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Short-Lived Positron Emitters in Beam-on PET imaging during Proton Therapy

Tom Buitenhuis

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In-vivo dose delivery verification

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Full exploitation of the dosimetric benefits of proton therapy requires in-vivo dose delivery verification !

Dose delivery verification:

- adds to quality assurance
- potentially allows
  - better treatment plans
  - treating new patient categories

How? Imaging of secondary radiation:

- positron emission tomography (PET)
- imaging of prompt gamma rays

Important p-induced positron emitters

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positron emitter	half-life (minutes)	target element
O-15	**2.04**	**oxygen**
C-11	20.4	carbon nitrogen oxygen
P-30	2.50	phosphorus
K-38^{g}	7.64	calcium

PET scanner installation options

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requirement: measure O-15 ($T_{1/2}$ = 2.0 minutes)

in-situ / beam-on **in-room**

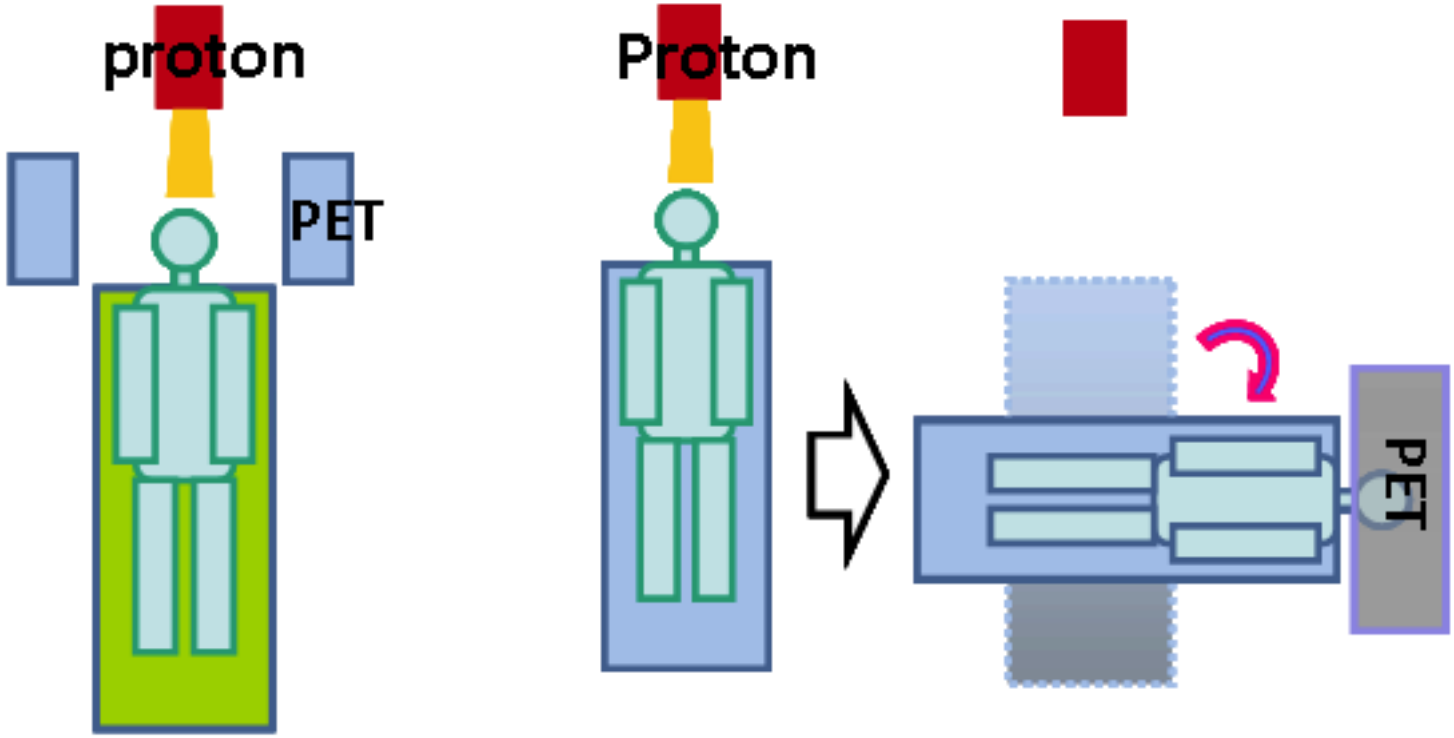

figure from Zhu X and El Fakhri G, Theranostics 3 (2013) 731

Optimized implementation of PET

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essential considerations:

- O-15 is most important
- biological washout
- small PET nuclide production
  - ~kBq/ml at end of irradiation
  - a few million counts in the whole image

PET "as soon as possible"
(beam-on/in-beam/on-line)
- minimal washout
- maximum number of counts

in-situ installation

limited-angle PET

time-of-flight

go for an in-situ TOF-PET installation and data acquisition while the beam is on → short lived nuclei will be seen ($t_{1/2}$ order milliseconds – seconds)

Limited production or cross section data previously available on short-lived nuclei

Experiment: production short-lived nuclides

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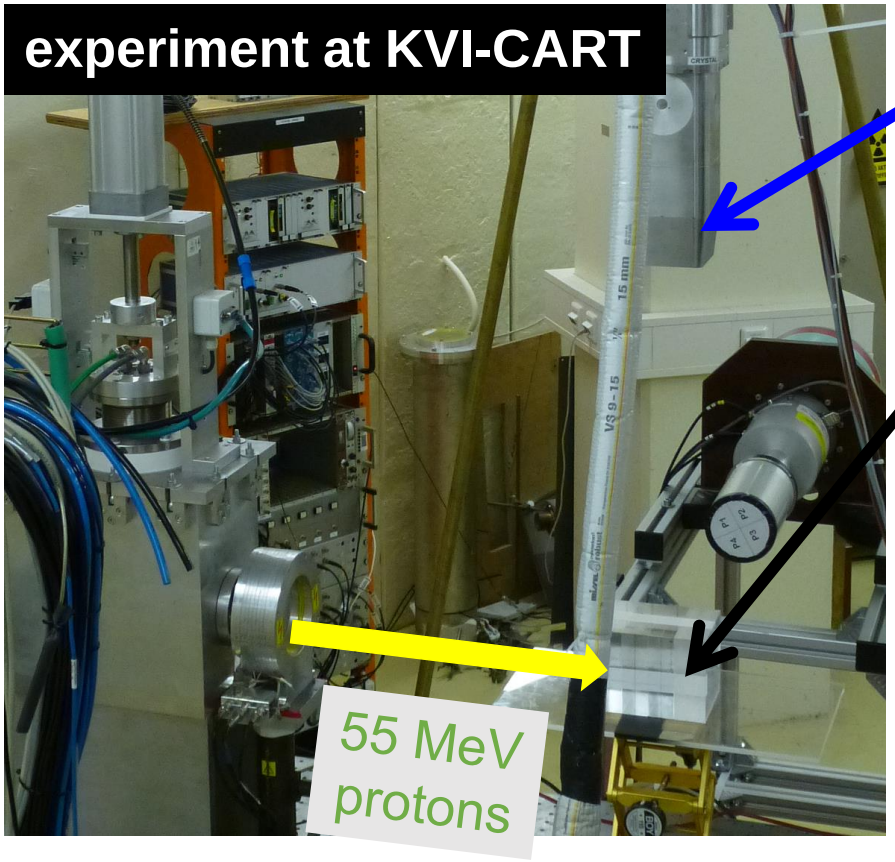

germanium detector

target:

water	O
carbon	C
phosphorus	P
calcium	Ca

method:

- 55 MeV pulsed proton beam
- measure 511 keV intensity vs. time
- disentangle nuclei via half-life analysis of beam-off part
- correction of escaping positron via Monte Carlo simulation

PG Dendooven, HJT Buitenhuis, *et al.* PMB **60** (2015) 8923

511 keV beam-off spectra analysis

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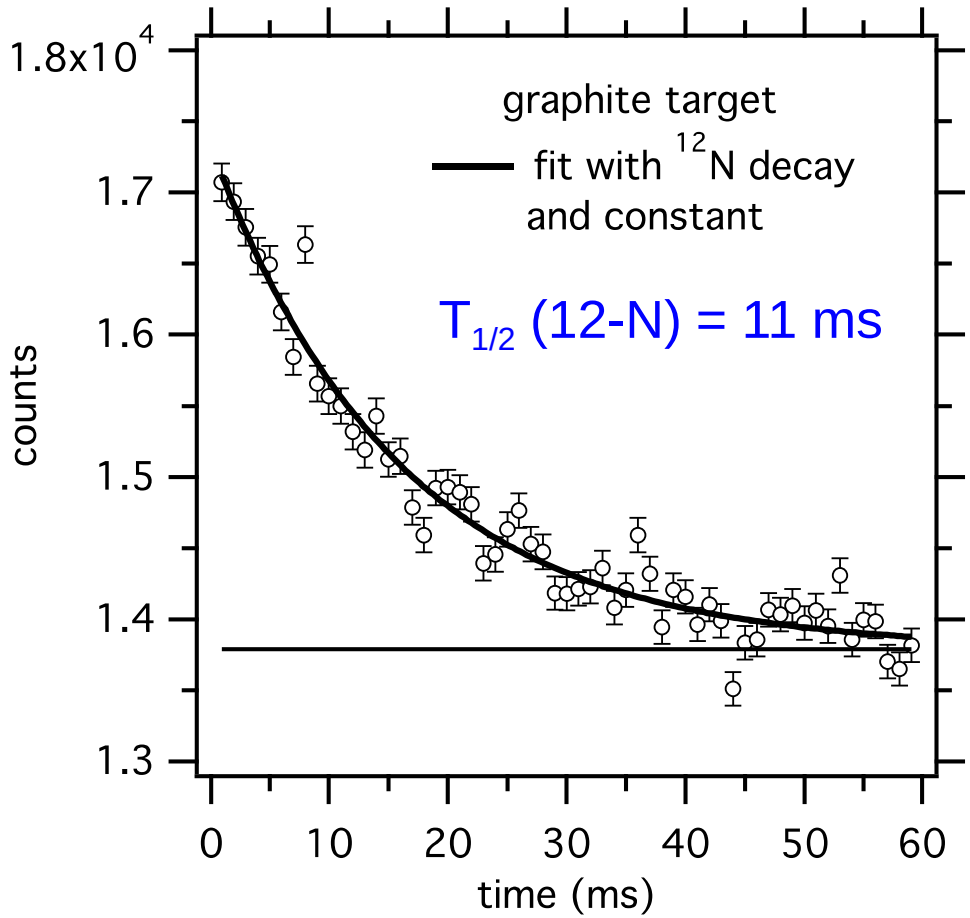
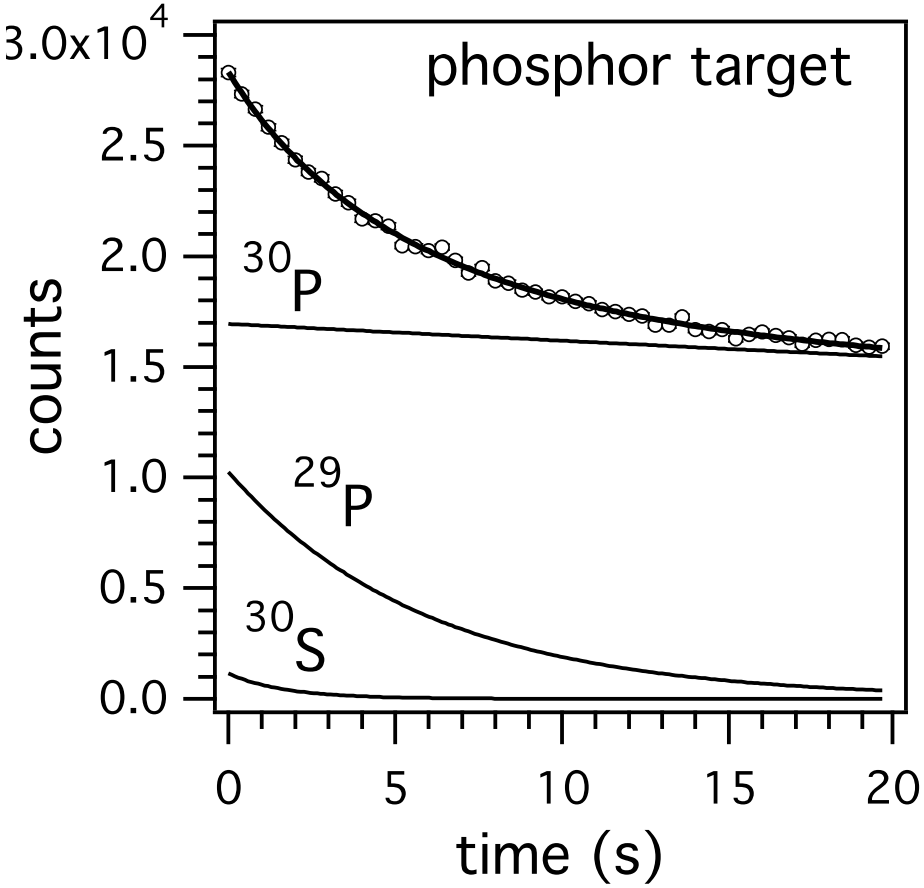


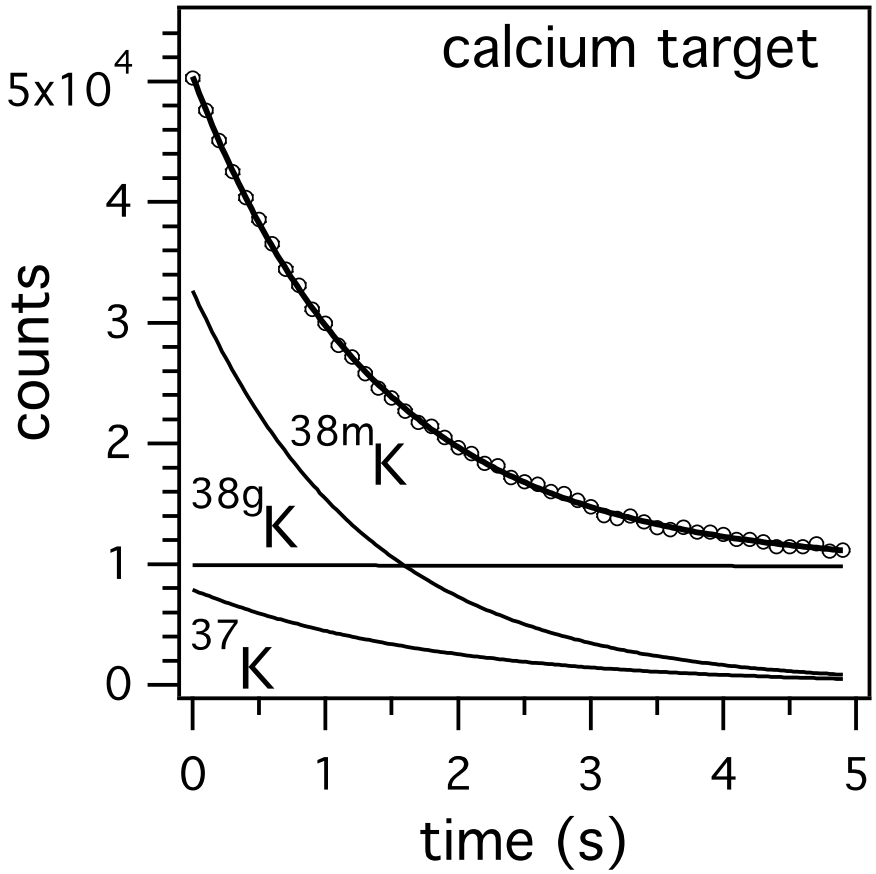
Note: no short-lived isotopes observed on water (oxygen)

511 keV beam-off spectra analysis

$T_{1/2}$ (29-P) = 4.1 s



$T_{1/2}$ (38m-K) = 0.92 s



Production rates

nuclide	target	production per proton (± statistical uncertainty)	systematic uncertainty (%)
O-15	water	$8.83 \pm 0.11 \times 10^{-3}$	3
O-14	water	$7.3 \pm 0.5 \times 10^{-5}$	20
N-12 + O-13	water	$< 7 \times 10^{-5}$	12
C-11	carbon	$8.04 \pm 0.10 \times 10^{-3}$	3
C-10	carbon	$3.08 \pm 0.08 \times 10^{-4}$	3
C-9	carbon	$< 5 \times 10^{-4}$	10
N-12	carbon	$7.32 \pm 0.16 \times 10^{-4}$	12
B-8	carbon	$1.1 \pm 0.3 \times 10^{-5}$	9
P-29	phosphorus	$1.11 \pm 0.02 \times 10^{-3}$	4
P-30	phosphorus	$5.44 \pm 0.03 \times 10^{-3}$	3
S-30	phosphorus	$1.3 \pm 0.2 \times 10^{-4}$	5
K-38g	calcium	$5.66 \pm 0.06 \times 10^{-4}$	3
K-38m	calcium	$6.38 \pm 0.17 \times 10^{-4}$	8

Short-lived vs. long-lived nuclides production

nuclide	$t_{1/2}$	production per proton	relative production
N-12 on C	11 ms	7.32×10^{-4}	9.1 % relative to C-11 on carbon
			8.3 % relative to O-15 on water
P-29 on P	4.14 s	1.11×10^{-3}	20 % relative to P-30 on phosphorus
K-38m on Ca	924 ms	6.38×10^{-4}	113 % relative to K-38g on calcium

PET counts from human tissue

- calculate production on a representative set of human tissues
- number of decays
  - integrated over an irradiation
  - as function of the duration of the irradiation
- one 55 MeV proton per second

PET counts from bone tissue

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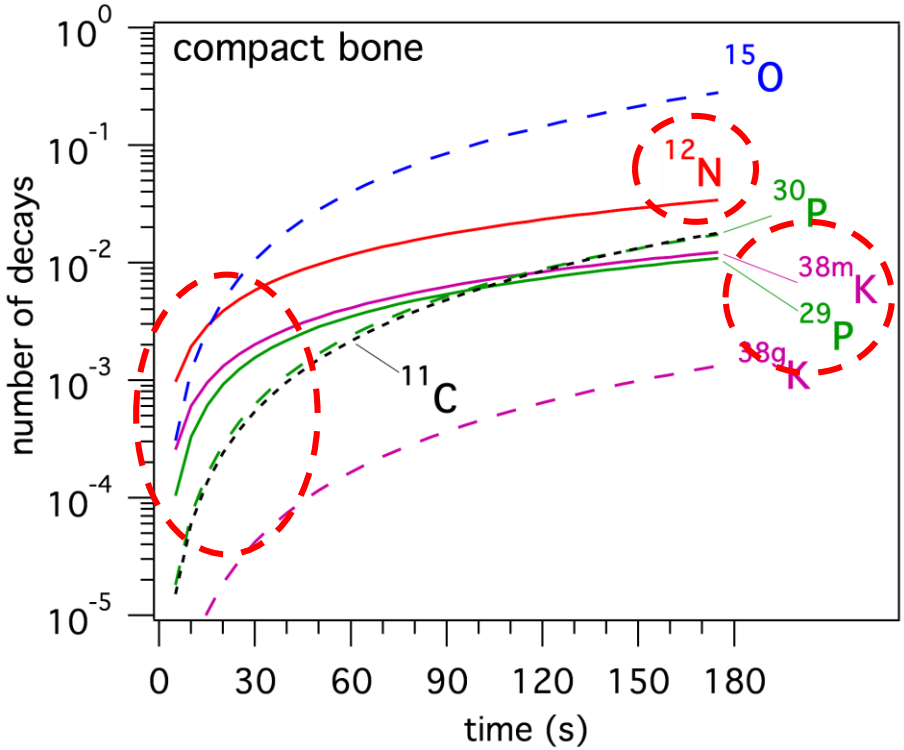
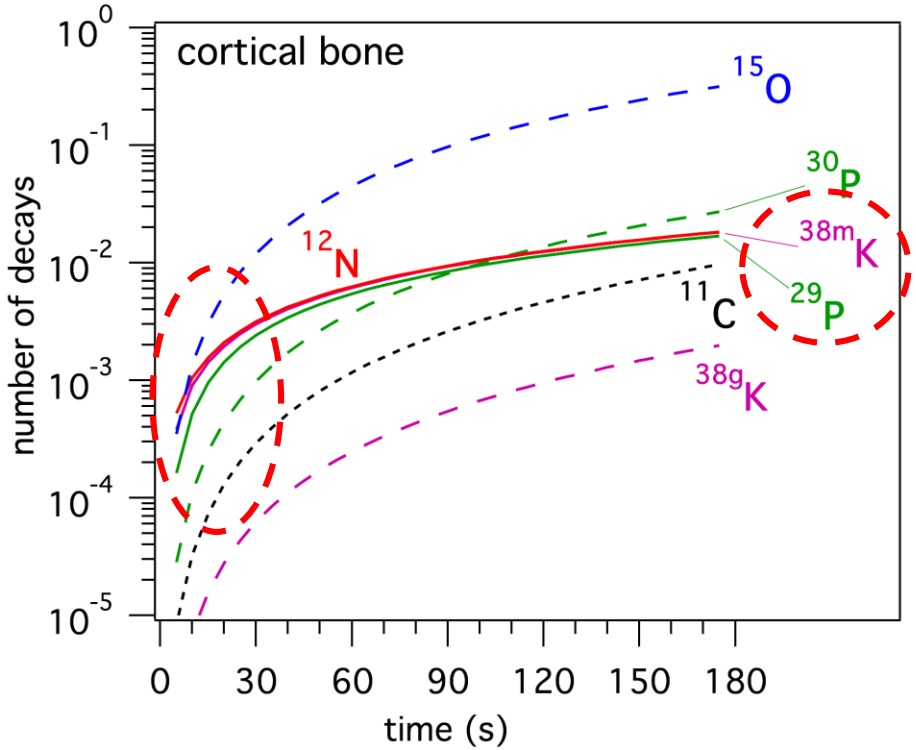
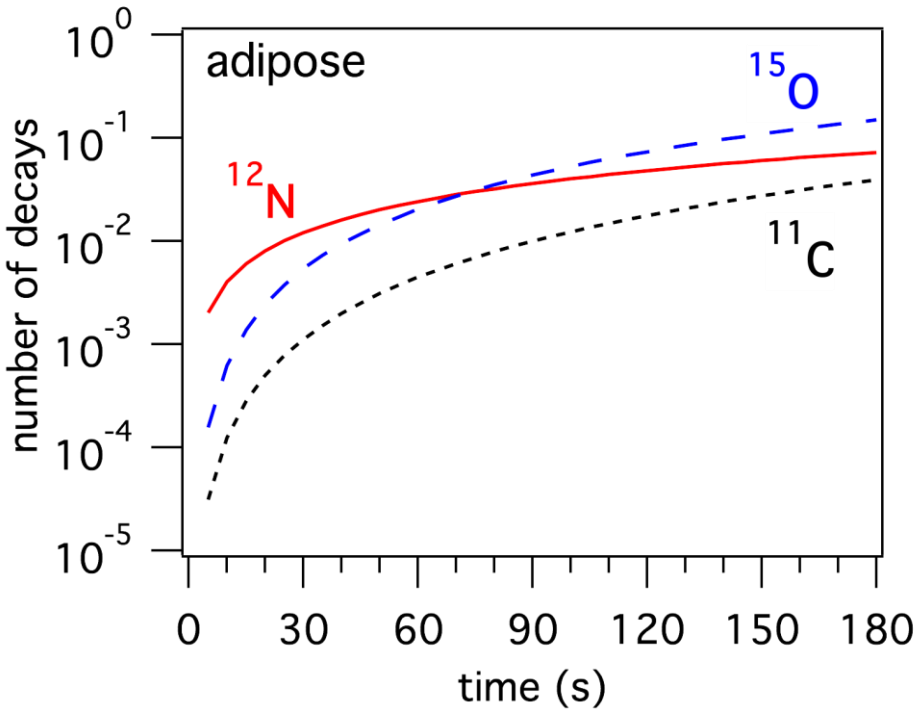
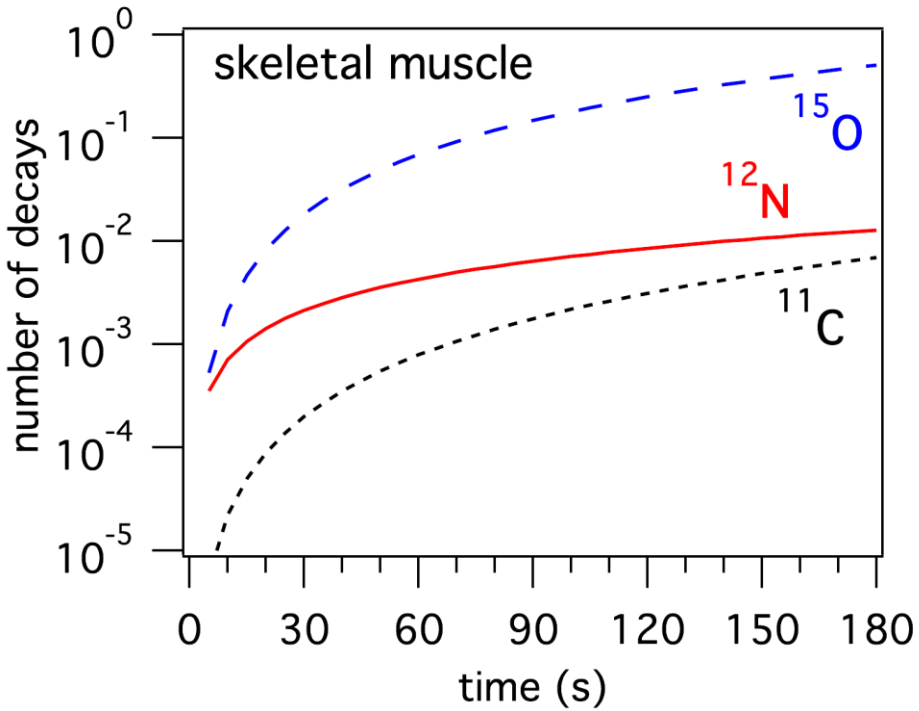




bone tissue is more visible early on

PET counts from soft tissue





C: 64 w%, O: 23 w% composition C: 11 w%, O: 76 w%

PET counts from soft tissue

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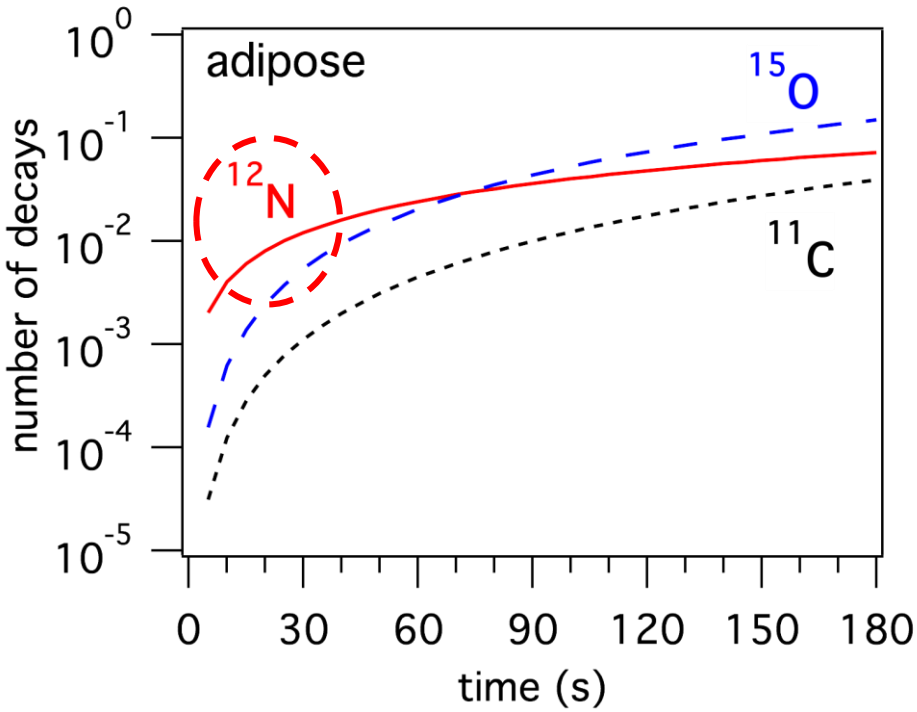

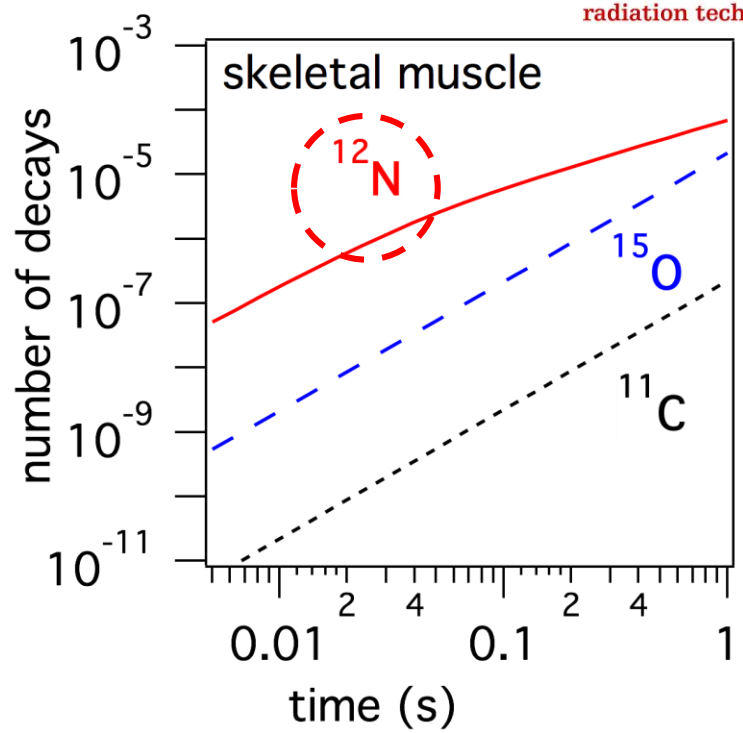

C: 64 w%, O: 23 w% composition C: 11 w%, O: 76 w%

N-12 ($T_{1/2}$ = 11 ms) dominates early on

- only produced on carbon
- prompt information ?
- rms positron range blurring = 18 mm

Prompt feedback from 12-N ?

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N-12 PET imaging

in PMMA

at time scale ≳ 50 ms:
4 x 10^{-4} N-12 decays
per 55 MeV proton

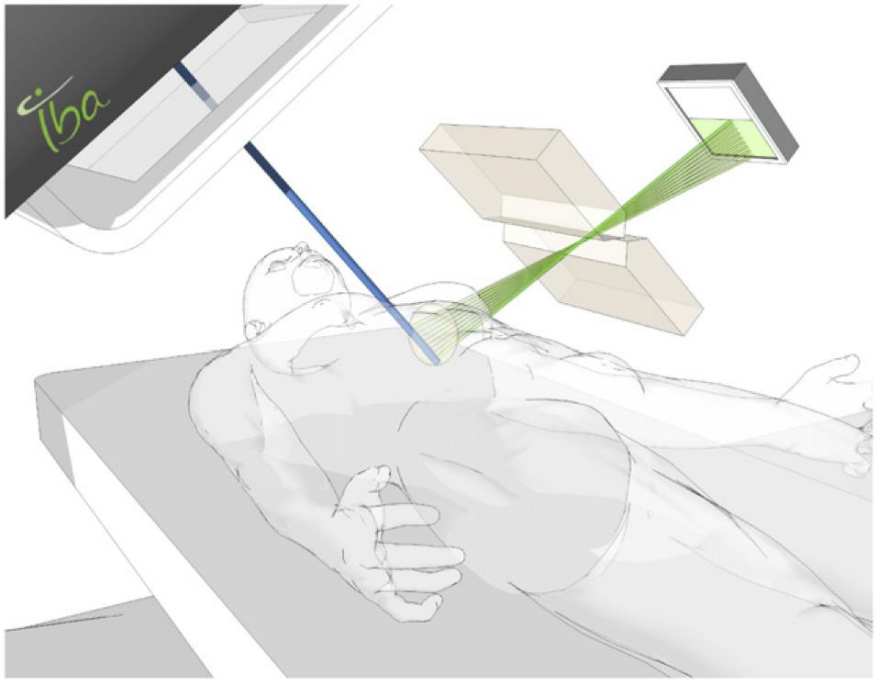
PET imaging efficiëncy: 6 %

Crespo P *et al*, *PMB* **51** (2006) 2143

2.4 x 10^{-5} PET counts/proton

prompt gamma imaging

J Smeets et al, Phys Med Biol 57 (2012) 3371



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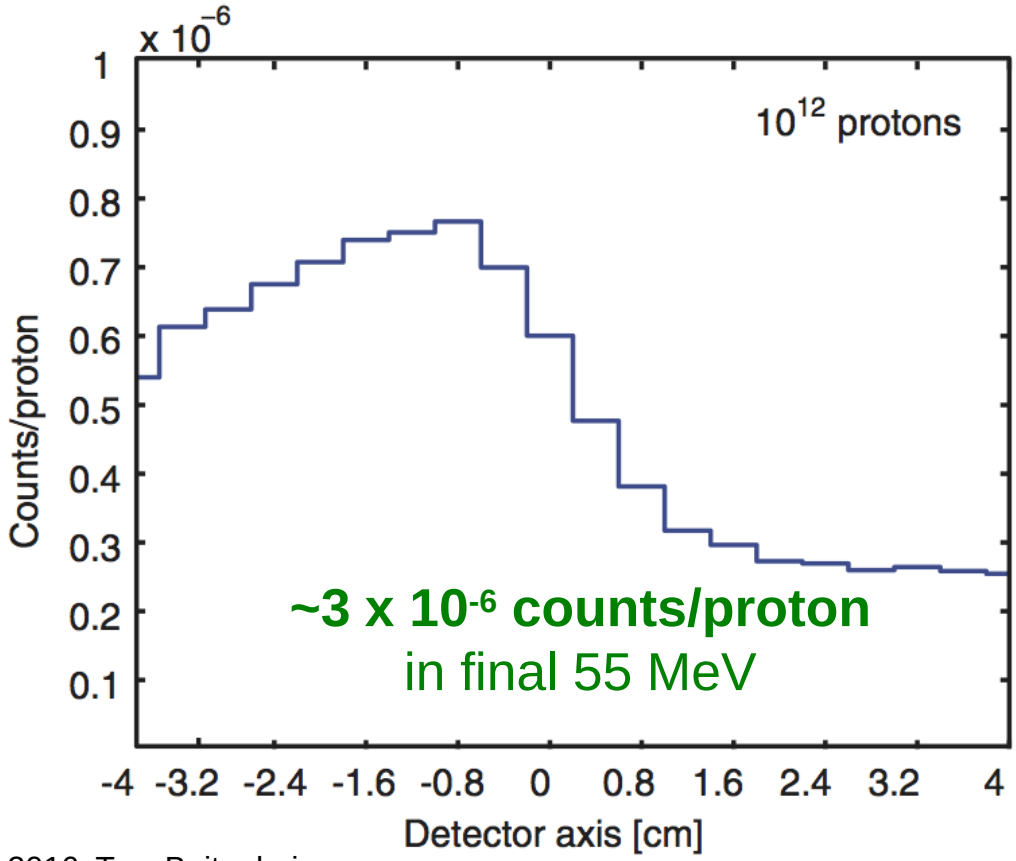

Prompt feedback from 12-N ?

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N-12 PET imaging

prompt gamma imaging

Perali I *et al*, *PMB* 59 (2014) 5849

2.4×10^{-5} PET counts/proton

$\sim 3 \times 10^{-6}$ counts/proton

$$\frac{\text{N-12 PET}}{\text{prompt gamma}} \sim 10$$

image blurring due to positron range

1D rms positron range = 18 mm

knife-edge slit collimator

resolution = 22 mm

depends strongly on carbon contents

quite independent of carbon contents

less interference from neutron-induced counts

Summary – conclusions

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- **short-lived positron emitters** potentially provide (extra) useful information on a short time scale (~ prompt feedback)
  - measured production of N-12, P-29, K-38m, and other nuclei
  - N-12: produced on carbon, can dominate up to 60 seconds

- beam-on TOF-PET **scanner requirements**:
  - high count rate capability
  - radiation hardness
  - event timing vs. accelerator RF (micropulse structure)

Outlook

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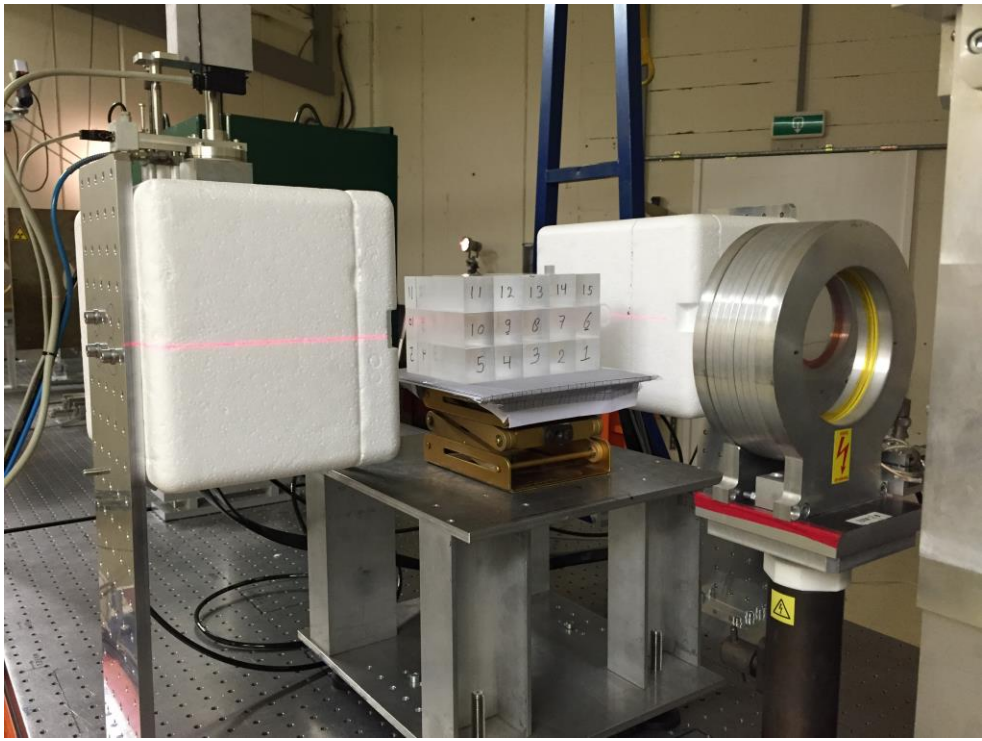
- beam-on imaging experiments
  at KVI-CART
  Philips Digital Photon Counting TOF-PET modules

- clinical protocols need to be worked out
  - relation with beam delivery and different fields
  - investigate using Monte Carlo simulations of patient cases



- measure the most important reaction cross sections vs. energy