# Gray as an impractical radiation dose unit


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- QUESTION: **Do Gray and its derivative units capture physiochemical processes that radiation induces in material media?**
- Note: Living organisms are material media too.
- We use these units to

    Medical: diagnostics and therapy

    Occupational: radiation workers

    Civilians : evacuations - uproot the population (Namie- Fukushima)

# Historical Developments

- 1895 - Discovery/Invention of X-rays Röntgen
- 1896 - Discovery of Radioactivity - Becquerel
- 1896 - First medical imaging - Glasgow hospital
- 1897 - Discovery of electron - Thomson
- 1906 - First UK patent of Food Irradiation -- Appleby &Banks
- 1932 - Cyclotron Invented - Ernest Lawrence
- 1936 - First Medical Isotope administered - John & Ernest Lawrence
- 1958 - World's first commercial use of Food Irradiation - Germany
- 1990 - First treatment by Proton Therapy - USA

Radiation dose has been of concern soon after the X-rays were discovered/invented

# Radiation dose - Exposure

Exposure- Röntgen = 1 esu of charge /cc of air (1908)

1 esu = $3.336 \times 10^{-10}$ C (0.336 nC)

Density of air STP = 1.225 mg/cc (1.225 kg/$m^3$)

RAD is the energy deposit corresponding to 1 REM exposure (1953)

1 RAD= $2.72 \times 10^{-4}$ C/kg = $1.61 \times 10^{15}$ charges/kg

Ionization is the measure of dose for nearly 45 years

Ionization changes molecular compositions, produces radicals, changes chemical composition with biological implications.

# Radiation Dose unit- ELDA E. ANDERSON, Ph.D.

https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2030726/pdf/pubhealthreporig01075-0073.pdf

(1952)

*A unit of radiation dose should be readily reproducible and should be measurable in terms of simple physical quantities by routine instrumentation.*

***In most cases the ultimate information desired is the biological damage produced by a given dose of radiation; hence, it would be desirable to have our unit of radiation dose proportional to the biological damage produced.***

However, the factors involved in radiation damage are so complex and so little known that it has not been possible to devise a unit having both these physical and biological characteristics.

**The physical quantity selected must be capable of being measured with reasonable accuracy and of being expressed in absolute units.**

***Thus, the unit of dose may be either the energy absorbed from the radiation per unit mass or the ionization produced per unit of mass.***

**Radiations do more than energy deposits and ionizations----**
**transmutations, induced radioactivities, non-local effects,**

# Elda Anderson

- 1 esu of ion pairs produced per cc. of air.
- 2.083X$10^9$ ion pairs produced per cc. of air.
- 1.61X$10^{12}$ ion pairs produced per gm. of air.
- 6.77X 10' MeV absorbed per cc. of air.
- 5.24X $10^7$ MeV absorbed per gm. of air.
- 83.84 ergs absorbed per gm. of air.
- The dose expressed in roentgens is totally independent of the absorbing medium exposed to the radiation and of the amount of energy that the particular medium absorbs.

# Elda Anderson

- The roentgen-equivalent-man (rem) is that dose of any ionizing radiation which, delivered to man, is biologically equivalent to the dose of 1 roentgen of X or gamma radiation.
- The rem is not a measure of energy absorption or of ionization produced in tissue, but is rather a measure of a quantity of radiation that produces certain observed biological effects.

**REM:** Biological equivalence of different radiations and not equal amount of ionization or energy deposit

We are trying to get REM from Gray or Röntgen, which know nothing about biological aspects of medium that radiation interacts with.

# Gray

In 1940, Gray et al , defined a unit of measure (effect of neutron damage on human tissue):

"that amount of neutron radiation which produces an increment in energy in unit volume of tissue equal to the increment of energy produced in unit volume of water by one roentgen of radiation"[.

This unit was found to be equivalent to 83.8 ergs/cc in air.

In water medium, 1 REM = 0.0193 J/kg. (193 ergs/cc)

ionization potential: 33 eV in air; 36 eV in soft tissue and….

Emphasis is on energy deposit, but measured by the induced ionization. -- *atomic/molecular processes*

# Ionization Potentials .....

- In elements vary from ~ 3.8 – 24.6 eV ( Francium to Helium)
  hydrogen & oxygen 13.6 eV, carbon 11.3 eV, Calcium 6 eV

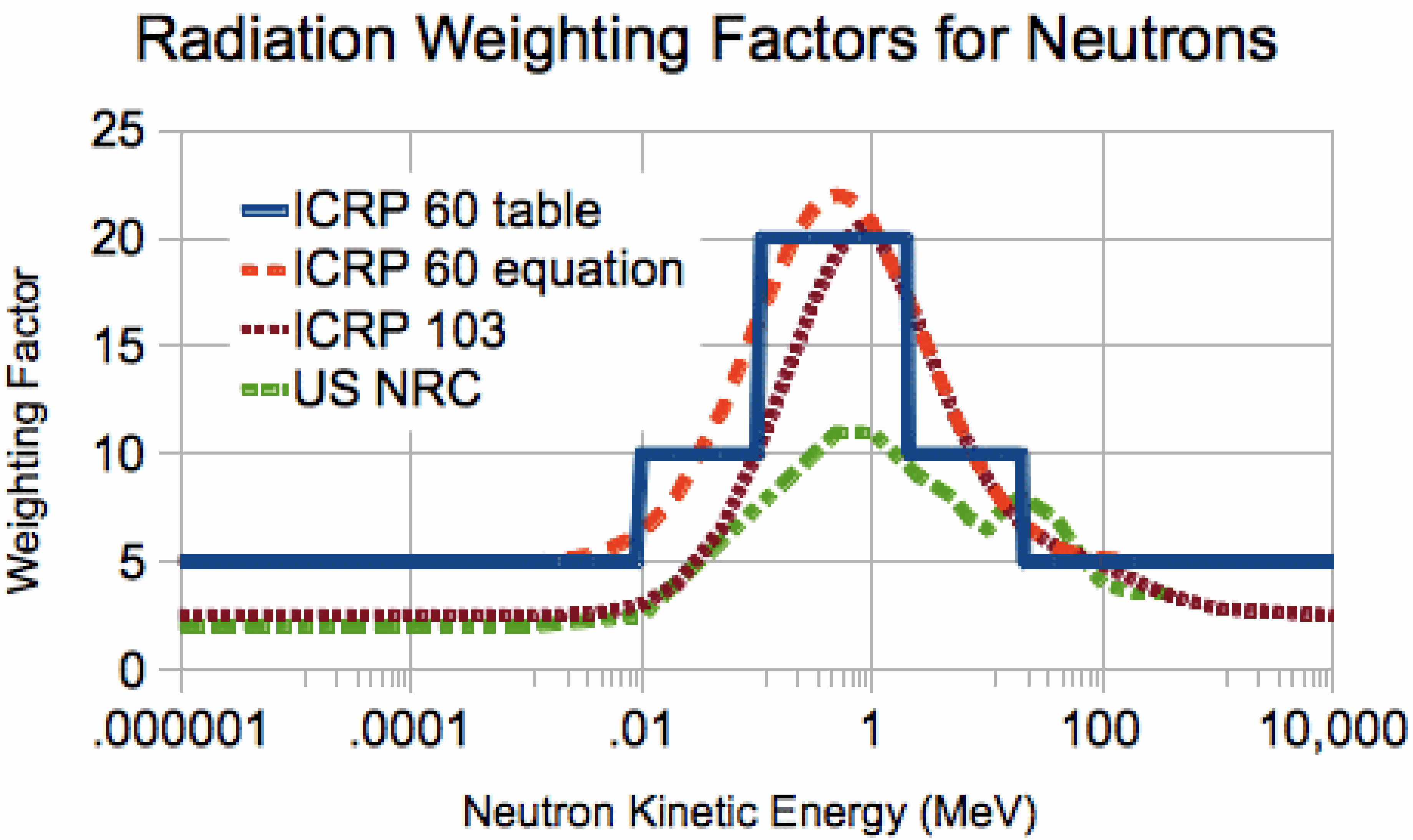
- Water 12.6 eV etc..

- Remember: Gray to Sievert

# Sievert

- We now define RBE H = Dose in Grays x Quality factor (Sv)

- Sievert = 100 REM, or Sievert is defined in terms of ionization.
- **Ignored that ionization potentials are medium dependent and ionization probabilities vary much with the type and energy of radiation**
- Adjust the quality factor for each radiation such that we get the SI equivalent of REM.
- For all practical purposes, we went back to pre-Gray era of focus on the ionization, but in an ambiguous way



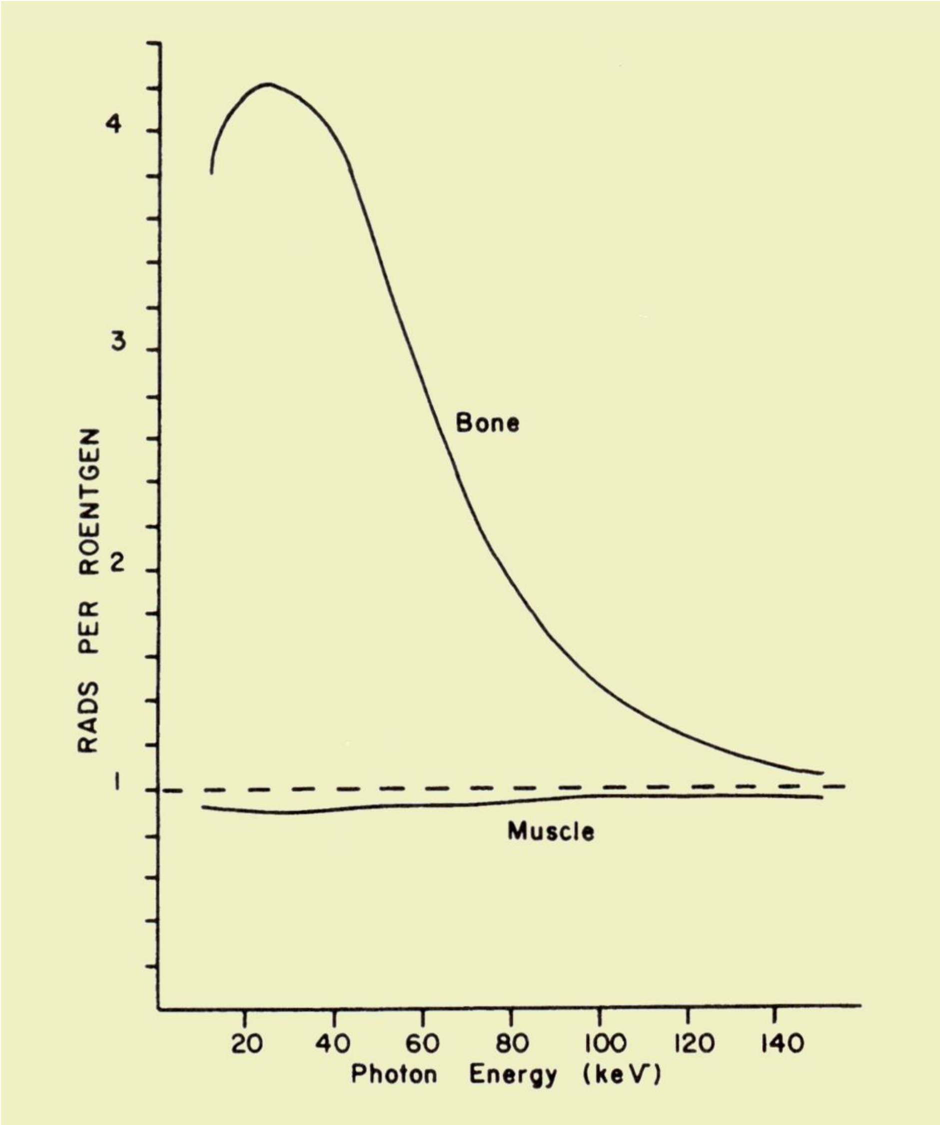

ICRP 103 (2007), ICRP 60 (1990)

How did they get this weighting factor?
Thermal neutrons can be deadly.

# Photons: RAD vs Röntgen

**Even for photons with Q=1, linear relation between RAD and Röntgen or GRAY and Sievert is not assured.**

**For bone, it changes about a factor of 4 for Photon energies 20-140 keV.**



# RBE - ICRP103, 2007

| Radiation | Energy WR (formerly Q) |
|---|---|
| x-rays, gamma rays, beta particles, muons | 1 |
| neutrons (< 1 MeV) | $2.5 + 18.2 \cdot e - [\ln(E)]^2/6$ |
| neutrons (1 - 50 MeV) | $5.0 + 17.0 \cdot e - [\ln(2 \cdot E)]^2/6$ |
| neutrons (> 50 MeV) | $2.5 + 3.25 \cdot e - [\ln(0.04 \cdot E)]^2/6$ |
| protons, charged pions | 2 |
| alpha particles, nuclear fission products, heavy nuclei | 20 |

**Does not recognize that pions decay producing muons and high energy electrons/positrons in the medium**

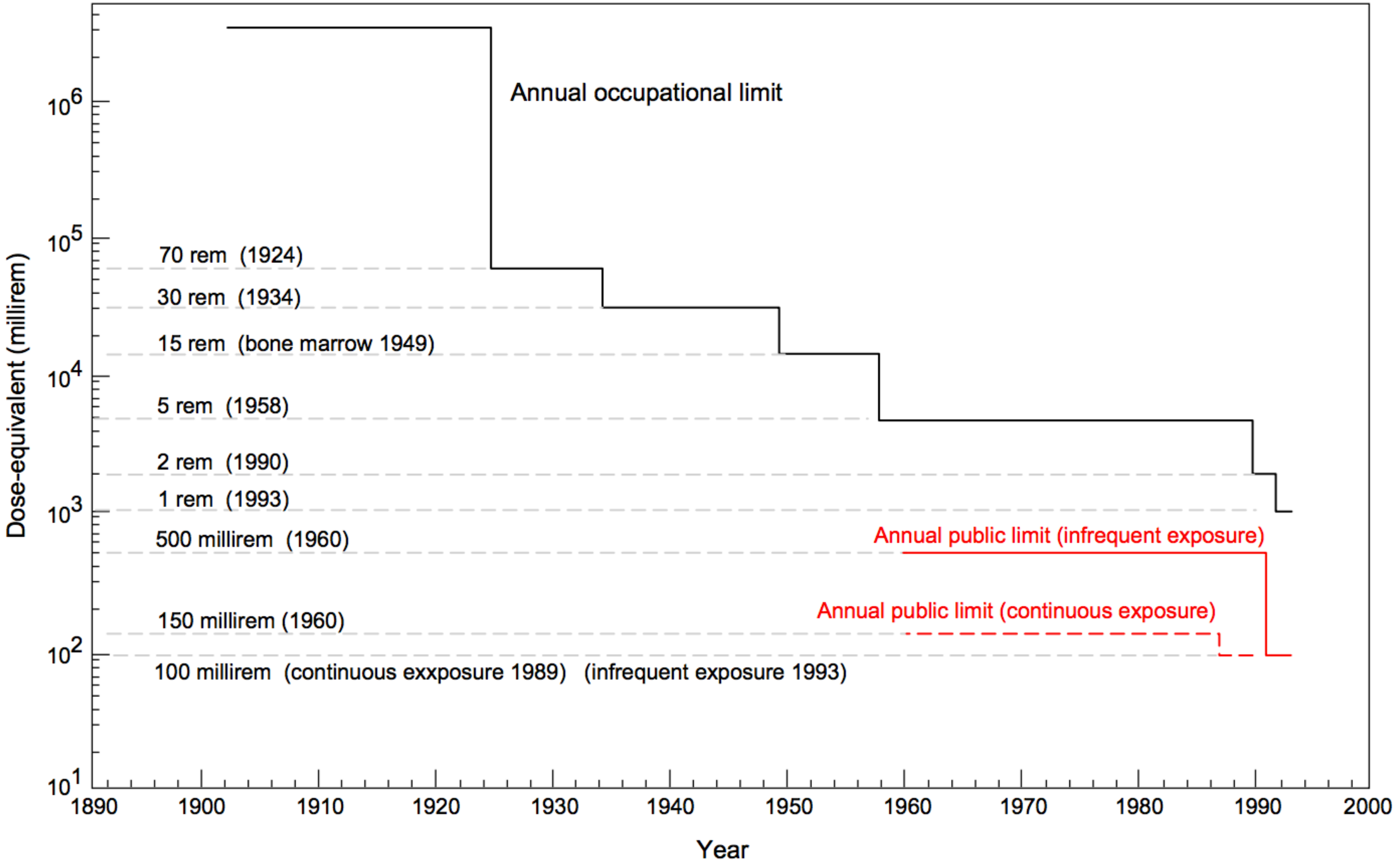
# US :  Nuclear Regulatory Commission

- For practical purposes,

1 R (exposure) = 1 rad (absorbed dose) = 1 rem or 1000 mrem (dose equivalent).

Thank you very much (Merci) that you clarified 1 rem = 1000 mrem

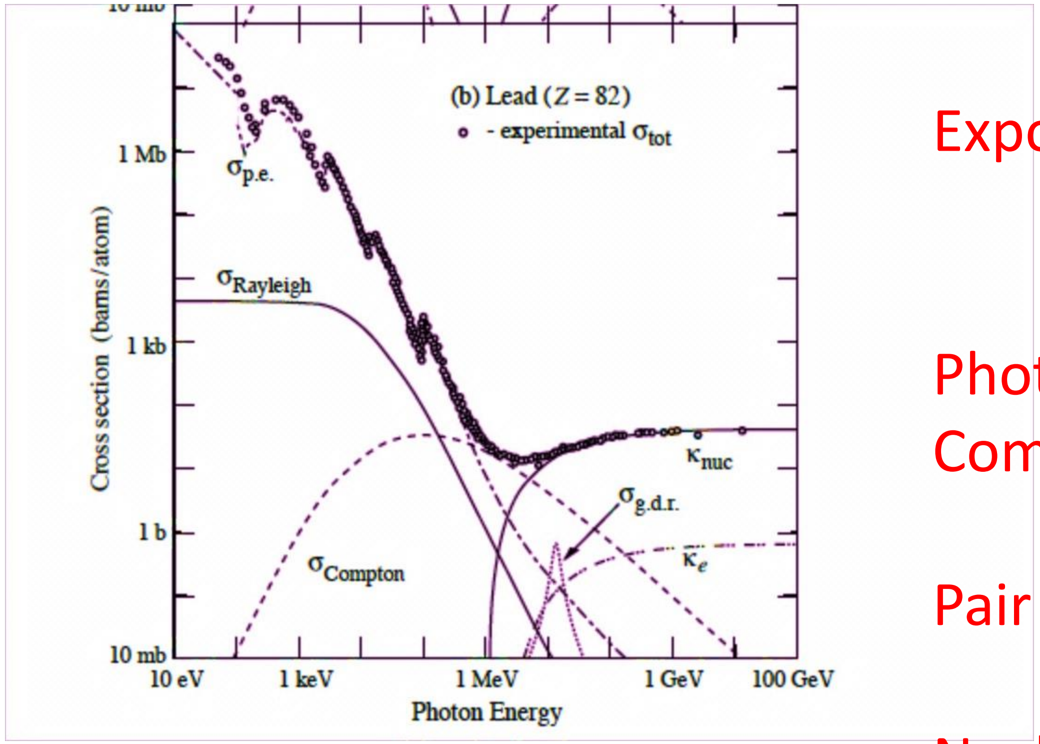
# Permissible Radiation Risk -




The trend is to make the limit lower and lower

- None of these prescriptions concern with nuclear transmutations or secondary radiations…..
- The units based on energy deposit or ionization do not either
- Might be okay with low energy photons, betas,  but ………

# Photon Interactions in Matter




Exponential Attenuation:

$$I(x)=I(0)e^{-\mu x}$$

Photo: Localized total energy deposit

Compton: Partial energy deposit in an interaction

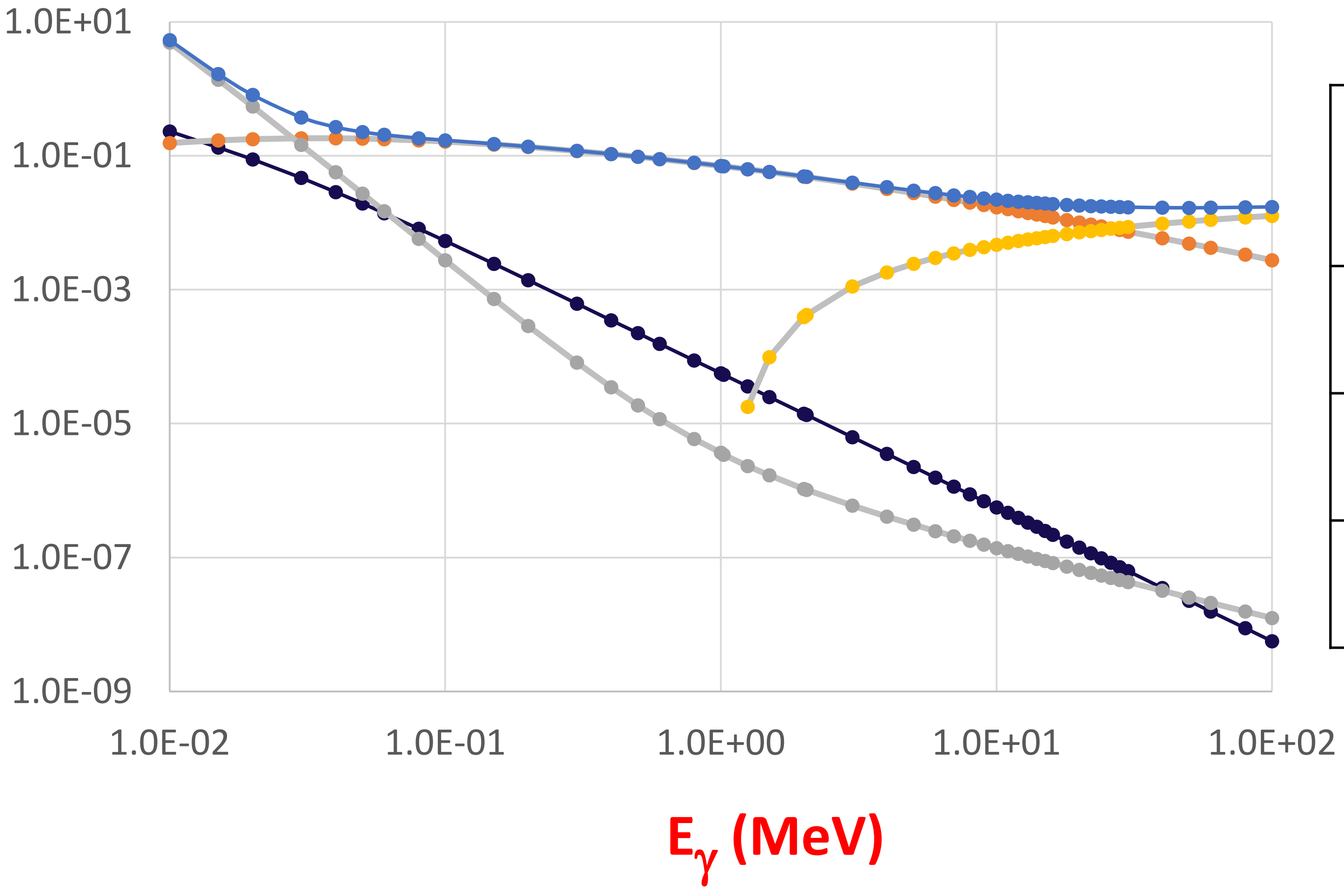
Pair production: secondary photons at a distance

Nuclear processes: Transmutations (permanent change in elemental composition of medium)

Note the neutron emitting GDR

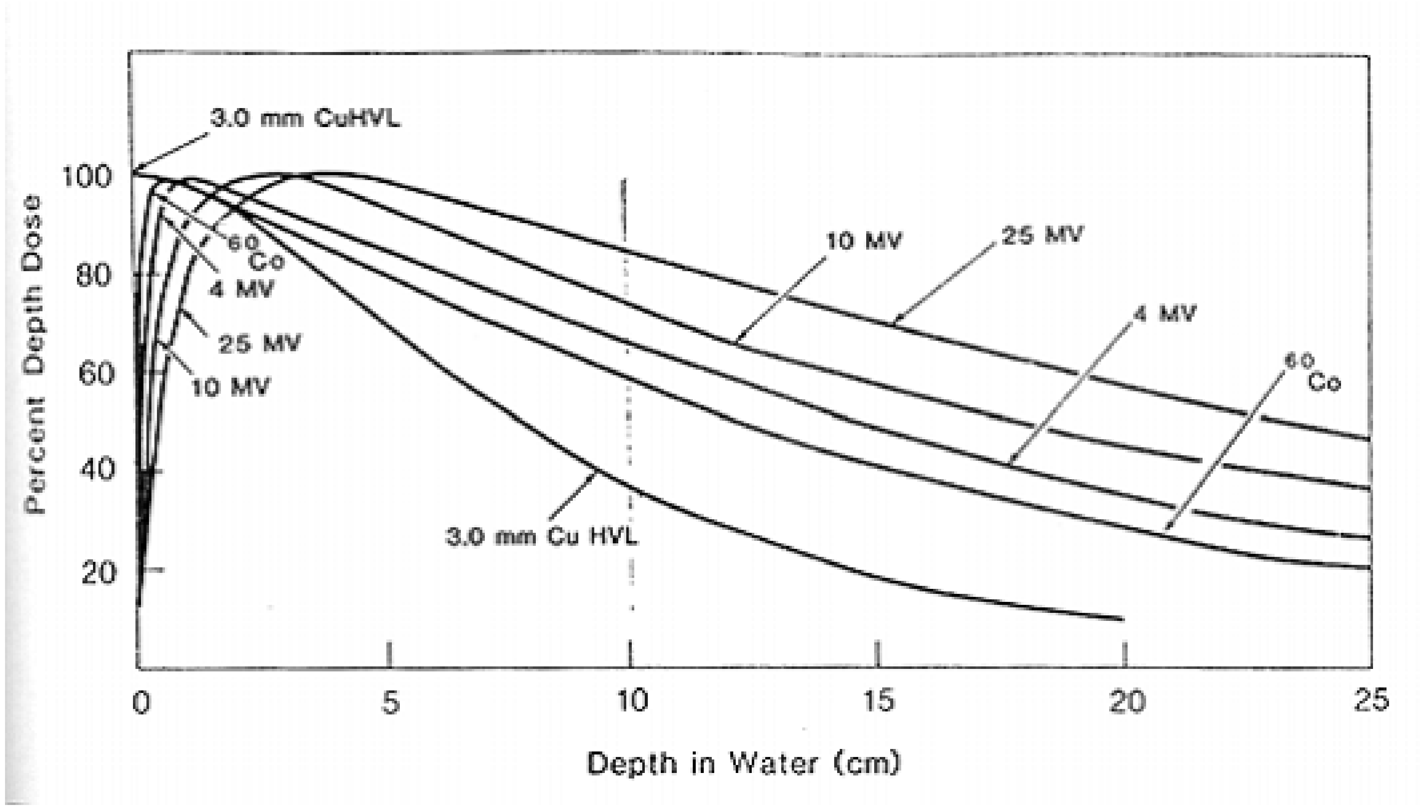
# Photon Interactions in Water

## Dose distribution is non-local

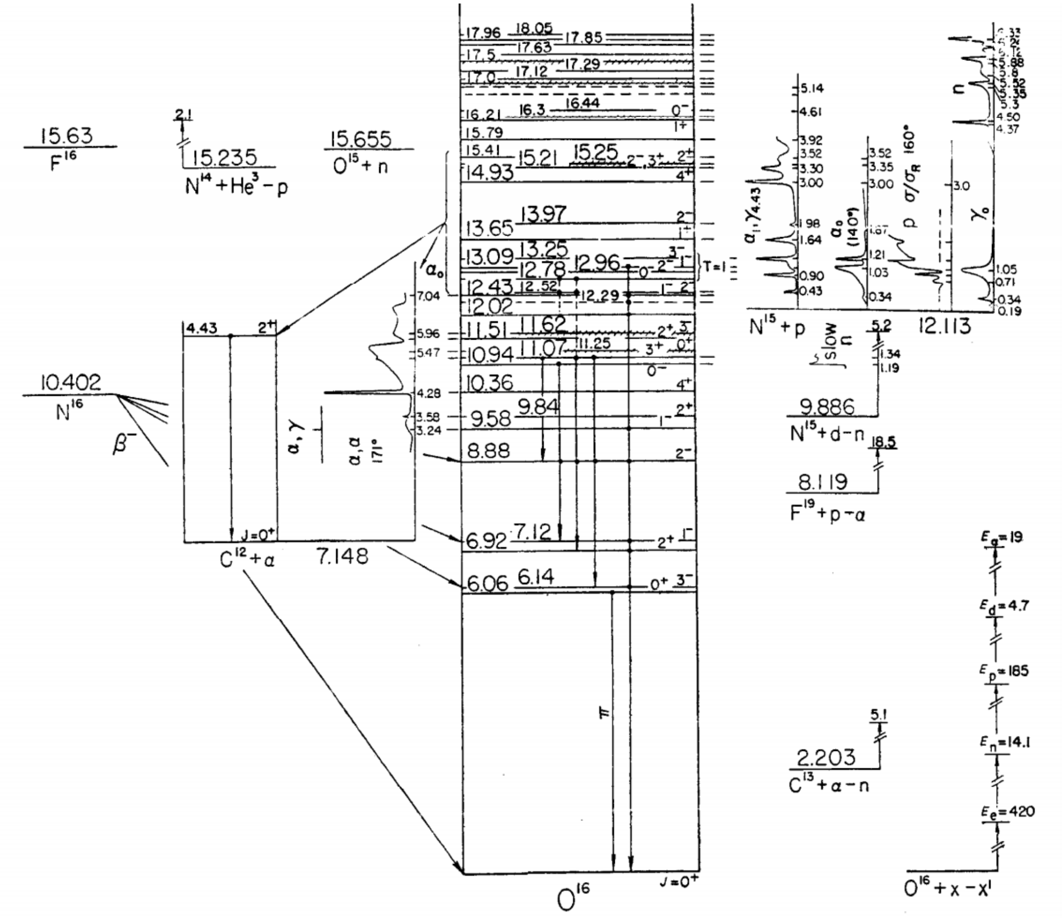



| E (MeV) | Photo | Total | Photo/Total |
|---|---|---|---|
| 0.1 | 2.8 E-03 | 0.17 | 1.6E-02 |
| 2.0 | 1E-06 | 0.05 | 3.2E-05 |
| 20 | 7E-08 | 0.02 | 3.5E-06 |

# Dose distribution of photons in water



# $^{16}O$ Levels

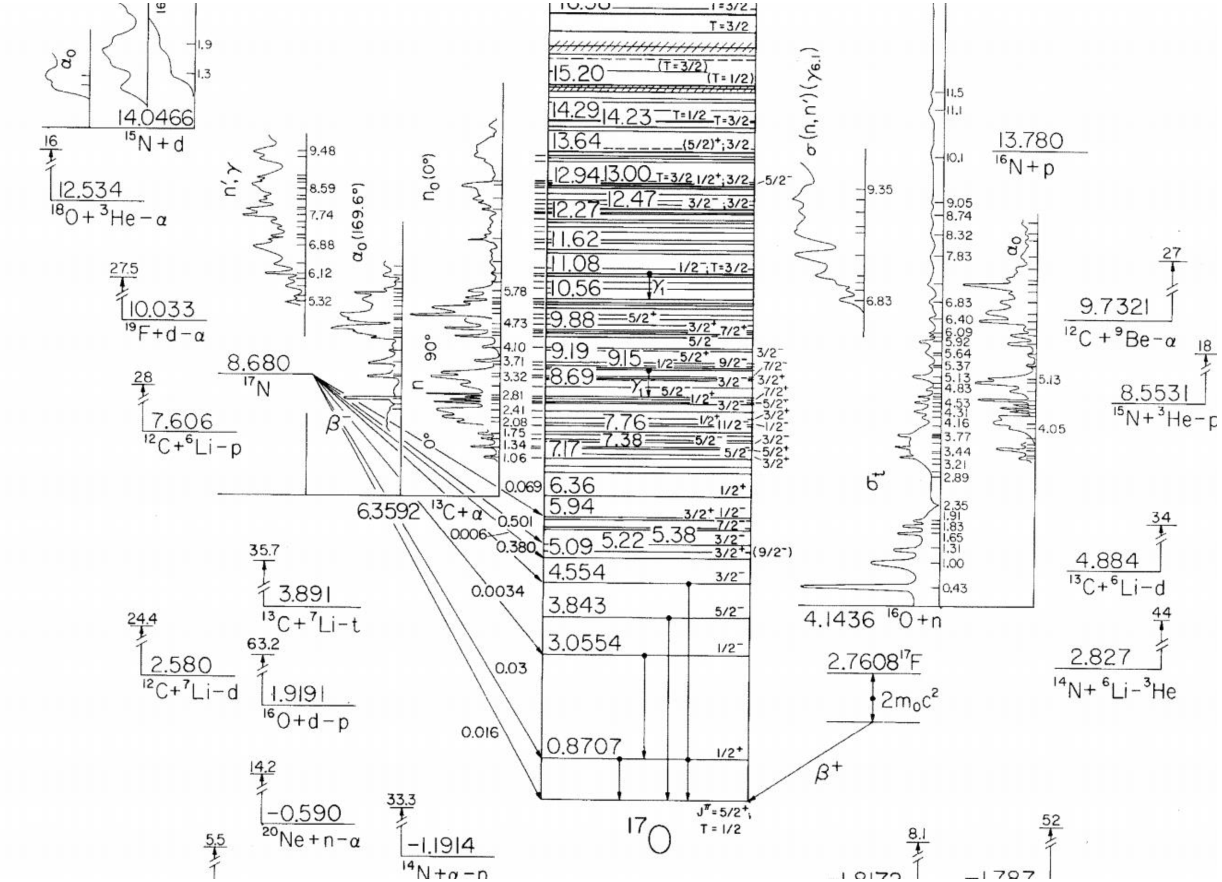



alpha emission threshold: 7.15 MeV

proton emission threshold: 12.11 MeV

neutron emission threshold: 15.65 MeV

# $^{17}$O level scheme

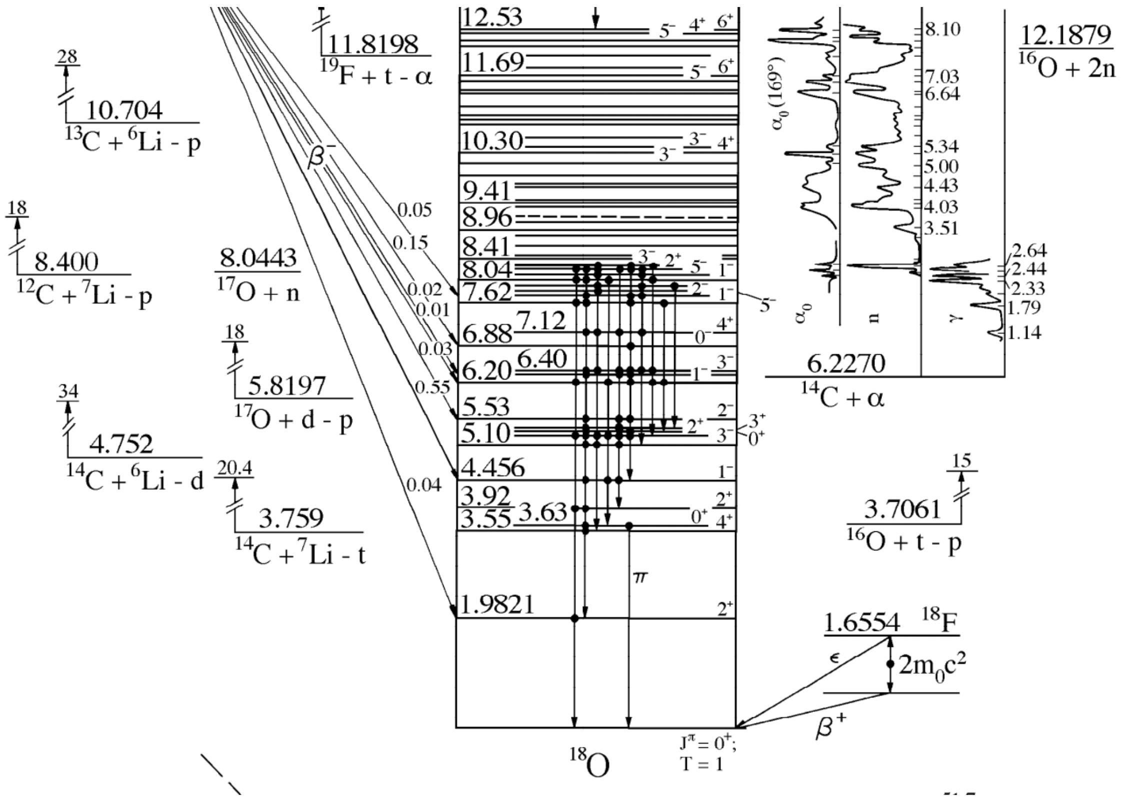



neutron emission threshold: 4.14 MeV

alpha emission threshold: 6.36 MeV

proton emission threshold: 13.78 MeV

# $^{18}O$- level scheme

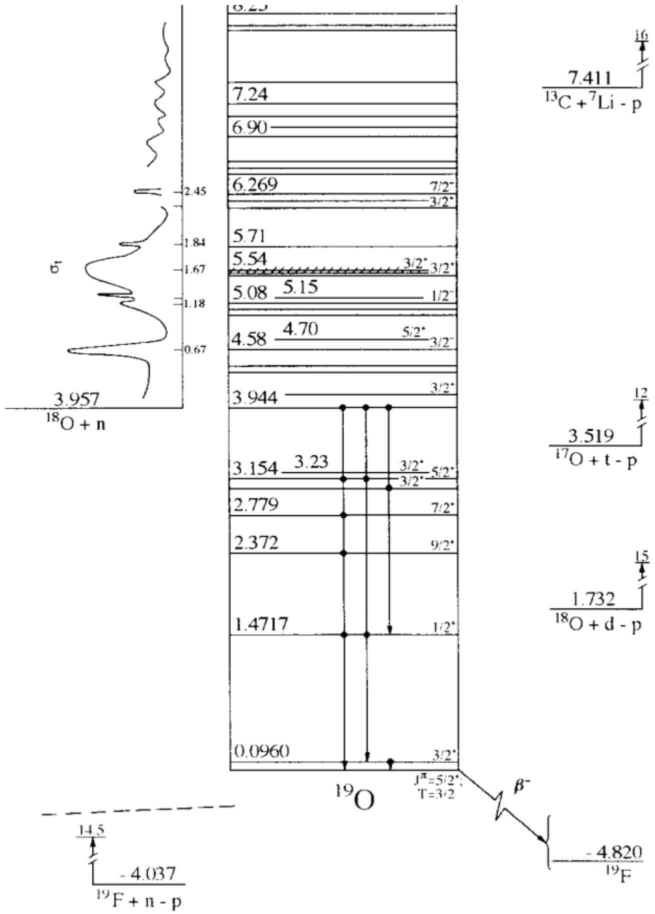



alpha emission threshold: 6.23 MeV

neutron emission threshold: 8.04 MeV

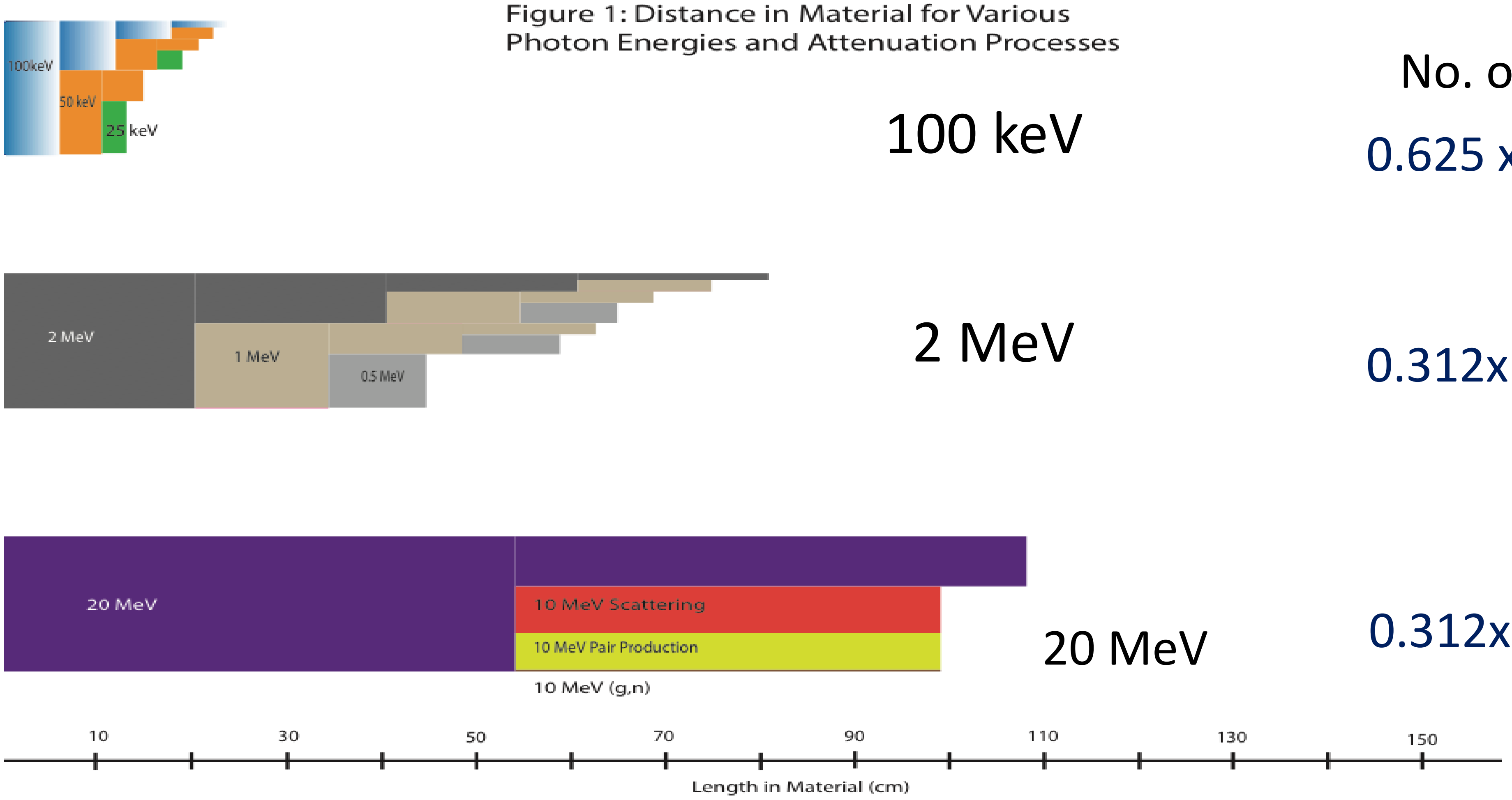
proton emission threshold: 15.95 MeV

# $^{19}O$ level scheme




- Up to 3.9 MeV gamma ray emission by neutron capture on 18-O

# Photon Intensity Losses in Water Medium




| | No. of photons |
|---|---|
| 100 keV | $0.625 \times 10^{14}$ |
| 2 MeV | $0.312 \times 10^{13}$ |
| 20 MeV | $0.312 \times 10^{12}$ |

**Small but non-zero nuclear transmutations & secondary neutrons at 20 MeV**

# Proton Interactions in Matter

- Continuous energy loss described by Bethe's formula $-\frac{dE}{dx} \propto \frac{Z}{A}\frac{\mathbb{Z}}{\beta^2}$

- Same particle continues its journey till it comes to rest (Bragg peak), not considering the nuclear processes.

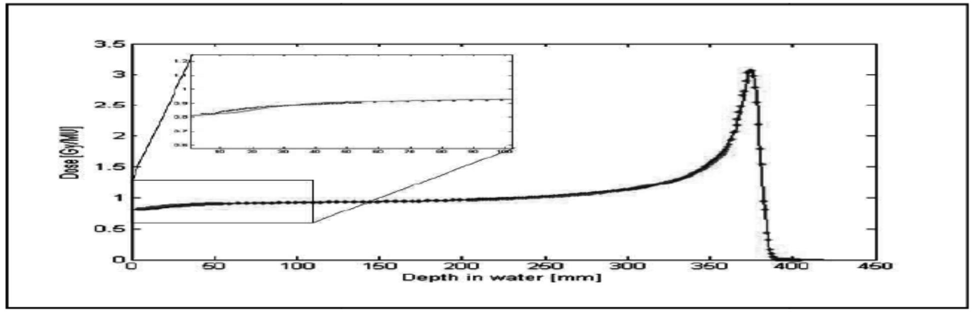
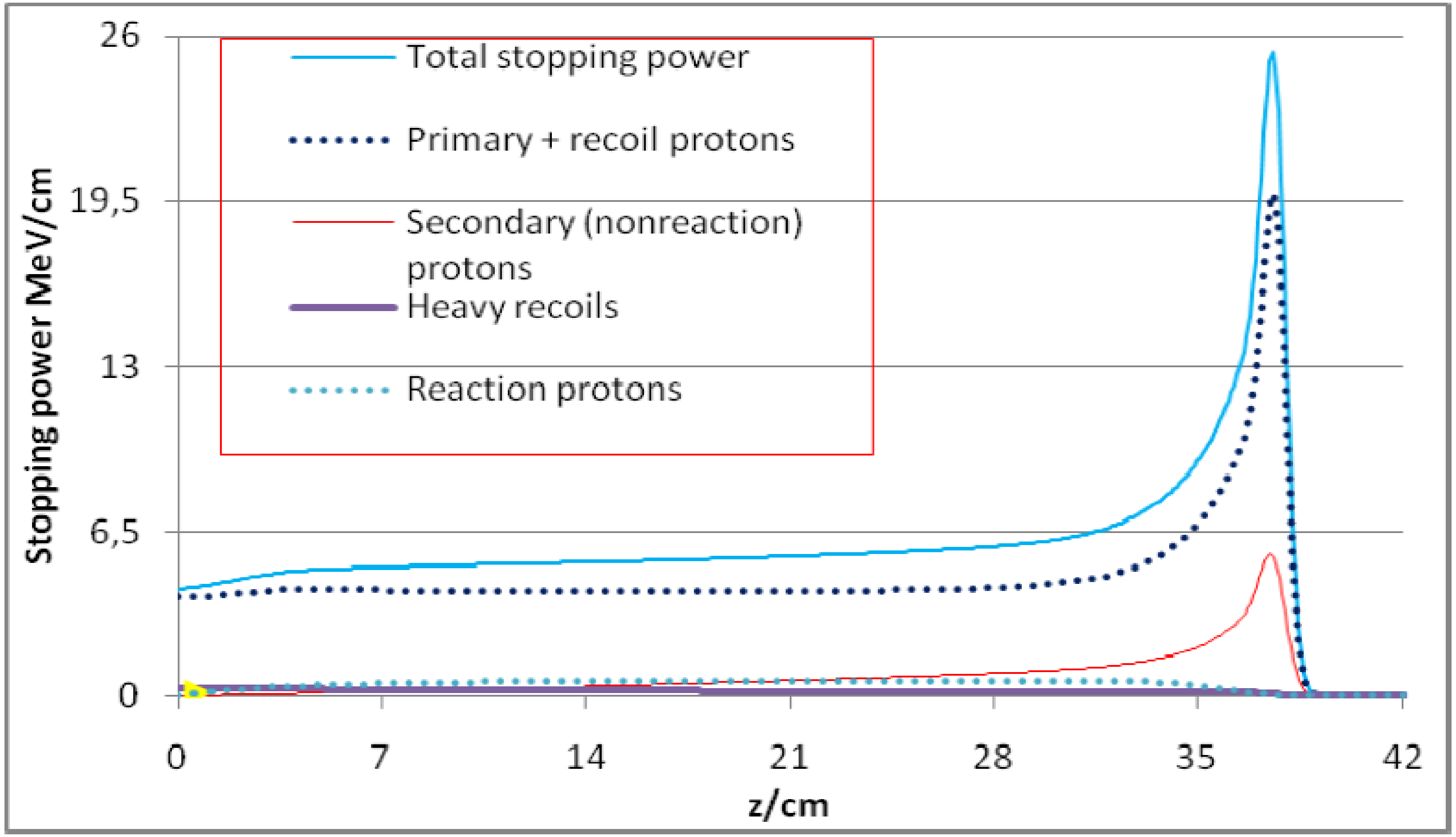



FIGURE 11.3: Energy loss distribution of 250 MeV protons in water medium. The points are experimental data and the line is theoretical calculation. The agreement between the theory and experiment for the energy loss and that of range with the website is striking. [Figure adopted from Ulmer and Matsinos, arxiv.org/pdf/1008.3645 (2010)]

# Energy loss distribution in water for 250 MeV protons




Ulmer, W. & Matsinos, E. Eur. Phys. J. Spec. Top. (2010) 190: 1. doi:10.1140/epjst/e2010-01335-7

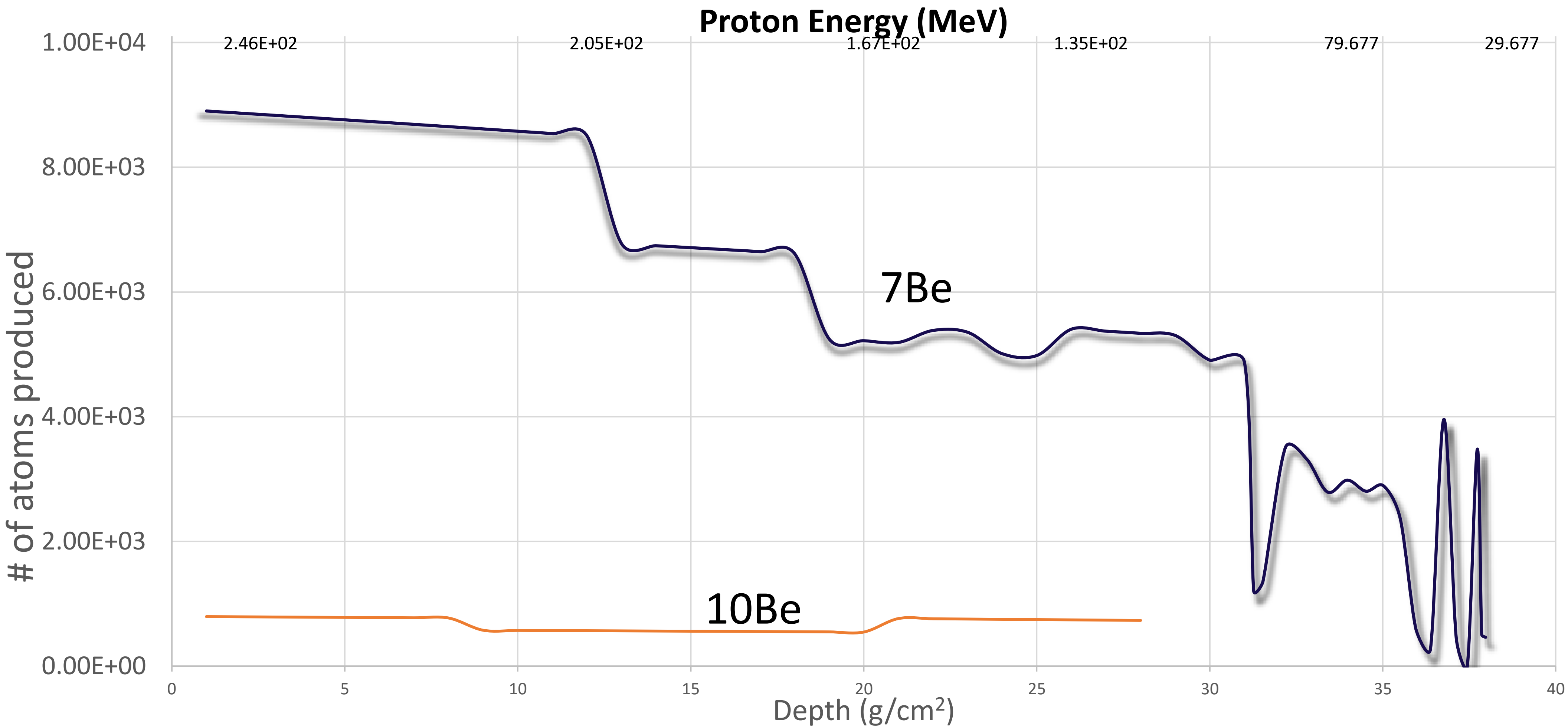
# A sample of nuclear processes of oxygen – protons interactions

K.E. protons < 250 MeV.

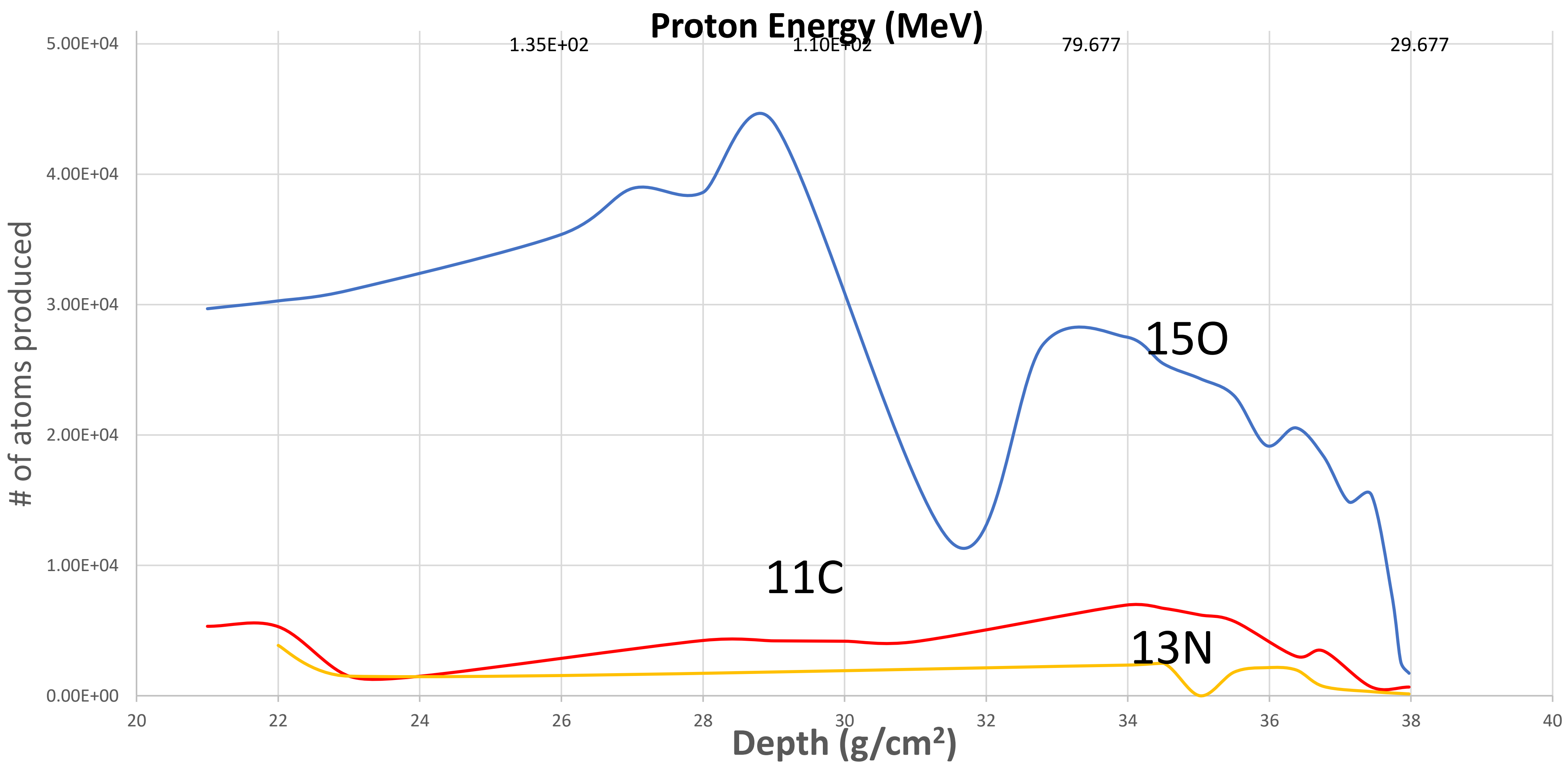
| Ejectile | Threshold energy (MeV) | Half-life |
|---|---|---|
| 7-Be | 26.9 | 53.3 days |
| 10-Be | 40.1 | 1.5 x $10^6$ years |
| 11-C | 23.6 | 20.4 minutes |
| 13-N | 5.6 | 9.9 minutes |
| 15-N | 12.9 | stable |
| 15-O | 14.3 | 2 minutes |
| Pions ($\pi^+$,$\pi^-$,$\pi^0$) | ~145 | 26 ns, ~0.1 fs |

**$^{11}C$, $^{13}N$ and $^{15}O$ are candidates for real-time PET imaging for proton radiation therapy**

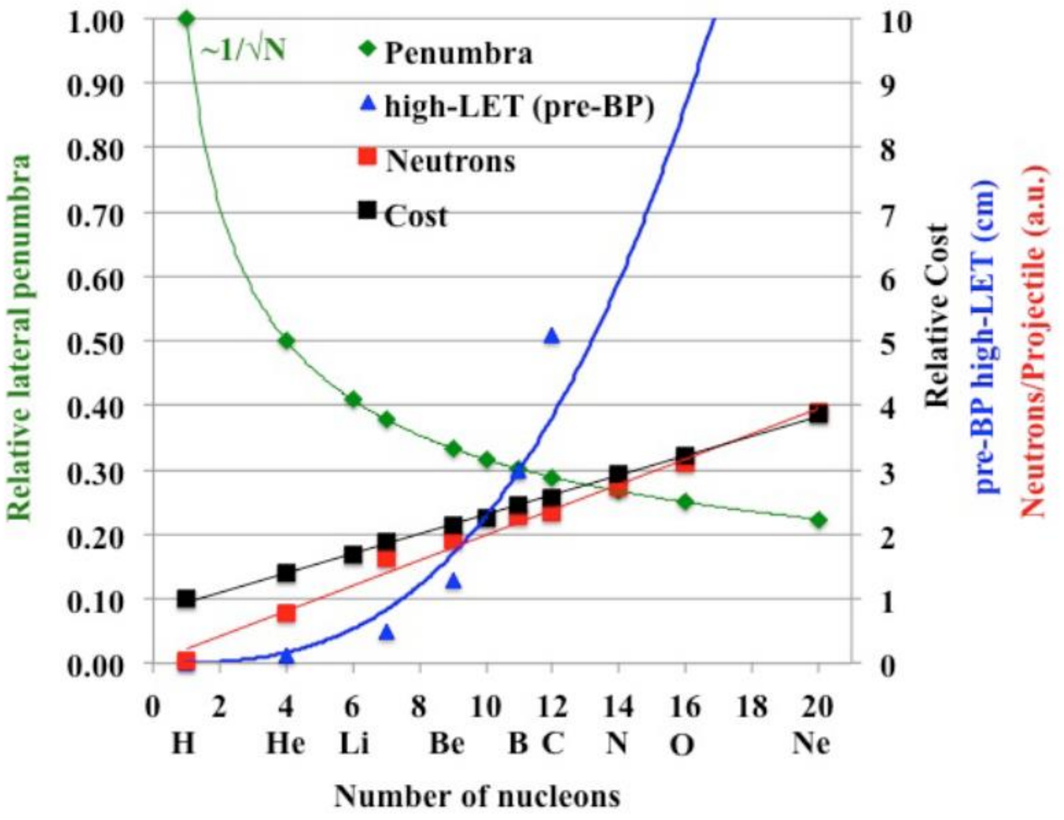
# Yield – depth distribution of $^{10}Be$ and $^{7}Be$



# $^{16}O(p,np)^{15}O$, $^{16}O(p,\alpha)^{13}N$ and $^{16}O(p,^{6}Li)^{11}C$



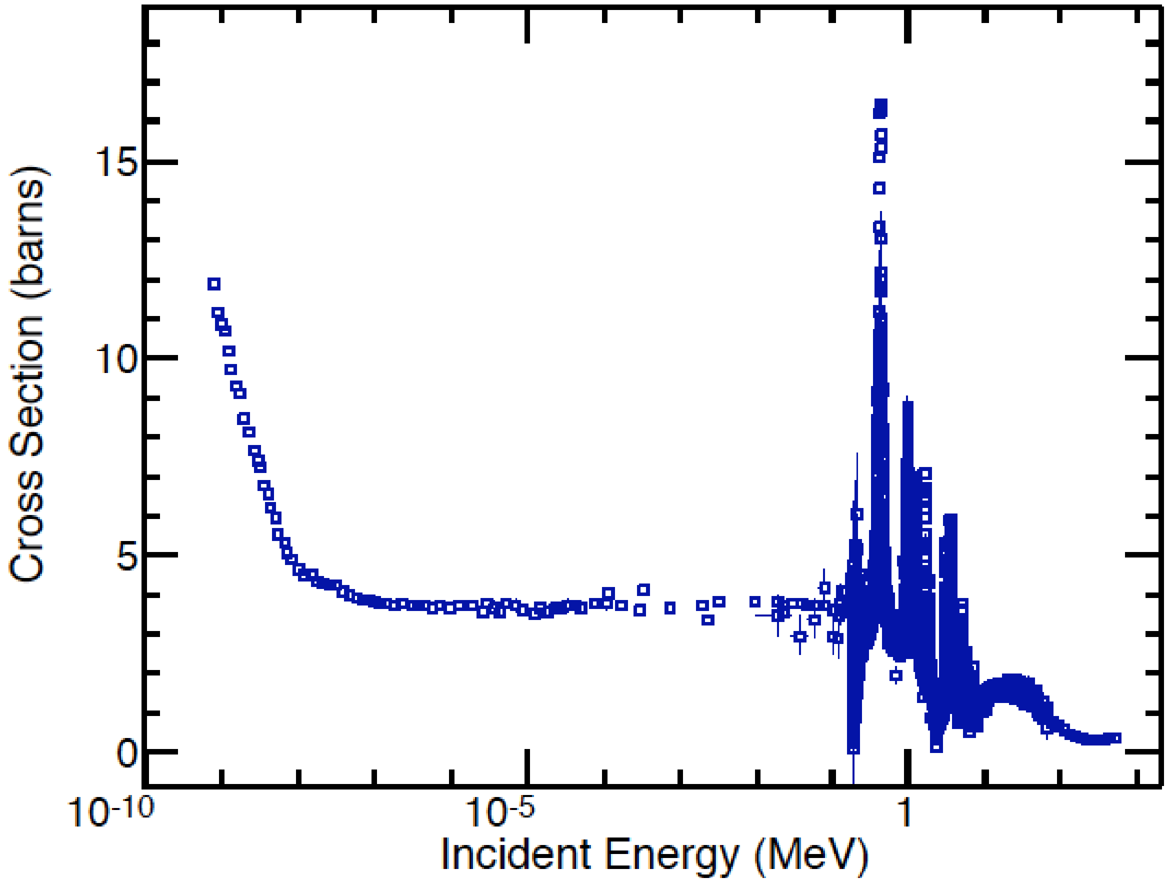
# Ion Beam Therapy - from Ute Linz




No. of neutrons ∝ mass number of ion beam

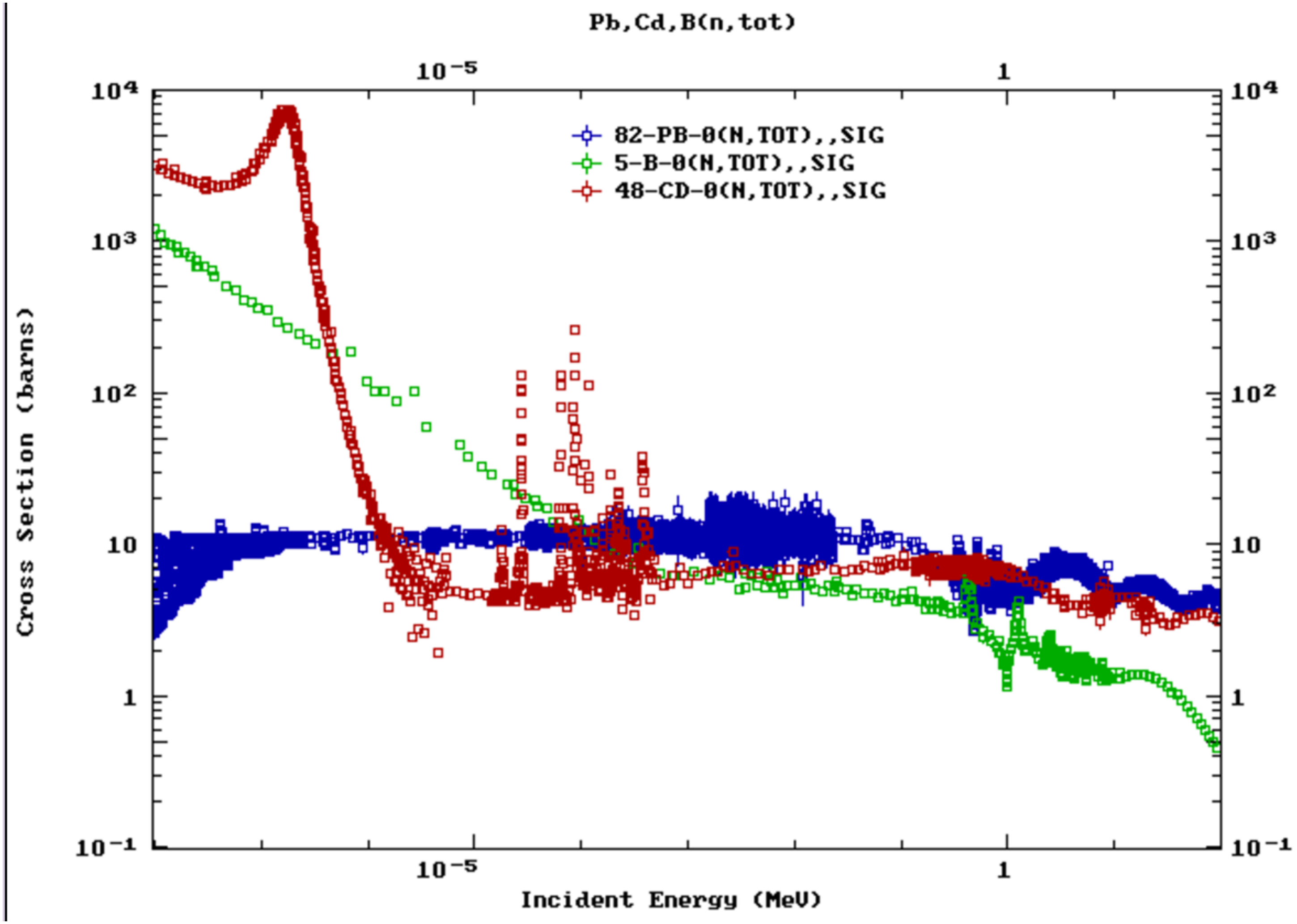
Eg: 12C produces 12 times as many neutrons as protons

# (n,tot) with natural oxygen




Note the non-linear energy dependence of interaction probabilities

# σ(n,tot) in B, Cd, Pb



# Conclusions

- We show that photon–medium interactions for $E_\gamma$ ~ 20 MeV can result in artificial transmutations.
- We also show that proton- medium interactions at $E_p$ ~ 250 MeV, can induce several varieties of artificial transmutations. These interactions are distributed over the entire trajectory of protons
- A similar point can be made for heavy ion ($^{12}C$ etc) radiation-medium interactions.
- Neutron interactions are specific to neutron energy- target isotope combinations.
- Radiological consequences due to the transmutations, in addition to the ionization mechanisms, are worth a quantitative study.

# Conclusions (contd)

- Exposure or energy deposits do not inform us  about a specific physico chemical transformations that a radiation can induce, let alone biological effects.
- Röntgen  or SI equivalent informs us of the exposure (ion pairs created)
- Gray tells us about the energy deposits
- Neither of them tell us any thing about biological effects.
- REM or Sievert tells us nothing concrete

# Boyd- http://www.wmsym.org/archives/2009/pdfs/9444.pdf

- Absorbed dose is an inadequate surrogate for managing radiation risk because different types of radiation cause differing degrees of biological harm for the same amount of absorbed dose.

- As is the case for absorbed dose, equivalent dose is also an inadequate surrogate for assessing radiation risk.

We cannot agree with him more.

# Conclusions(contd)

- Will gladly collaborate with interested researchers to further investigate the significance of these observations

**MERCI/THANK YOU/Kinanâskomitinawaw**