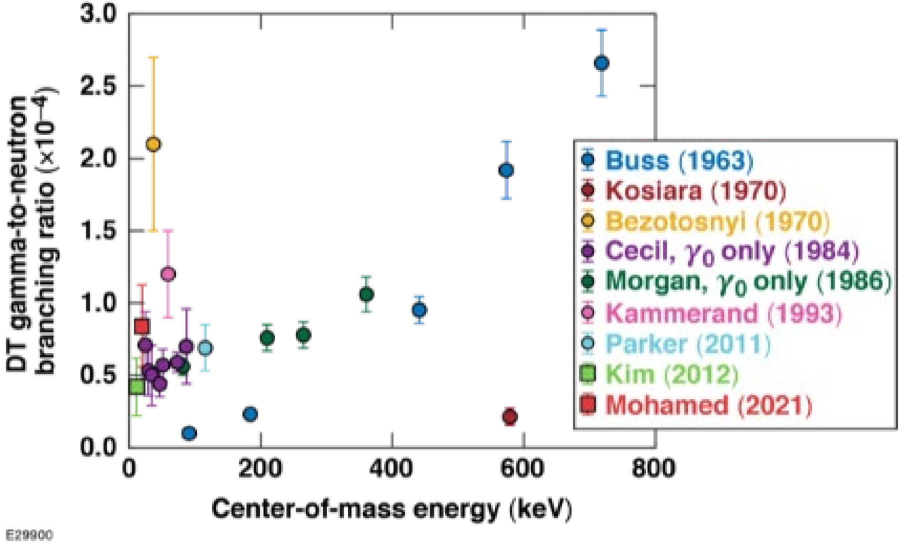




- *Horsfield *et al.*, “First spectral measurement of deuterium-tritium fusion γ rays in inertial fusion experiments.” *PRC 104* (2021): 024610.

DT γ-to-n branching ratio was determined based on DAD data with carbon calibration

- **Final branching ratio of $(8.42 \pm 0.86_{stat} \pm 1.98_{sys}) \times 10^{-5}$**
  - **Uncertainty includes contribution from Cherenkov statistics***
- **This is ~2x larger than the previous implosion-based measurement**, but agrees within error bars**
  - **This measurement is more consistent with accelerator measurements of γ_0 if the recently measured $\gamma_1 : \gamma_0$ ratio ≈ 2:1*** is assumed**



- Mohamed *et al.*, "Updated DT gamma-to-neutron branching ratio determined using HED plasmas." In preparation, to be submitted to *PRC*.
- *Zylstra *et al.*, "^{2}H(p,γ)^{3}He cross section measurement using high-energy-density plasmas." *PRC* (2020): 042802.
- **Kim *et al.*, "D-T Gamma-to-Neutron Branching Ratio Determined from Inertial Confinement Fusion Plasmas." *PoP 19* (2012): 056313.
- ***Horsfield *et al.*, "First spectral measurement of deuterium-tritium fusion γ rays in inertial fusion experiments." *PRC 104* (2021): 024610.

HT & HD experiments were designed to span a wide range of ion temperatures

- **Ion temperature was varied using fill pressure, laser energy, and/or pulse shape**

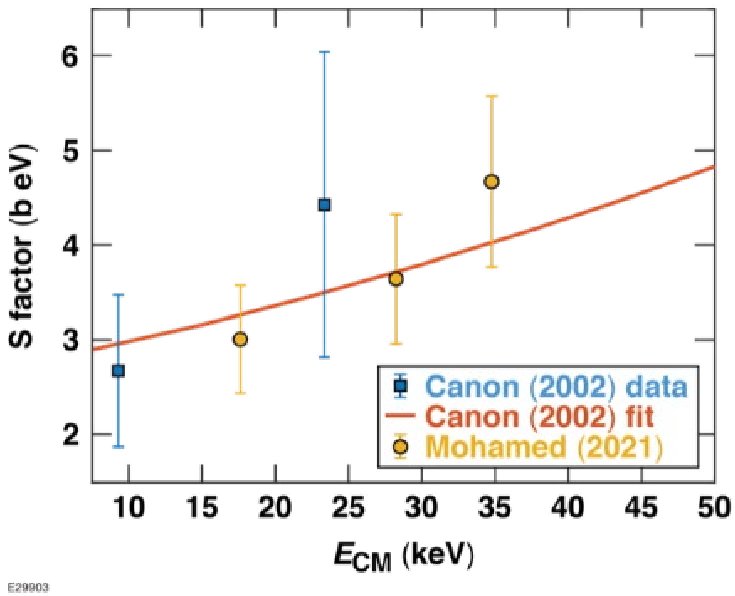
	$H(T,^4He)\gamma$ $E\gamma$ = 19.8 MeV	**$H(D,^3He)\gamma$ $E\gamma$ = 5.5 MeV**
Neutrons measured from	$D(T,^4He)n$	$D(D,^3He)n$
Ion temperatures (keV)	4.6, 9.0, 12.7	5.2, 7.6, 16.3
CM energies (keV)	18, 28, 36	18, 23, 40
Gamma background from	$D(T,^5He)\gamma$ *	$D(D,^4He)\gamma$
Gamma detectors	GCD-1 (100 psi CO_2)	GCD-3 (400 psi CO_2)

- *Kim *et al.*, "D-T Gamma-to-Neutron Branching Ratio Determined from Inertial Confinement Fusion Plasmas." *PoP 19* (2012): 056313.

H(T,^{4}He)γ S factor was inferred using the D(T,^{4}He)n S factor** as reference

- **Only one previous measurement was available within this range of low CM energies**
- **Trend in GCD-1 measurement appears to agree with fit to accelerator data***

$$S_{HT\gamma} = S_{DTn}\frac{Y_{HT\gamma}}{Y_{DTn}}\left[\frac{n_D A_{HT}}{n_H A_{DT}}\frac{\xi_{DT}{}^2 e^{-3\xi_{DT}}}{\xi_{HT}{}^2 e^{-3\xi_{HT}}}\right]$$

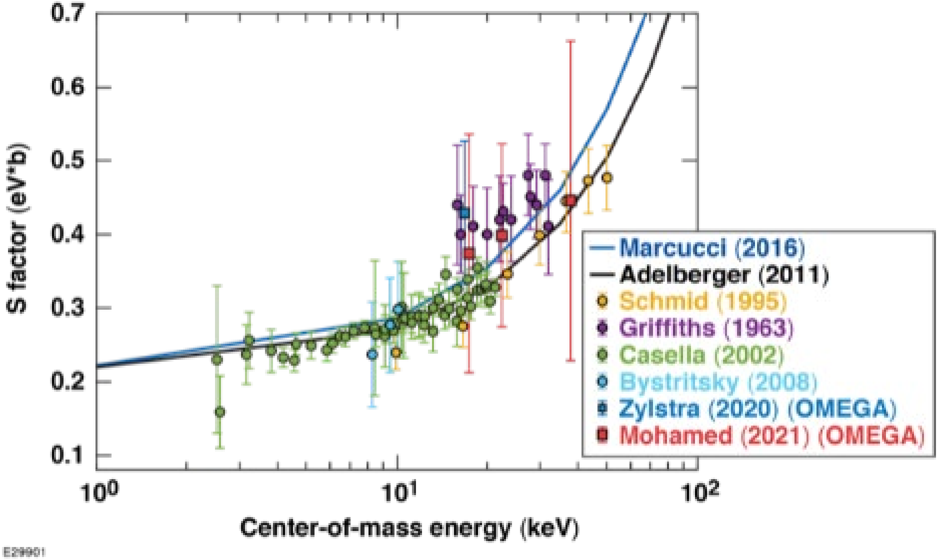


- *Canon *et al.*, "^{3}H(p,γ)^{4}He reaction below Ep = 80 keV." *PRC* (2002): 044008.
- **Bosch & Hale, "Improved formulas for fusion cross-sections and thermal reactivities." *Nucl. Fus. 92* (1992): 043546.

H(D,^{3}He)γ S factor was inferred using the D(D,^{3}He)n S factor** as reference

- **Relatively large error bar is due to calibration uncertainty (13%)** and statistics**
  - **Could be improved with additional shot days to improve statistical uncertainty**
- **The inferred S factor appears to agree with accelerator results**

$$S_{HD\gamma} = S_{DDn}\frac{Y_{HD\gamma}}{Y_{DDn}}\left[\frac{n_D A_{HD}}{2n_H A_{DT}}\,\frac{{\xi_{DD}}^2 e^{-3\xi_{DD}}}{{\xi_{HD}}^2 e^{-3\xi_{HD}}}\right]$$



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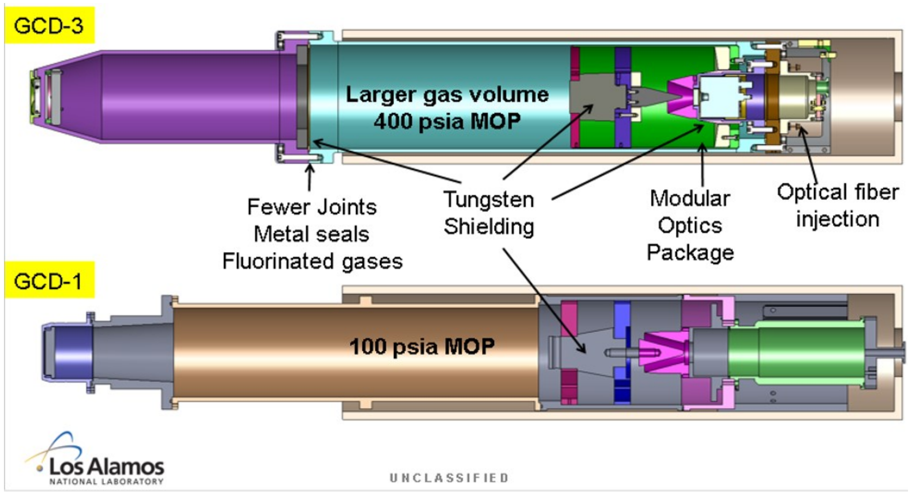
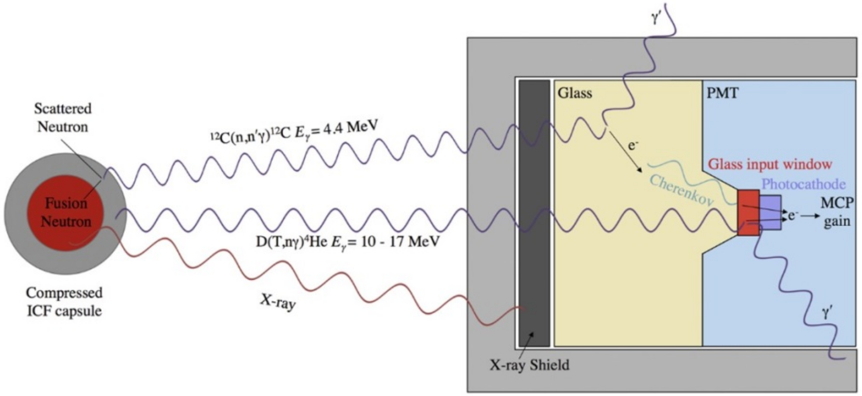
Backup slides

Cherenkov detectors were used to study γ-branch fusion reactions D(T,^{5}He)γ, H(D,^{3}He)γ, H(T,^{4}He)γ





Gas Cherenkov Detectors (GCD-1/GCD-3)

- **TIM-based detectors**
- **Pressurized gas is used as Cherenkov radiator**

Diagnostic for Areal Density (DAD)

- **Located on target chamber wall**
- **Quartz is used as Cherenkov radiator**

- Berggren *et al.*, "Gamma-ray-based fusion burn measurements." *RSI 72* (2001): 873.
- McEvoy *et al.*, "Gamma ray measurements at OMEGA with the Newest Gas Cherenkov Detector GCD-3." *J. Phys. Conf. Ser 717* (2016): 012109.
- Rubery *et al.*, "First measurements of remaining shell areal density on the OMEGA laser using the Diagnostic for Areal Density (DAD)." *RSI 89* (2018): 083510.

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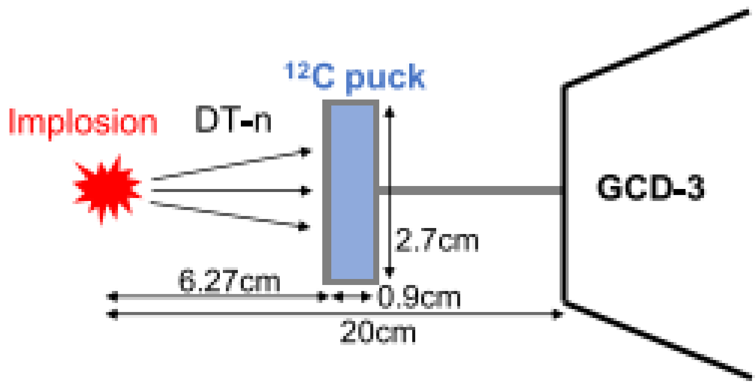

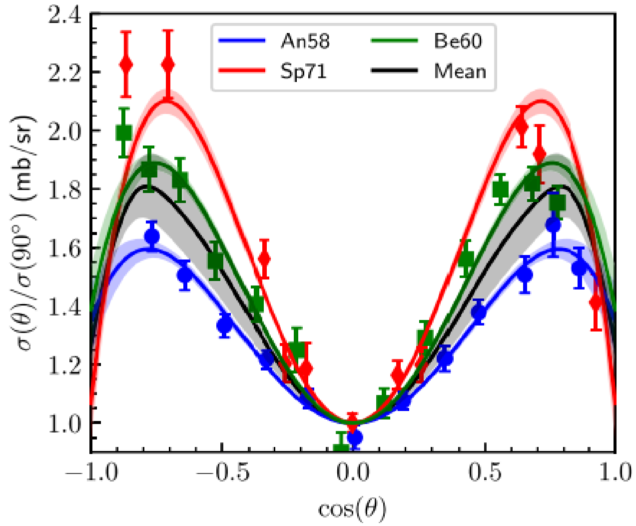

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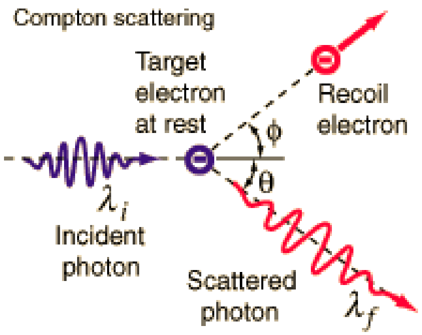
Gamma rays can be measured using Cherenkov detectors

- These detectors usually consist of a crystal, glass, or reservoir of gas coupled to a photomultiplier tube (PMT)
- Incident gamma rays Compton scatter with electrons
  - If an electron has a speed greater than c/n, electromagnetic radiation is produced in the form of photons ("Cherenkov radiation")
- Cherenkov detectors can also detect neutrons
  - Neutrons strike a nucleus, which enters an excited state and emits a gamma ray when returning to the ground state



http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/comptint.html

Error analysis for gamma-channel reactions includes statistical contribution from Cherenkov photons*

- Poisson statistics are applicable to the number of detector events (i.e., Cherenkov electrons)
  - Each electron can produce several Cherenkov photons
  - There is variation in the bunch size
- Statistical uncertainty can be calculated such that $\sigma_N = N\sqrt{\frac{1}{N_{Ch}} + \frac{V_{Ch}}{\mu_{Ch} N} + \sqrt{N}}$
  - N_{Ch} = number of Cherenkov photons
  - μ_{Ch} = mean bunch size
  - V_{Ch} = variance of the bunch size
  - $N = N_{Ch}/\mu_{Ch}$ = number of detector events (i.e., number of Cherenkov-radiating electrons)

Cherenkov photon and bunch size distributions were generated via Geant-4 simulations* performed by M. S. Rubery (LLNL)

GCD-1 HT γ

DAD HT γ