Activation Products in Proton Therapy

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Topics

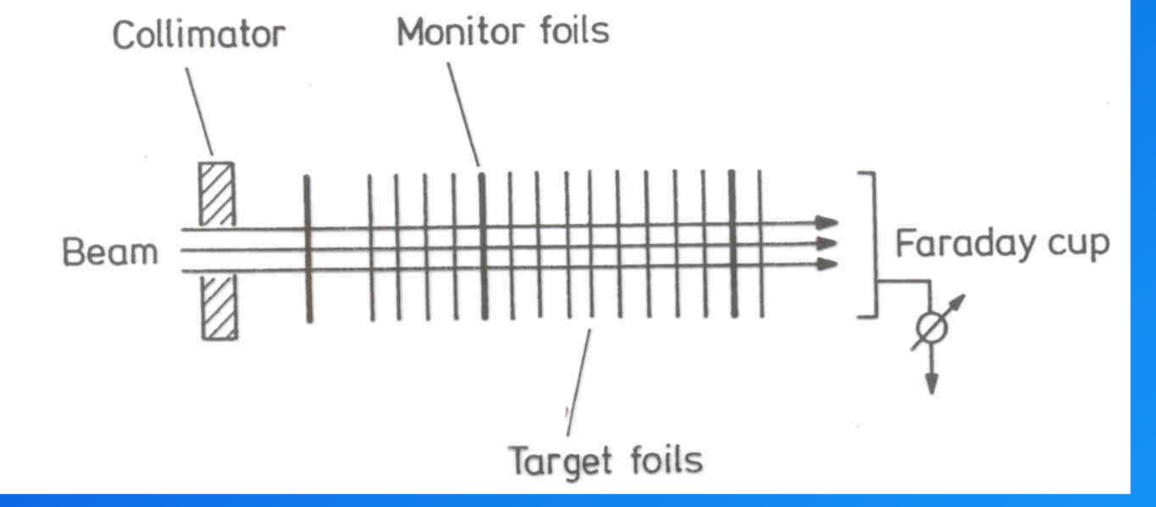
- General considerations
- Determination of activation cross sections
- Beam collimator activation
- Long-lived activation products in biologically relevant elements
- Formation of short-lived β^+ emitters in human tissue
- Conclusions

General Considerations

- For therapy purposes, well collimated proton beams are needed
- Proton energy is tailored between 70 and 250 MeV, depending on the application
- In proton therapy atomic and molecular data are of great significance
- Nuclear interactions are of lesser importance, except for cases where high energy secondary particles are emitted
- Data for the formation of activation products are not of paramount importance; however, they are needed in several special contexts

Determination of Activation Cross Sections in the Medium Energy Range

Experimental Method



- Irradiation of target material with protons at a low current.
  Very often a stack of thin samples is irradiated (***stacked-foil technique***).
- Calculation of proton energy effective in each sample
- Determination of proton flux via a monitor reaction
  (or via a Faraday cup)
- Determination of absolute activity of the product nuclide ,
  non-destructively or after chemical separation
- Calculation of cross section
- Construction of excitation function

Irradiation Facilities

Several types of cyclotrons and accelerators are needed to cover the full energy range.

The Jülich group used following machines:

compact cyclotron (≤ 21 MeV); injector of COSY (≤ 45 MeV); accelerators at PSI (≤ 72 MeV), Uppsala (≤ 180 MeV), iThemba LABS (≤ 200 MeV) and Saclay (≤ 350 MeV)

Nuclear Model Calculations

- Hauser-Feshbach and precompound formalism successfully applied up to 50 MeV

  Commonly used codes: GNASH, STAPRE, EMPIRE II

- Hybrid exciton model commonly used in higher energy region

  Common code: ALICE-IPPE

- Direct interactions needed to be included

- Complex particle emission extremely difficult to treat

Activation Cross Section Needs

- Estimation of collimator activation in proton therapy facilities

- Estimation of long-lived activation products in biologically relevant elements
  - formation of ^{7}Be
  - formation of $^{22,24}Na$ and other medium mass products

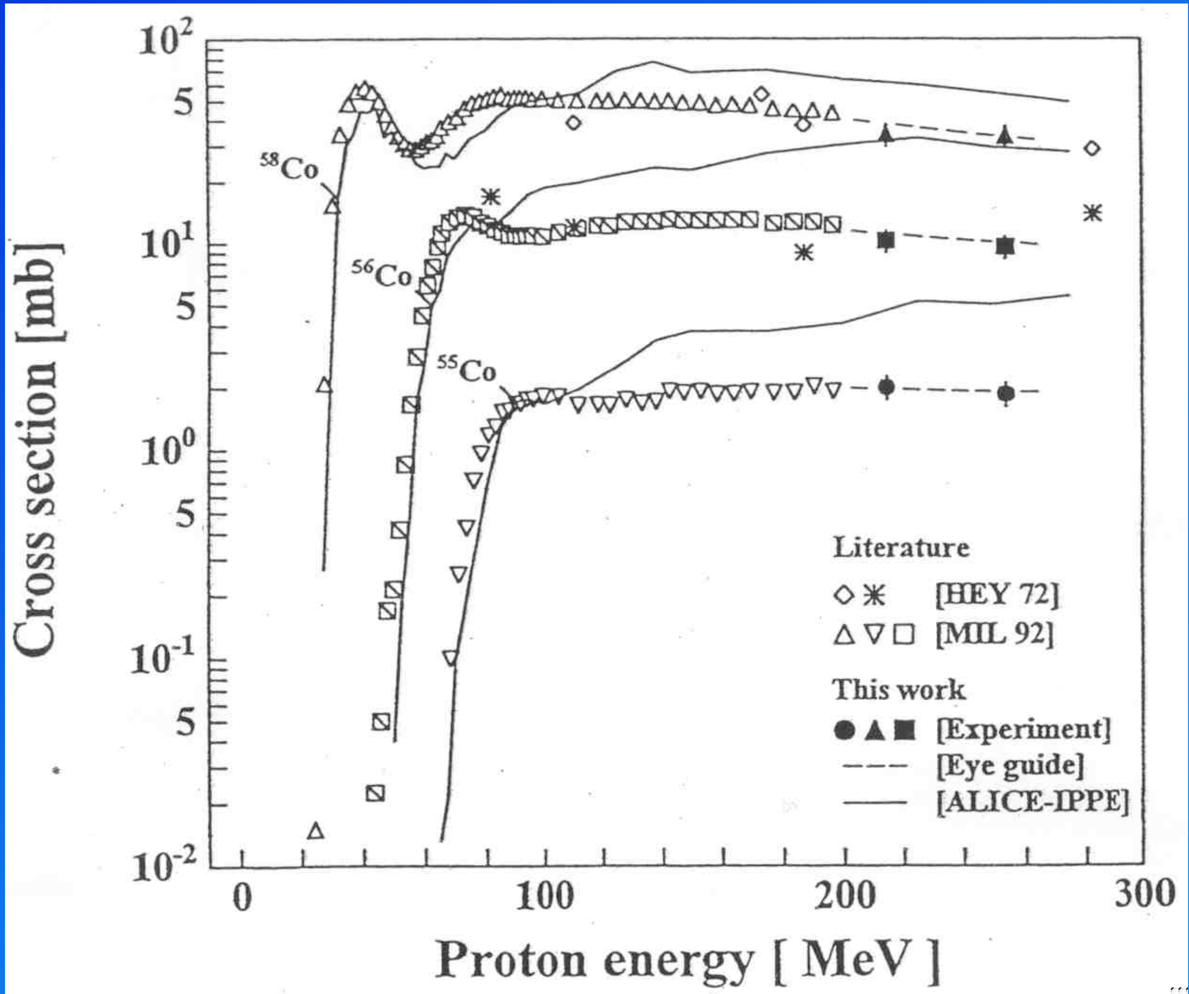
- Formation of short-lived β^{+} emitters in human tissue

Activation of Beam Collimators

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

Results for a Pure Element as Target
(Easily detectable products)

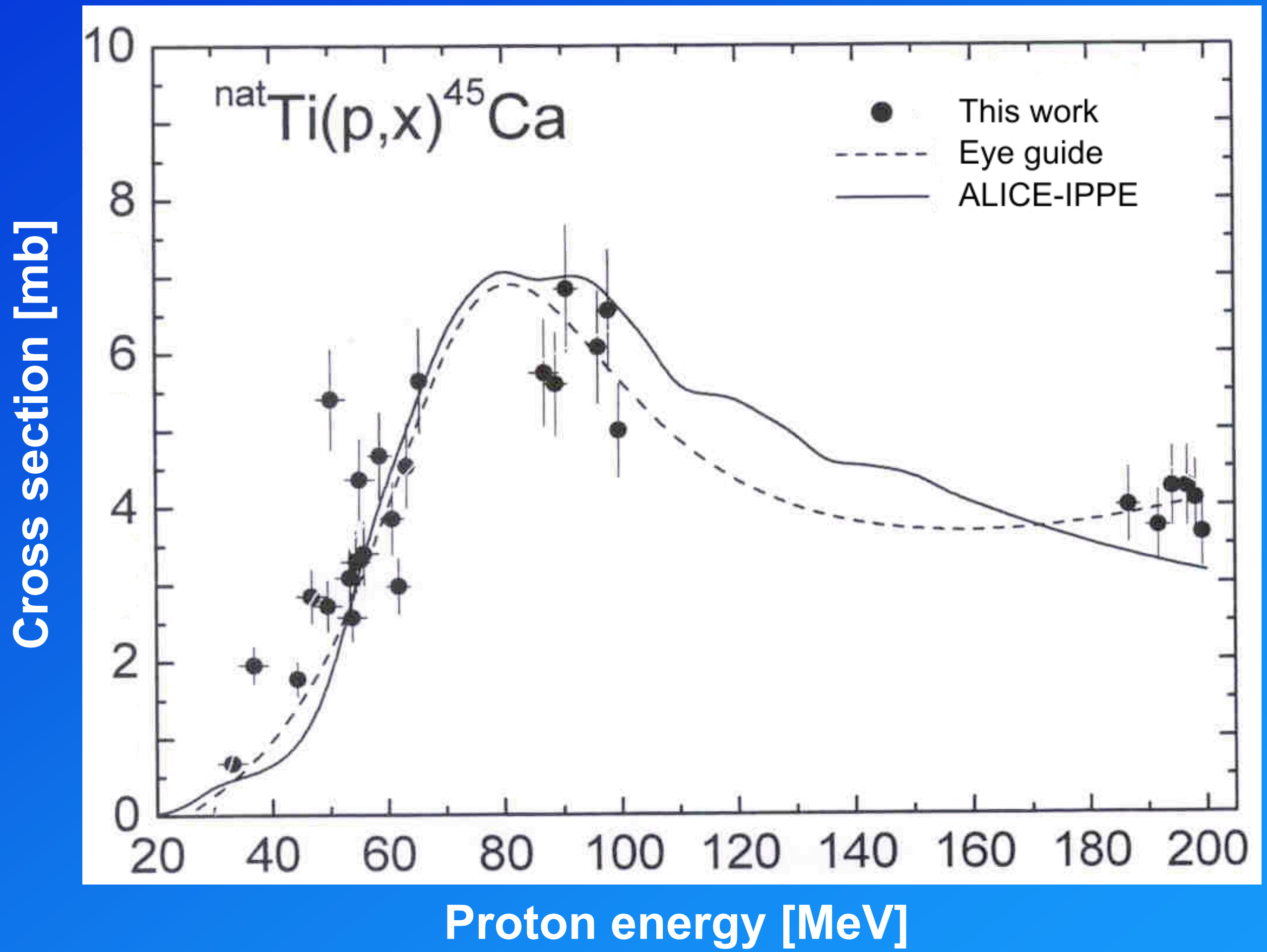
Example: $^{nat}Cu(p,x)^{55,56,58}Co$ processes



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

Results for a Pure Element as Target
(Difficult to detect product)

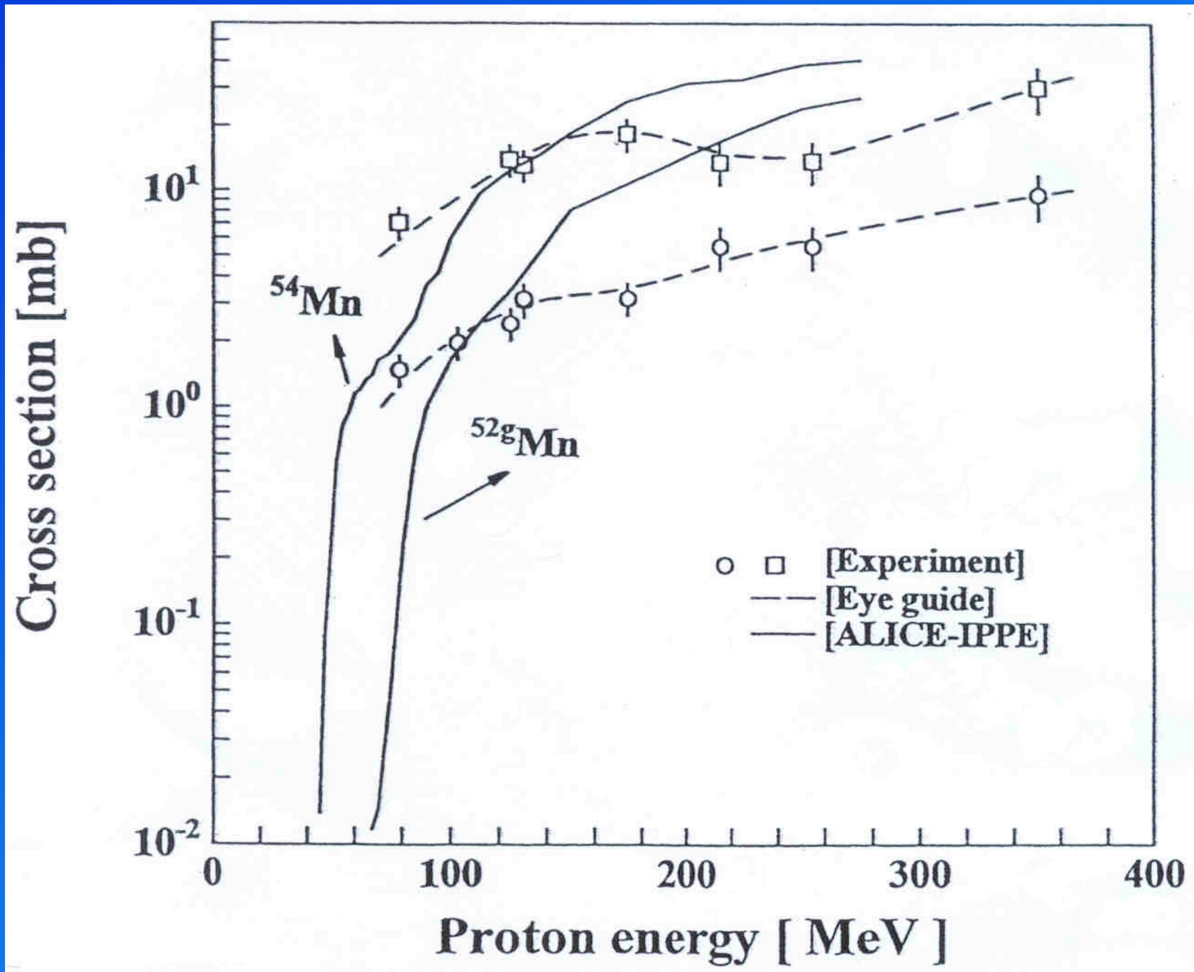
Example: $^{nat}Ti(p,x)^{45}Ca$



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

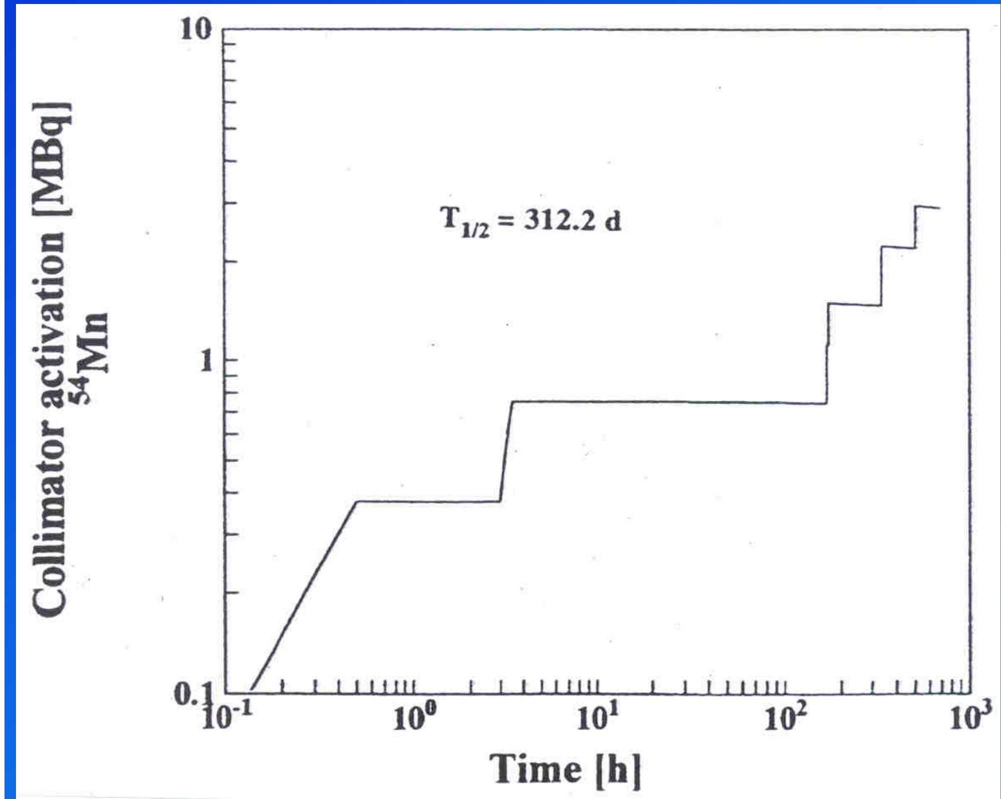
Results for an Alloy as Target

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



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

Activation of Brass Collimator



Assumptions

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

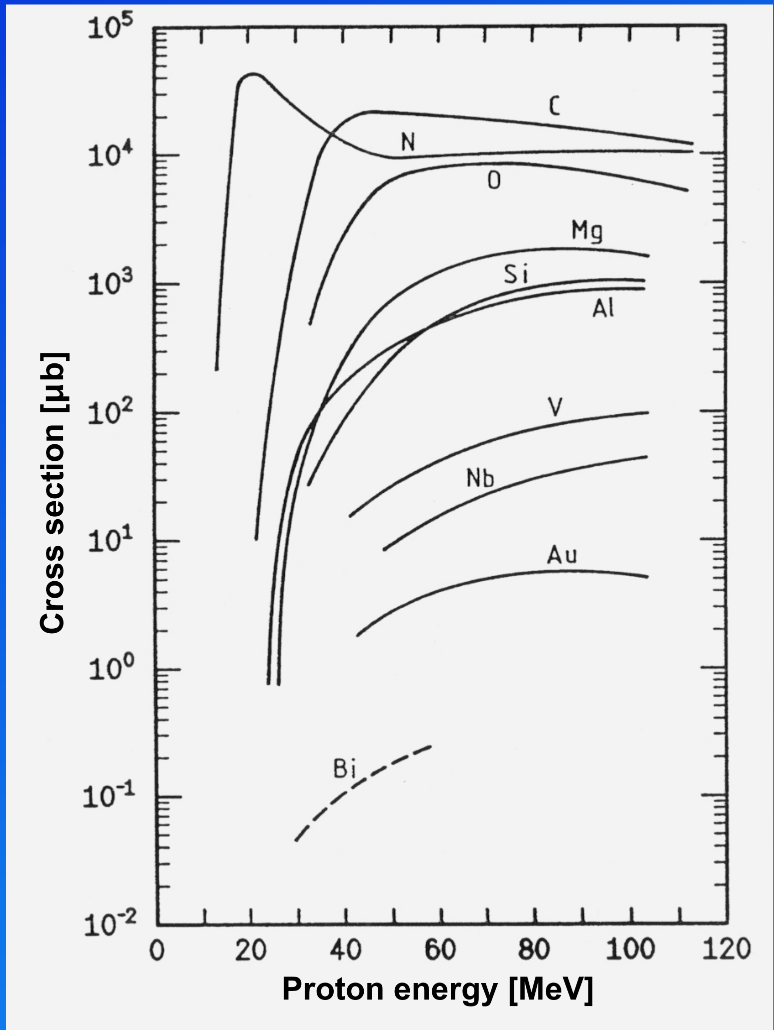
• Estimated ^{54}Mn activity/year: 37.5 MBq
• Dose rate (at 1m) : 4.8 µSv/h

Proper shielding of therapy facilities is mandatory

Long-Lived Activation Products in Biologically Relevant Elements

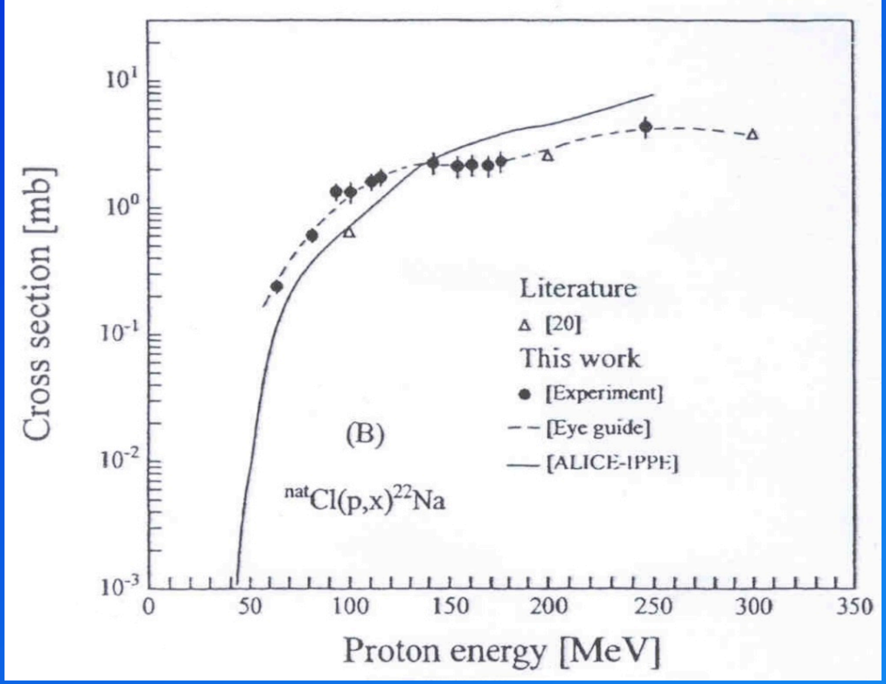
- Biologically relevant elements include H, C, N, O, F, Na, Mg, Si, P, S, Cl, Ca, Fe etc.
- Longer-lived activation products formed during proton therapy may include ^{7}Be ($T_{½}$ = 53 d), ^{22}Na ($T_{½}$ = 2.6 a), ^{24}Na ($T_{½}$ = 15.0 h) and several other medium mass products, like ^{42}K ($T_{½}$ = 12.4 h), ^{43}K ($T_{½}$ = 22.2 h), ^{51}Cr ($T_{½}$ = 27.7 d), ^{52}Mn ($T_{½}$ = 5.6 d), ^{54}Mn ($T_{½}$ = 312 d), ^{55}Co ($T_{½}$ = 17.5 h), etc.
- ^{7}Be formation in interactions of protons with light elements C, N, O, F and Na involves both ^{7}Be-emission (as a complex particle) and residual nucleus formation (after emission of several nucleons and α-particles). For heavier target elements, emission of complex particle ^{7}Be is more probable.
- ^{22,24}Na and heavier mass radioactive products are formed as residual nuclei

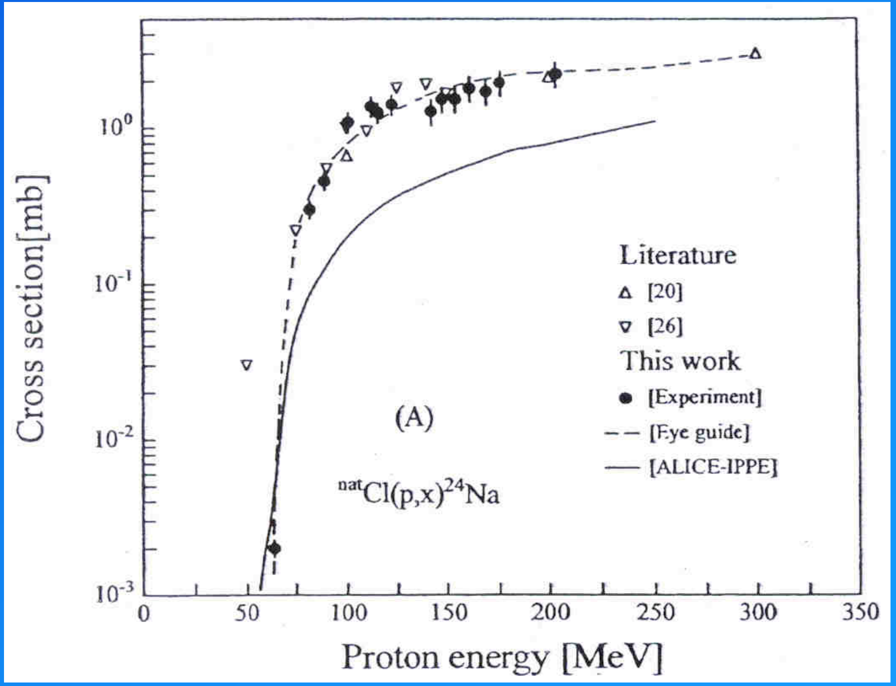
Systematics of Excitation Functions of $(p,^{7}Be)$ Reactions



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

Formation of ^{22,24}Na in the Interactions of Protons with ^{nat}Cl





- Cross sections for the formation of ^{22,24}Na are relatively small (2 – 5 mb).
- Theory reproduces formation cross section with varying degree of success.

Formation of Short-lived β^+ Emitters in Human Tissue

Interactions of protons with constituents of human tissue generate short-lived β^+ emitters like ^{11}C ($T_{½}$ = 20 min), ^{13}N ($T_{½}$ = 10 min), ^{14}O ($T_{½}$ = 1.15min), ^{15}O ($T_{½}$ = 2 min), ^{18}F ($T_{½}$ = 110 min), etc.

Examples of contributing nuclear reactions

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

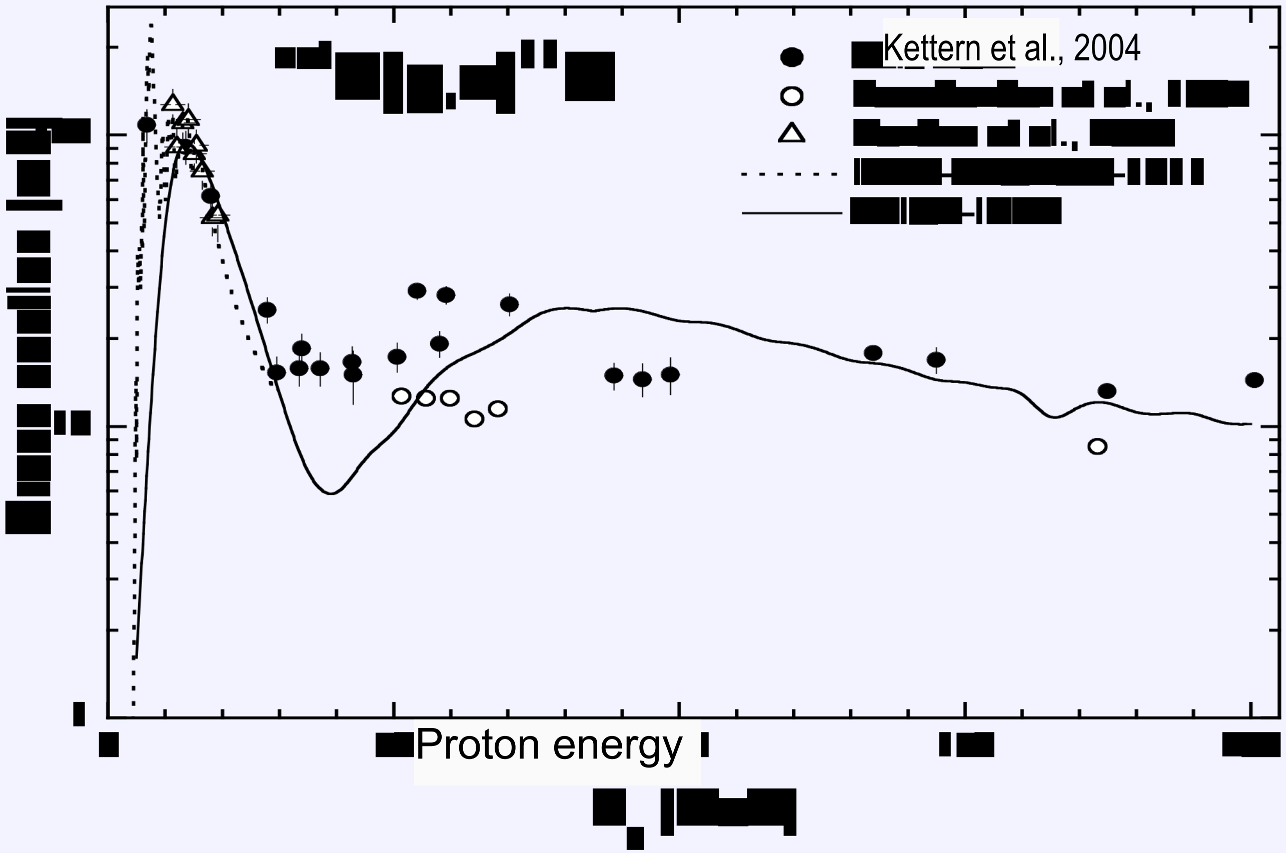
Significance of production data

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

Formation of Short-lived β^+ Emitters

(Protons on human tissue)

Example : ^{11}C formation



- Improved data base > 50 MeV

Estimated Activity in Human Tissue and Bone as a Result of Proton Therapy

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

Radionuclide	Activity (MBq)		
	Muscle tissue	Adipose tissue	Bone tissue
^{11}C	6.5	19.2	6.4
^{13}N	3.9	2.2	2.3
^{15}O	2.4	0.7	1.4

Total activity of β^+ emitters : 10 – 25 MBq
^{7}Be activity : 40 kBq
^{22,24}Na activity (in bone) : < 250 Bq

Conclusions

- Activation of beam collimators at proton therapy facilities is of some concern regarding the therapy personnel.
- Formation of long-lived radioactive products in tissue and bone can be regarded as negligible.
- Formation of short-lived β^+ emitters is of some significance. Total activity (10 – 25 MBq) is sufficient for dose localisation via PET studies; the extra radiation dose from β^+ emitters is, however, negligible (< 1 %).