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Formation of Activation Products in Radiation Therapy

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Topics

- General considerations
- Activation products in photon therapy
- Activation products in fast neutron therapy
- Activation products in proton therapy

  - short-lived β^+ emitters formed in human tissue

  - activation of beam collimators
- Conclusions

Materials of Interest in Radiation Therapy

Composition of main materials

Material	Elements (mass %)								
	H	C	N	O	P	S	Mg	K	Ca
Muscle tissue	10.06	10.78	2.77	75.48	0.20	0.24	0.2	0.3	
Cortical bone	4.72	14.43	4.20	44.61	10.50	0.32	0.22		20.99
Collimators	Ti, Cu, Zn, brass, W, Pb, etc. (varying compositions)								

Activation Cross Section Needs

- Formation of short-lived β^+ emitters in human tissue
- Estimation of long-lived activation products in biologically relevant elements

  - formation of tritium

  - formation of ^{7}Be

  - formation of $^{22,24}Na$ and other medium mass products
- Estimation of collimator activation in therapy facilities

Some Possible Activation Products

Material	Activation product	
	Short-lived β^+ emitters	**others**
Tissue	^{10}C (19.3 s); ^{11}C (20.3 min); ^{13}N (10 min); ^{14}O (70.6 s); ^{15}O (2 min); ^{17}F (64.8 s); ^{18}F (110 min)	^{3}H (12.3 a); ^{7}Be (53.3 d); ^{14}C (5730a), etc.
Bone	above mentioned nuclides; additionally ^{30}S (1.18 s); ^{31}S (2.58 s); ^{30}P (2.5 min); ^{38}K (7.6 min)	^{22}Na (2.6 a); ^{24}Na (15.0 h); ^{42}K (12.4 h); ^{43}K (22.2 h)
Trace elements		^{51}Cr (27.7 d); ^{52}Mn (5.6 d); ^{55}Co (17.5 h), etc.
Collimator materials		^{54}Mn (312 d); ^{58}Co (71 d) ^{204}Tl (3.8 a), etc.

Types of Radiation Therapy

- **Photon therapy**

  - using γ-rays emitted from radionuclides (^{60}Co, ^{137}Cs, ^{192}Ir, etc.)
  - using high energy photons from accelerators

- **Fast neutron therapy**

  - using p(Be) or d(Be) neutrons (at E_p or E_d above 50 MeV)

- **Charged particle therapy**

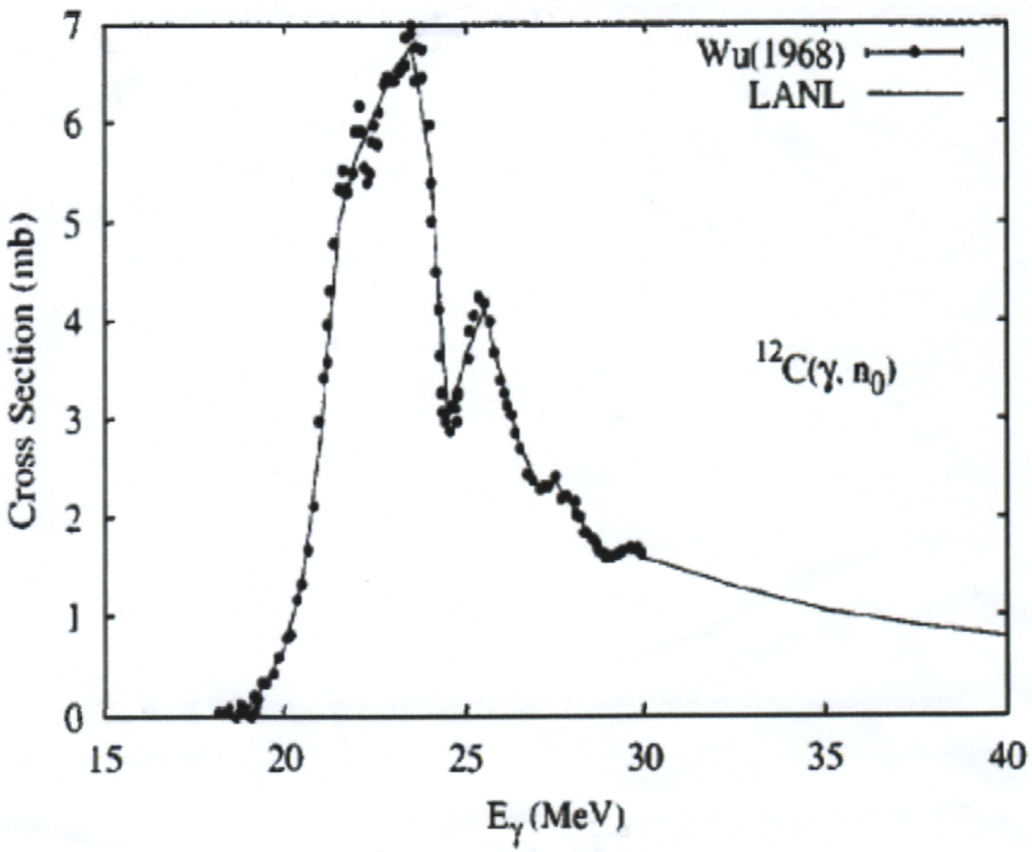
  - proton therapy with E_p = 70 – 250 MeV
  - heavy-ion beam therapy (rather specialized)

Photon Therapy

- Most common form of radiotherapy
- Due to very high thresholds of photonuclear reactions, formation of activation products in tissue is negligible.

Example: $^{12}C(\gamma,n)^{11}C$ ($T_{½}$ = 20 min)

IAEA-TECDOC-1178 (2001).

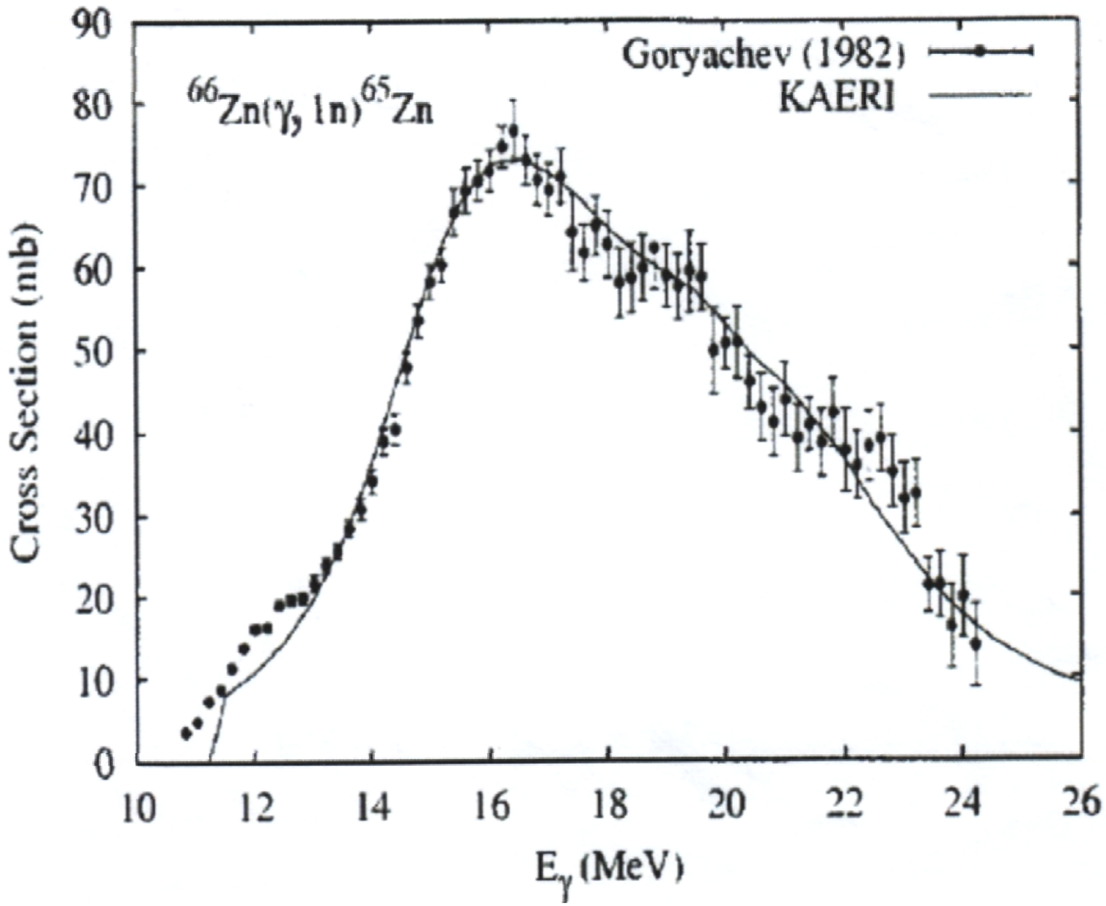


Only very high-energy bremsstrahlung could produce some positron emitter.

Photon Therapy (cont´d)

The activation of collimator material is also expected to be low, because the thresholds of photonuclear reactions are rather high.

Example: $^{66}Zn(\gamma,n)^{65}Zn$ ($T_{½}$ = 244.3 d)



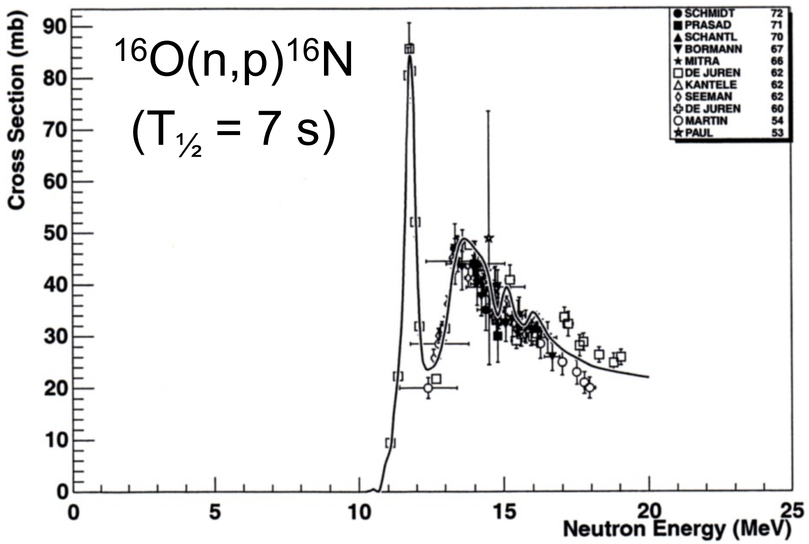
IAEA-TECDOC-1178 (2001).

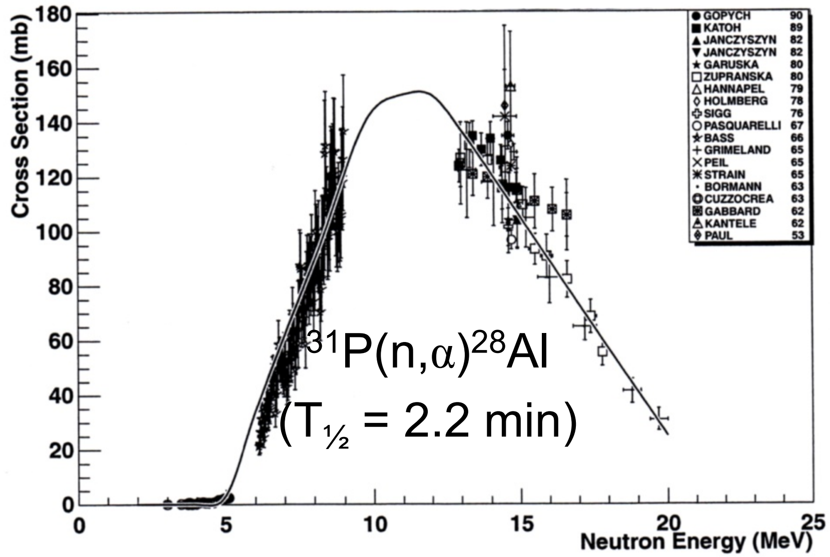
Fast Neutron Therapy

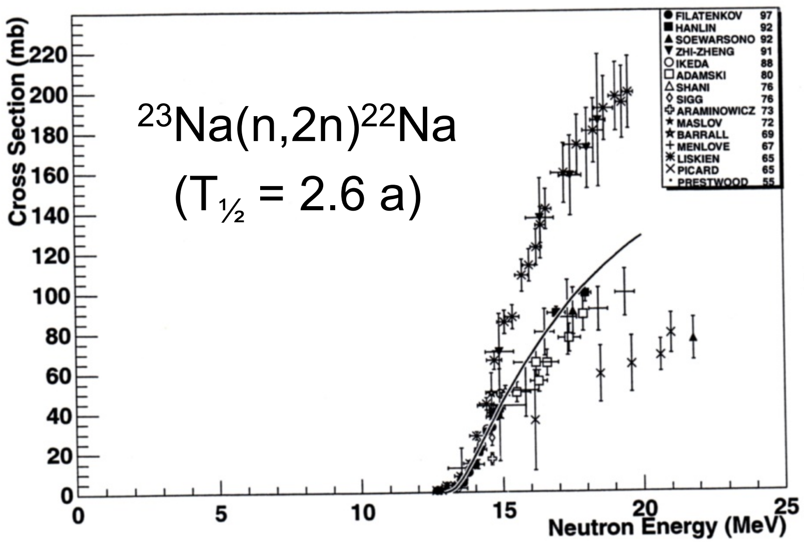
- Many nuclear reactions are possible, e.g. (n,γ), (n,xn), (n,xp), $(n,x\alpha)$, (n,t), etc.
- Kinetic energy released in matter (KERMA factor) makes LET-value of neutrons high.
- Several activation products are formed.
- Activation of medium and heavy mass elements is much stronger than that of light elements.
- Activation data needs in fast neutron therapy are extensive, but this therapy mode is being abondoned.

Fast Neutron Activation

Examples of Excitation Functions

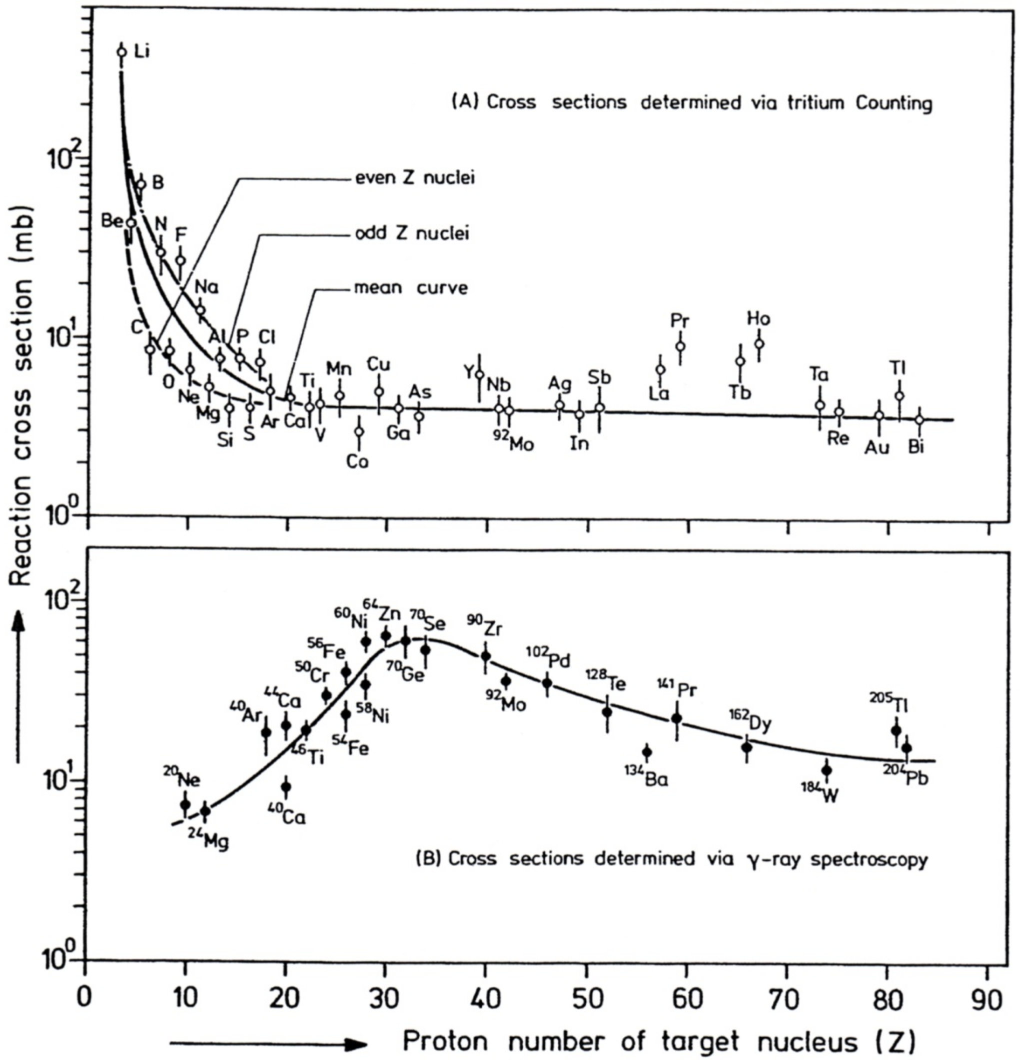






IAEA-TECDOC-1285 (2002).

Tritium Formation in Neutron Interactions



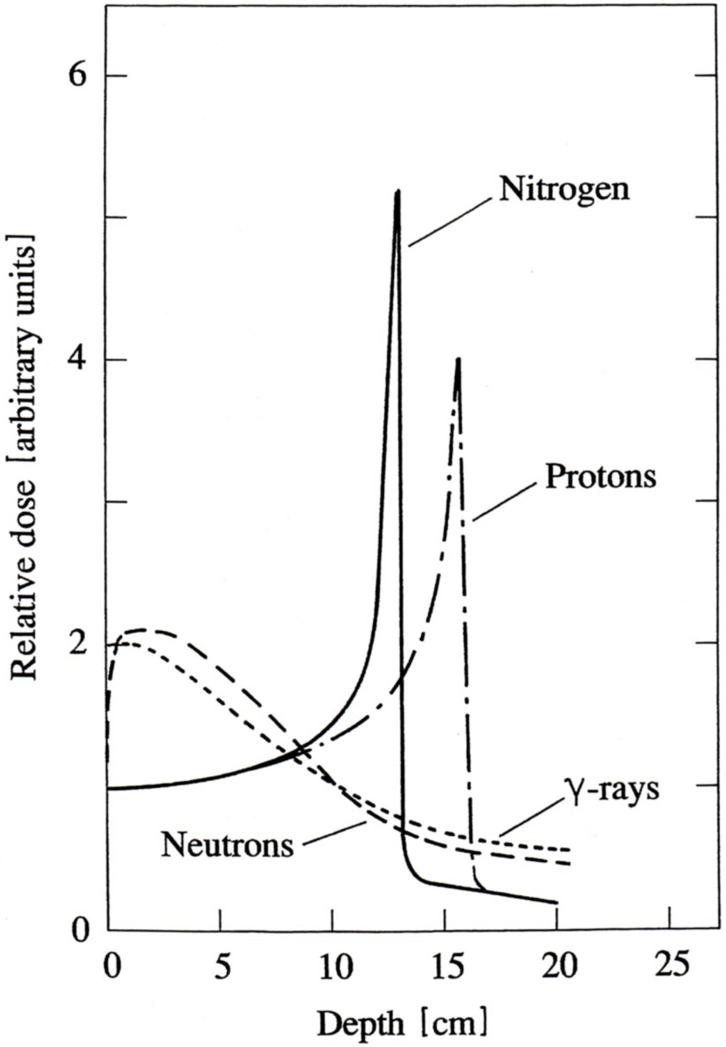
Qaim and Wölfle,
NP **A295**, 150 (1978).

- 53 MeV d(Be) neutrons on elements
- Tritium formation cross section is fairly high in light mass region.
- In heavier mass region the formation of activation product via (n,p2n) process is much stronger than via (n,t) reaction

Charged-Particle Therapy

- Charged particles used: p, α, ^{12}C, ^{14}N, etc.

Depth-dose relationship



- Charged-particle dose increases with the penetration depth, reaching a maximum in the Bragg peak area.
- Major advantage of charged-particle therapy is the capability to treat deep-lying tumours, close to critical structures (due to high-selectivity of the Bragg peak).
- Heavy-ion therapy is specialized; proton therapy is more common and cheaper.

Formation of Short-Lived β^+ Emitters in Human Tissue in Proton Therapy

Short-lived β^+ emitters generated:

^{11}C ($T_{½}$ = 20 min), ^{13}N ($T_{½}$ = 10 min), ^{14}O ($T_{½}$ = 1.15 min), ^{15}O ($T_{½}$ = 2 min), ^{18}F ($T_{½}$ = 110 min), etc.

Examples of nuclear reactions

$^{12}C(p,pn)^{11}C$	$^{14}N(p,\alpha)^{11}C$
$^{14}N(p,pn)^{13}N$	$^{16}O(p,\alpha)^{13}N$
$^{14}N(p,n)^{14}O$	$^{15}N(p,n)^{15}O$
$^{18}O(p,n)^{18}F$	$^{16}O(p,pn)^{15}O$

Significance of data

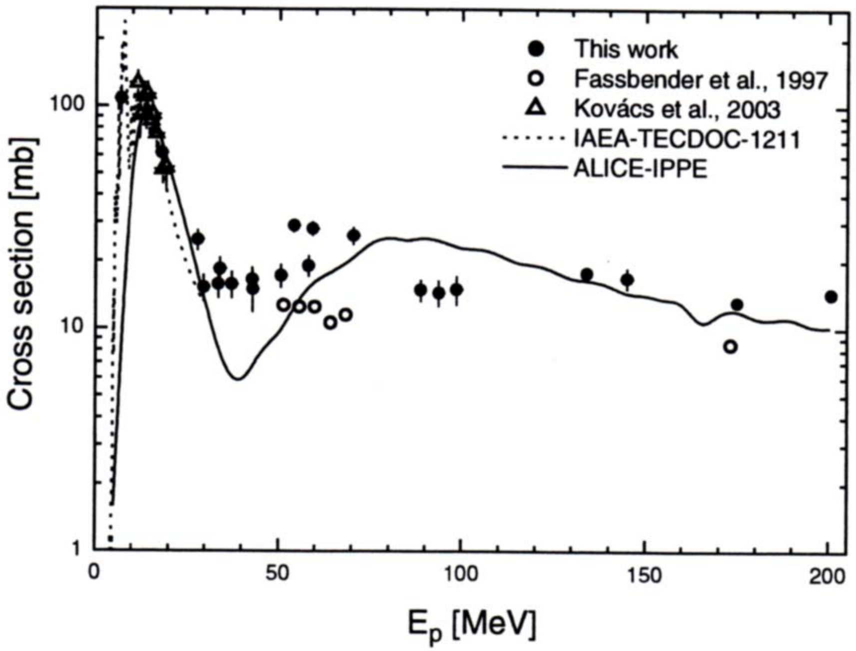
a) Estimation of extra dose due to activation products
b) PET investigation of the patient after proton therapy (utilizing the ^{11}C formed in the tissue); localises dose distribution in the treated area

Formation of Short-Lived β^+ Emitters

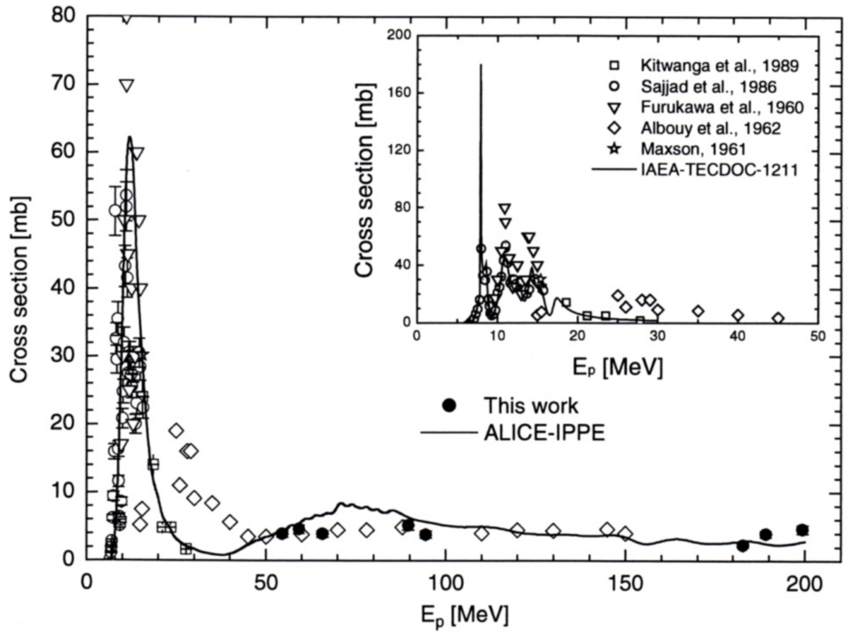
(Protons on human tissue)

Examples : Kettern et al, ARI 60, 939 (2004).

$^{nat}N(p,x)^{11}C$



$^{nat}O(p,x)^{13}N$



- Improved data base > 50 MeV

Estimated Activity in Bragg Peak Region as a Result of Proton Therapy

Assumption: 200 MeV proton, 2 nA, 2 min irradiation

Radionuclide	Activity (MBq)	
	Muscle tissue	Cortial bone
^{11}C	6.5	
^{13}N	3.9	
^{15}O	121	22

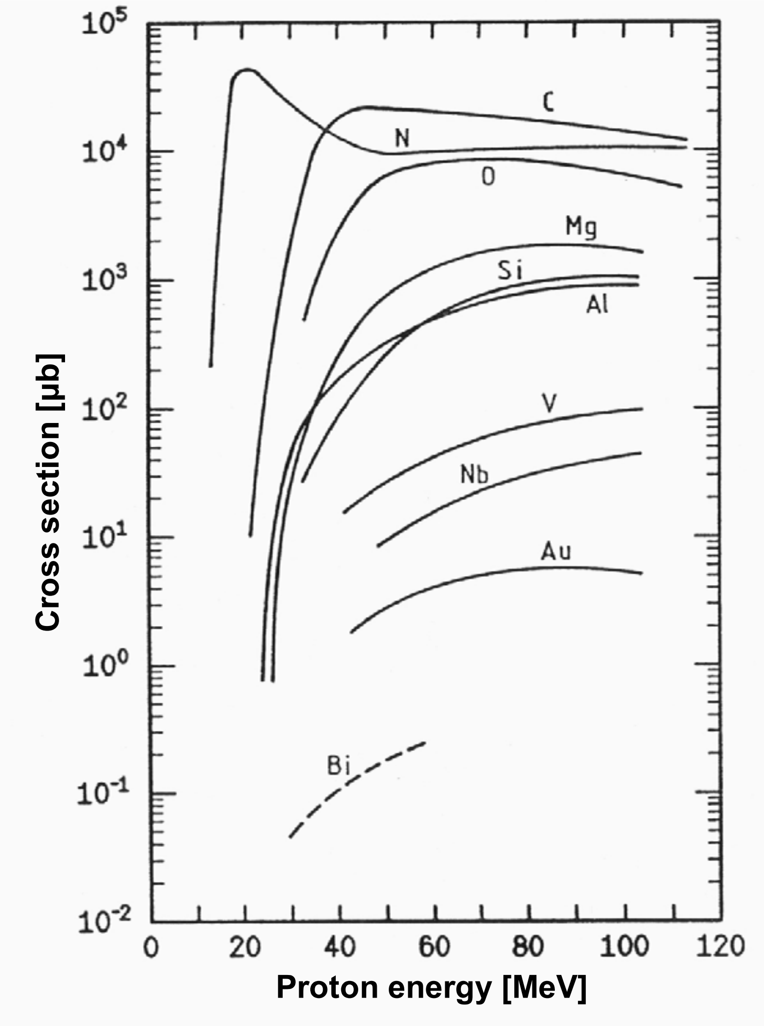
Total activity of β^+ emitters : 131 MBq (in muscle tissue)
: 22 MBq (in cortial bone)

Other activities

^{7}Be (in muscle tissue) : 40 kBq

$^{22,24}Na$ (in bone) : < 250 Bq

Systematics of Excitation Functions of (p,^{7}Be) Reactions



- **Probability of ^{7}Be emission decreases with increasing mass of the target nucleus**

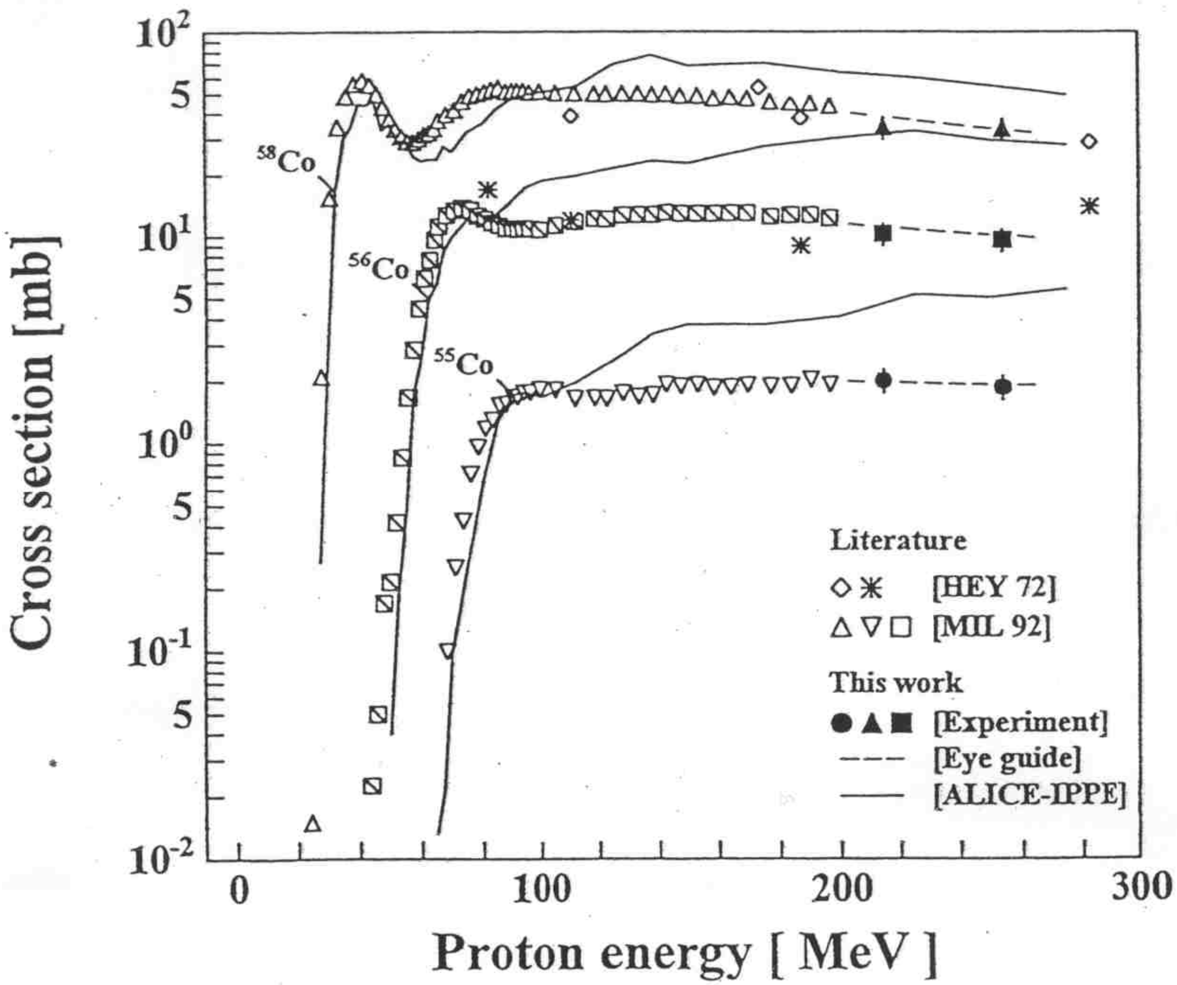
Scholten et al.,
RCA **65**, 81 (1994).

Activation of Beam Collimators

- Proton therapy demands high quality beams
- Tailoring of energy and homogenisation of intensity are achieved through collimators
- Activation of collimators is of some concern
- Commonly used collimators include titanium, brass, tungsten, etc.

Results for an Element as Collimator
(Easily detectable products)

Example: $^{nat}Cu(p,x)^{55,56,58}Co$ processes

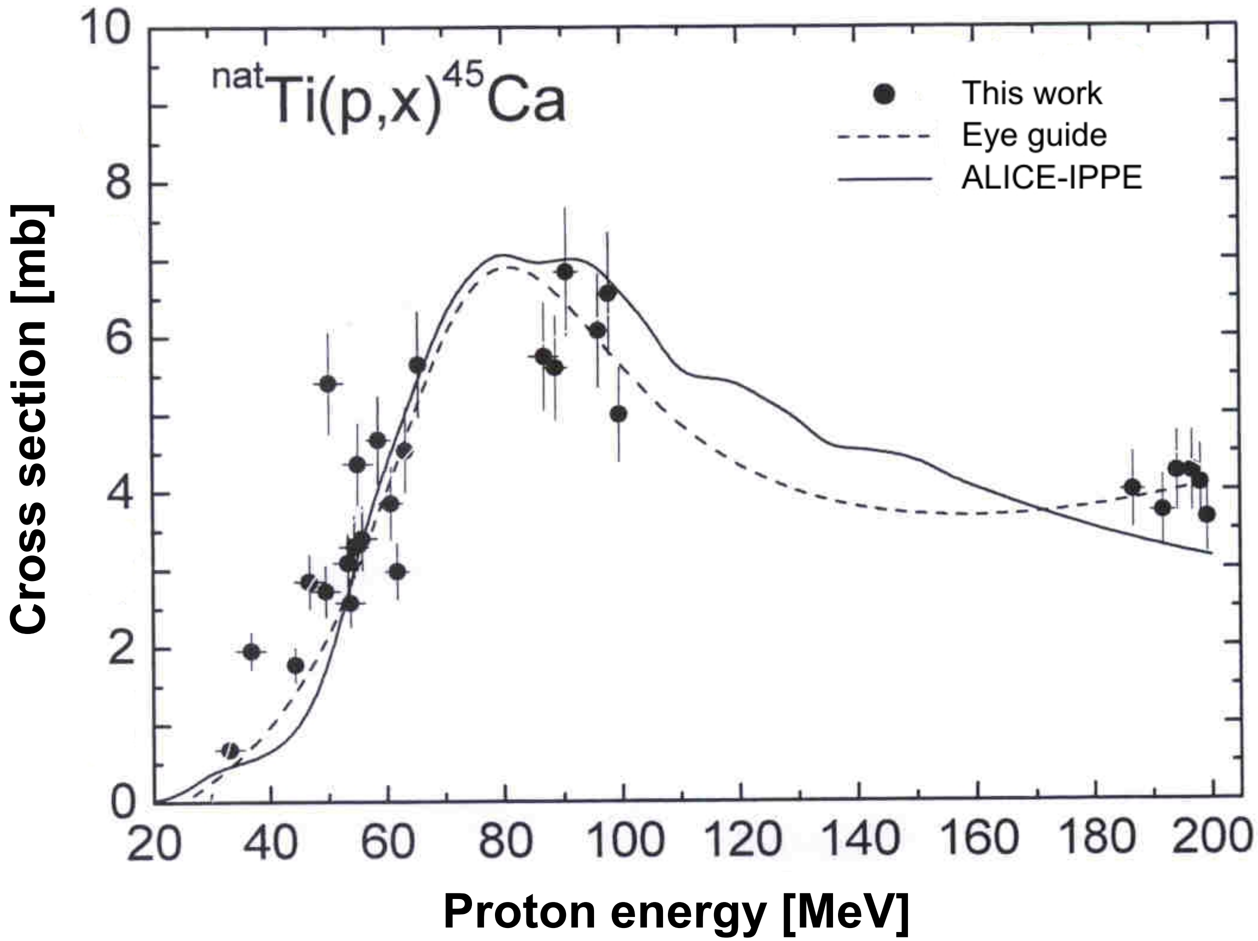


- Model calculations reproduce experimental data well up to $E_p \leq 120$ MeV

Fassbender et al.,
ARI **48**, 1221 (1997).

Results for an Element as Collimator
(Products difficult to detect)

Example: $^{nat}Ti(p,x)^{45}Ca$ ($T_{½}$ = 163 d)

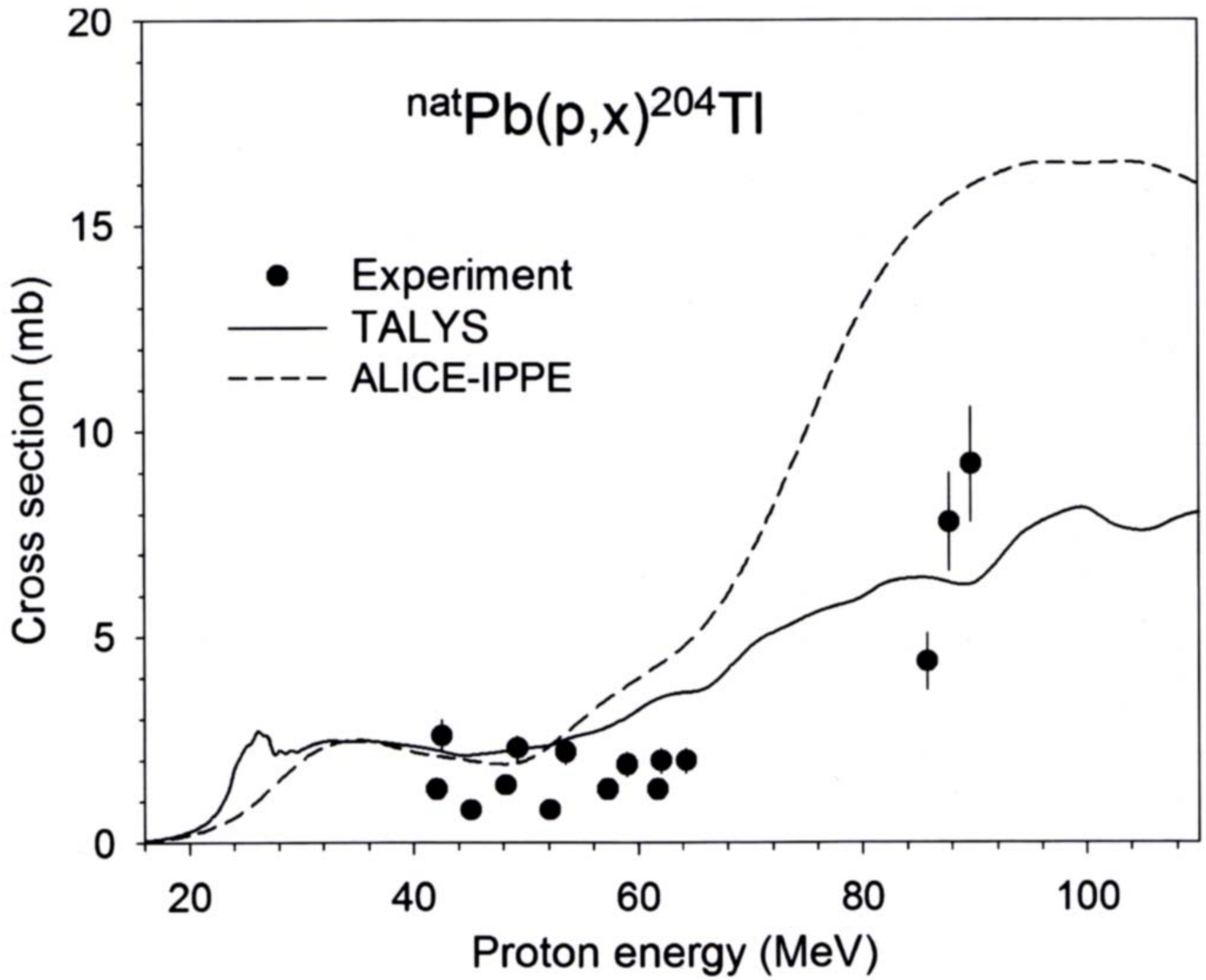


- Radiochemical measurement
- Good agreement between experiment and theory over the whole energy range

Qaim et al.,
RCA **98**, 447 (2010).

Products difficult to detect (cont´d)

Example: $^{nat}Pb(p,x)^{204}Tl$ ($T_{½}$ = 3.78 a)

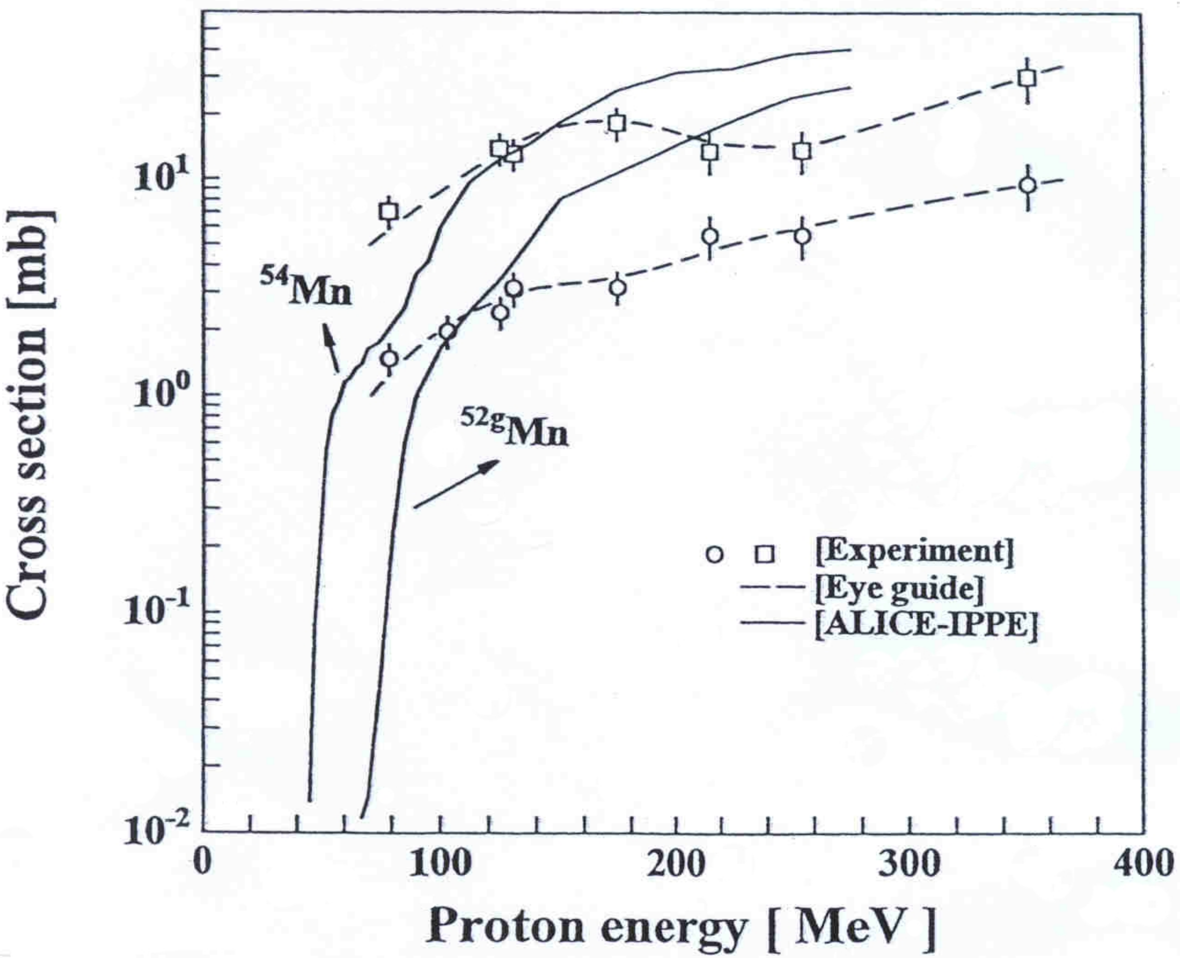


Qaim et al.,
RCA **98**, 447 (2010).

- Radiochemical measurement
- Good agreement between experiment and model calculations up to 60 MeV; at higher energies TALYS results are closer to experiment

Results for an Alloy as Collimator

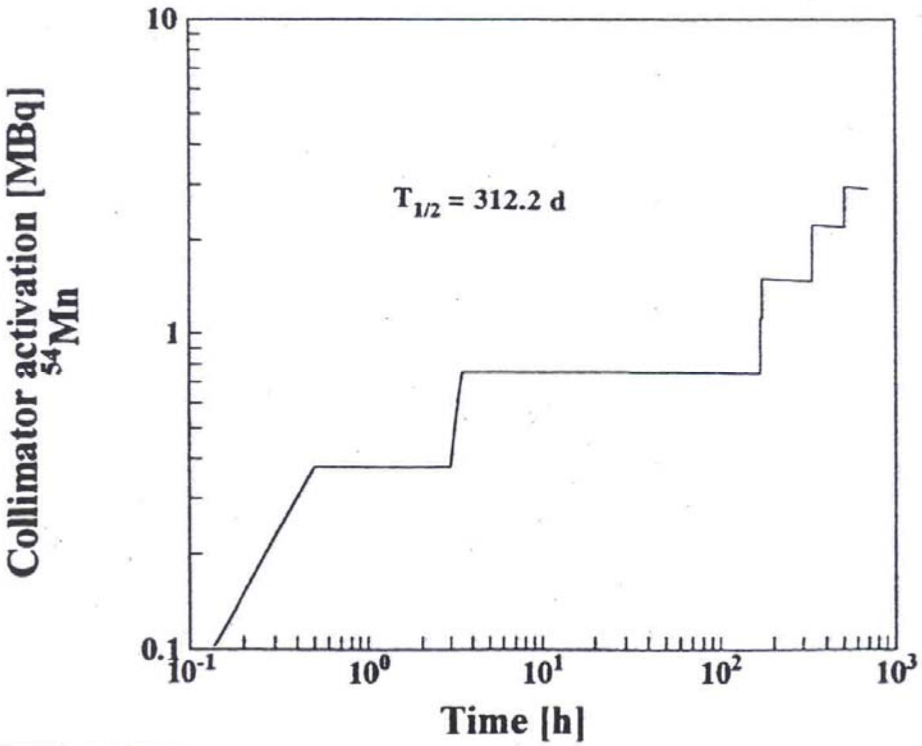
Example: Formation of ^{52,54}Mn from brass



- Model calculation reproduces experimental data with partial success up to proton energies of about 120 MeV.

Fassbender et al.,
ARI **48**, 1221 (1997).

Activation of Brass Collimator



Assumptions

- 200 MeV, 400 nA p beam
- periodical running sequence
- two patients treated on one day of the week

- **Estimated ^{54}Mn activity/year:** 37.5 MBq
- **Dose rate (at 1m) :** 4.8 µSv/h

Proper shielding of therapy facilities is mandatory

Conclusions

- Activation products formed in human tissue during photon and neutron therapy can be regarded as negligible.
- Formation of short-lived β^+ emitters is of some significance in proton therapy. The total activity (~ 120 MBq) is sufficient for dose localisation via PET studies; the extra dose from β^+ emitters is, however, negligible (< 1 %).
- Activation of beam collimators (both at neutron and proton therapy facilities) is of some concern regarding the therapy personnel.