Medical Neutron Science

03 Neutron Activation Analysis

The use of NAA techniques for medical applications was first reported in 1964 for measurement of sodium in the body

J. Anderson, S.B. Osborn, R.W. Tomlinson, D. Newton, J. Rundo, L. Salmon, and J.W. Smith, Neutron-Activation Analysis in Man in Vivo. a New Technique in Medical Investigation, Lancet 2, 1201–1205, (Dec 5 1964).

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$$Na^{23} + n \Rightarrow Na^{24} \quad (\gamma\ 1.37;\ 2.75\ MeV)$$

Between 1968 and 1972, Chamberlain reported the measurement of body calcium and sodium in the body and described techniques for whole-body NAA and pulsed NAA.

$$^{48}Ca + n \Rightarrow {}^{49}Ca + \gamma\ (3.1\ MeV)$$

M.J. Chamberlain, J.H. Fremlin, D.K. Peters, and H. Philip, Total body calcium by whole body neutron activation: new technique for study of bone disease, Br. Med. J. 2, 581–3, Jun 8 1968.

^{40}Ca	20	20		stable	0	0+	96.941 *18*
^{41}Ca	20	21	ε	1.03E+5 y *4*	0	7/2-	
^{42}Ca	20	22		stable	0	0+	0.647 *9*
^{43}Ca	20	23		stable	0	7/2-	0.135 *6*
^{44}Ca	20	24		stable	0	0+	2.086 *12*
^{45}Ca	20	25	β^-	162.61 d *9*	0	7/2-	
^{46}Ca	20	26		stable	0	0+	0.004 *3*
^{47}Ca	20	27	β^-	4.536 d *3*	0	7/2-	
^{48}Ca	20	28	β^-, ββ	>6E+18 y	0	0+	0.187 *4*

Cohn and Dombrowski reported the measurement of calcium, sodium chlorine, nitrogen, and phosphorus in the human body through in vivo NAA.

Since then, NAA and PGNAA have been used for a variety of applications, such as the measurement of nitrogen, carbon and oxygen, cadmium, and manganese in the body and in trace element research to identify cancerous tissue.

Inelastic neutron scatter analysis (INSA) using fast neutrons use 14 MeV neutrons from a (d,T) sealed-tube neutron generator to determine whole body carbon content as a measure of energy expenditure in the body.

K. Kyere, B. Oldroyd, C.B. Oxby, L. Burkinshaw, R.E. Ellis, and G.L. Hill, The feasibility of measuring total body carbon by counting neutron inelastic scatter gamma rays, Phys. Med. Biol. 27, 805–17 (Jun 1982).

TABLE 1. IN VIVO NEUTRON ACTIVATION REACTIONS

Reaction	$T_{1/2}$	Decay scheme*	Measured total activity (nCi)†	Yield‡
$^{23}Na(n,\gamma)^{24}Na$	15.0 h	1.389 β(100), **2.75 γ(100)**, 137 γ(100)	9.6	1.0
$^{37}Cl(n,\gamma)^{38}Cl$	37.2 m	4.81 β(53), 2.77 β(16), 1.11 β(31), 1.60 γ(31), **2.17 γ(47)**	23.4	1.55
$^{48}Ca(n,\gamma)^{49}Ca$	8.7 m	1.95 β(88), 0.9 β(12), **3.1 γ(89)**, 4.05 γ(10), 4.68 γ(0.3)	19.3	0.99
$^{31}P(n,\alpha)^{28}Al$	2.31 m	2.86 β(100), **1.79 γ(100)**	1331.0	7.66
$^{14}N(n,2n)^{13}N$	9.99 m	1.19 β^+(100), **(0.51 γ from β^+)**	107.0	25.90
$^{37}Cl(n,p)^{37}S$	5.06 m	4.3 β(10), 1.6 β(90), **3.1 γ(90)**	2.1	0.06
$^{24}Mg(n,p)^{24}Na$	15.0 h	1.389 β(100), **2.75 γ(100)**, 1.37 γ(100)		
$^{26}Mg(n,\gamma)^{27}Mg$	9.5 m	1.75 β(58), 1.59 β(42), 0.18 γ(0.7), **0.84 γ(70)**, 1.01 γ(30)		
$^{31}P(n,2n)^{30}P$	2.56 m	3.24 β^+(99.5), 1.01 β^+(0.5, 2.16 γ(0.5), **(0.51 γ from β^+)**		
$^{39}K(n,2n)^{38}K$	7.7 m	2.68 β^+(100), 2.17 γ(100), **(0.51 γ from β^+)**		
$^{41}K(n,\gamma)^{42}K$	12.5 h	3.56 β(82), 1.97 β(18), **1.52 γ(18)**		
$^{41}K(n,\alpha)^{38}Cl$	37.2 m	4.81 β(53), 2.77 β(16), 1.11 β(31), 1.60 γ(31), **2.17 γ(47)**		

* Principal energy used for detection of the nuclide of concern is in bold face.

† Normalized to standard man and based on ϕ_{th} of 4.54×10^4, 5-min bilateral irradiation, and 15-min count starting at 6-min postirradiation. Total measured activity is the activity at the end of the irradiation.

‡ Measured counts of principal energy relative to ^{24}Na counts.

The use of **nuclear resonance scattering** (NRS) is used for detection of iron in the liver and in the heart using an **indirect** method of nuclear excitation by gamma rays generated through neutron capture (INSA).

Recently, 14 MeV neutrons has been used for in vivo measurement of liver iron through INSA and NRS.

Neutron Stimulated Emission Computed Tomography:

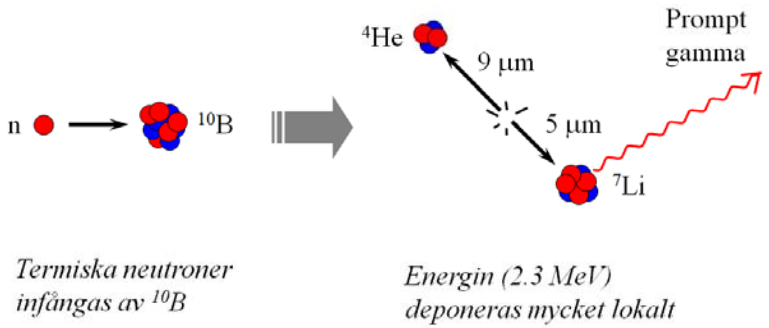
A New Technique for Spectroscopic Medical Imaging

Radiation therapy activation analysis

2002 Prompt-gamma spektroskopi (PGS)

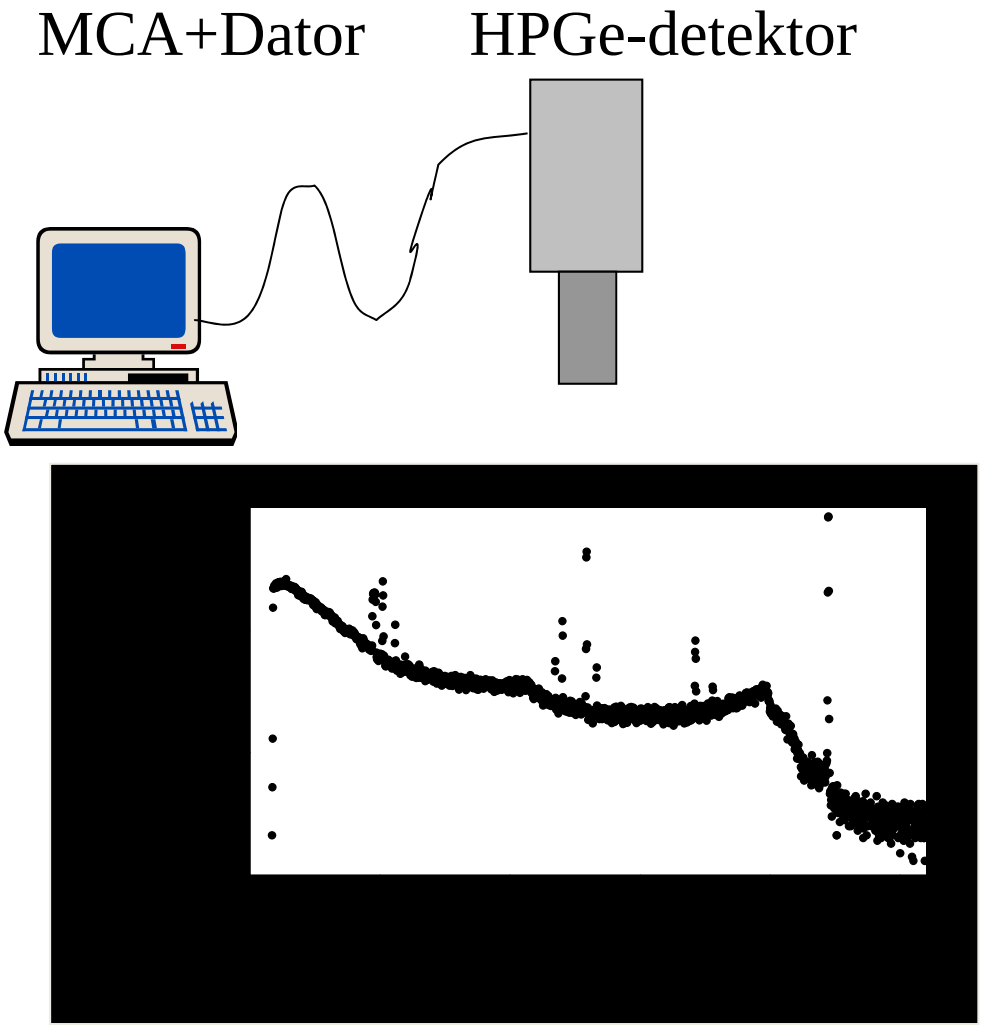
- Mätning av infångningsgamma utsända från bor och väte i patient under bestrålning med epitermiska neutroner.

$$n + p \longrightarrow D^2 + \text{gamma}$$



2002 Prompt-gamma spektroskopi (PGS)

- Mätning av infångningsgamma utsända från bor och väte i patient under bestrålning.
- Räknehastigheten i detektorn för linjerna kan relateras till borkoncentrationen *in-vivo*.



Tidigare resultat med PGS

- Mättider kring 3 min.
- Borkoncentrationer kring 5 ppm.
- Vid homogen borfördelning blir noggranheten 3% (1 SD).

Neutron stimulated emission computed tomography (NSECT), was pioneered at Duke University in 2003 by the late Dr. Carey E. Floyd Jr. for the purpose of diagnostic medical imaging.

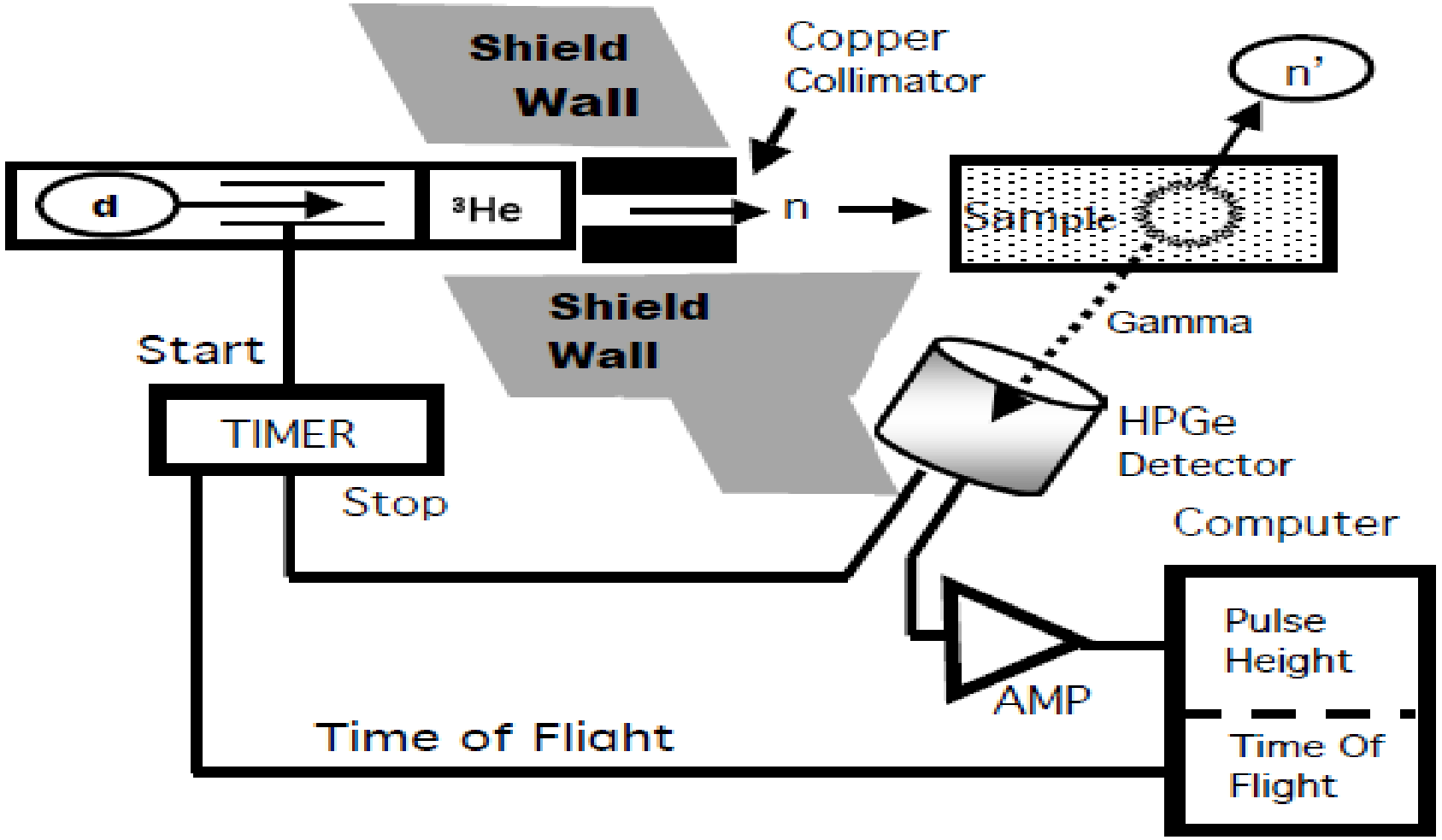
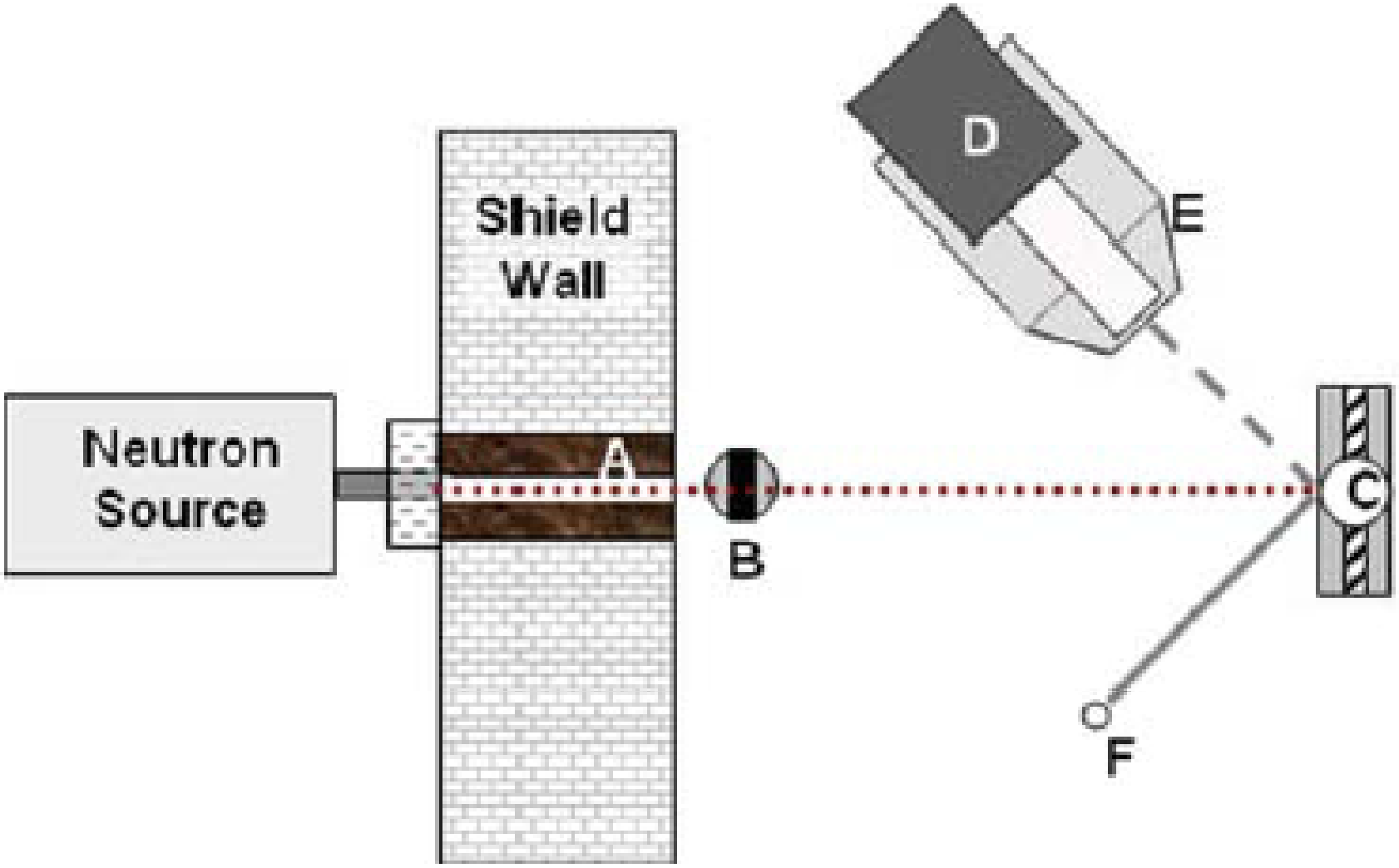
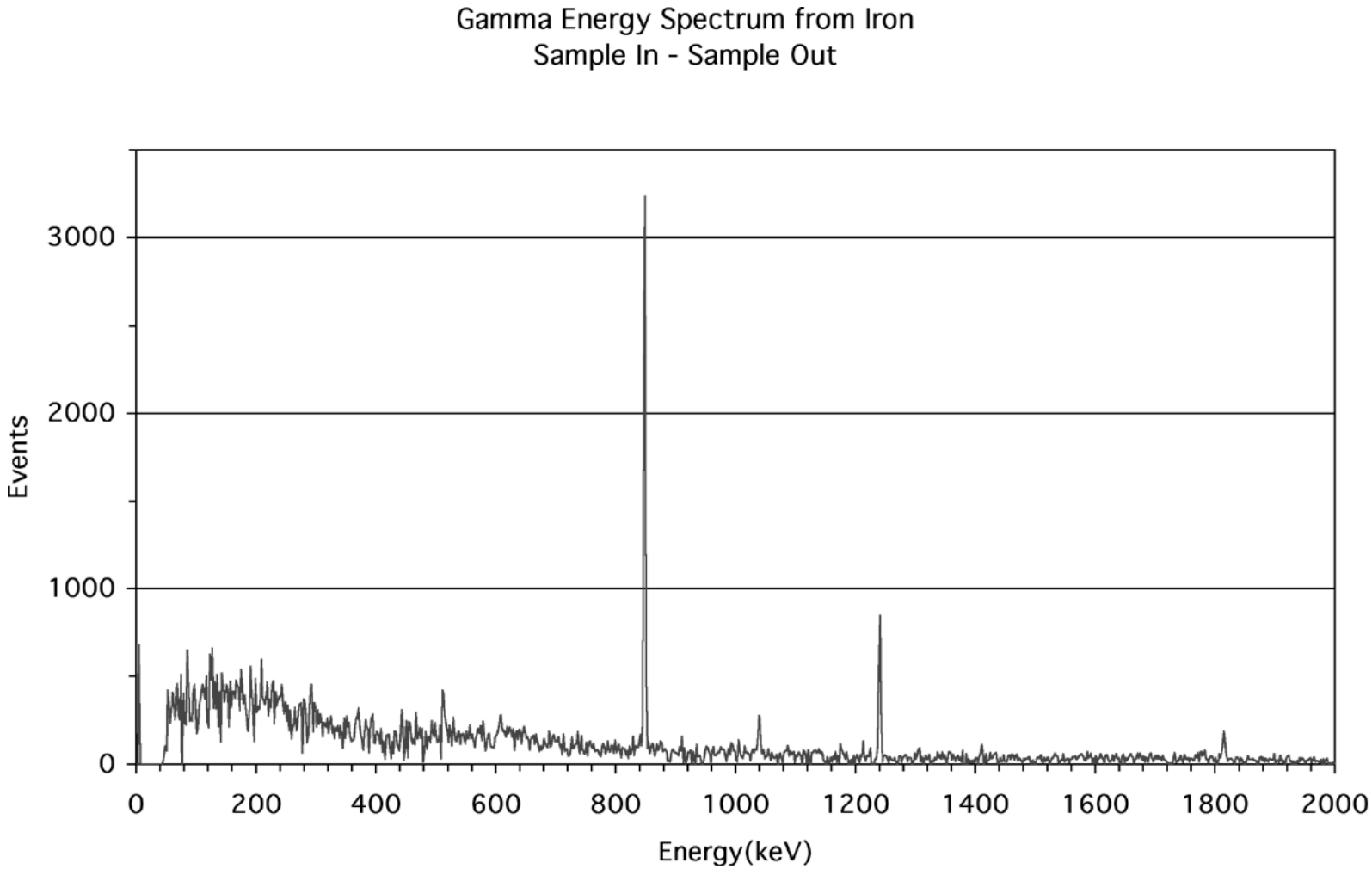


Fig. 1 Schematic of the target area showing a deuteron beam pulse arriving from the accelerator from the left, passing through the beam pick-off tube to generate the start signal for the Time-Of-Flight electronics, traveling into the deuterium gas cell, creating neutrons through the d(d,n) reaction leaving 3He in the gas cell. The neutron travels through the collimator to the sample where it scatters inelastically to produce a neutron of reduced energy n' and a gamma photon which is collected by the HPGe detector. The signal from the detector stops the timer while the amplified signal from the detector is stored as a pulse height that is proportional to he absorbed gamma energy. The Time-Of-Flight from the deuteron entering the gas cell to the detection of this photon is also stored.

A neutron incident on a sample travels freely along its projected path until it collides with an atomic nucleus of an element present in the sample. If the collision with the atomic nucleus results in inelastic scatter, the nucleus can get excited to one of its quantized higher-energy states. The excited nucleus is often unstable and will rapidly decay to a lower energy state, emitting a gamma-ray photon with energy equal to the difference of the two states. These energy states are well established for most elements and isotopes and are mostly unique for the elements commonly found in the body. Therefore, the energy of the emitted gamma photon can be treated as a unique signature of the emitting element. Tomographic detection and analysis of gamma lines in the emitted spectrum provide quantitative information about the spatial distribution of the element in the sample


Shield
Wall
Neutron
Source
A
B
C
D
E
F

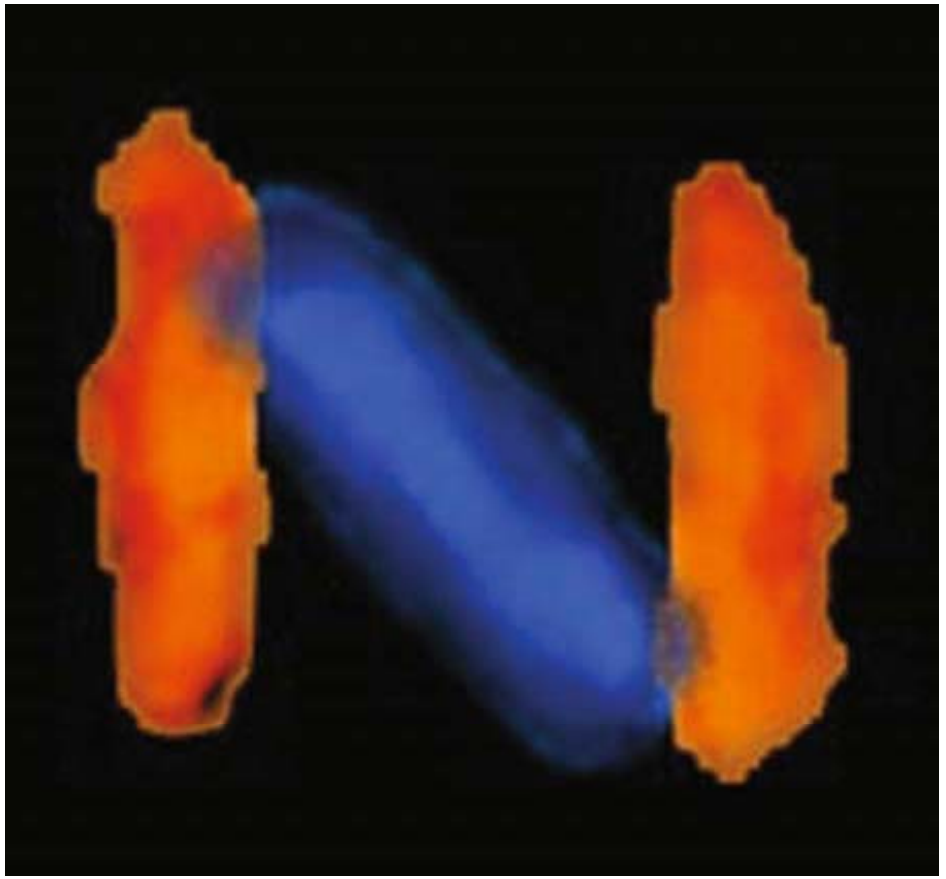


Spectrum for Fe with the sample-out spectrum subtracted from the sample-in spectrum.

Geometry of the phantom imaged in the tomography experiment.

The vertical outer bars represent copper while the diagonal inner (gray) bars represent iron.

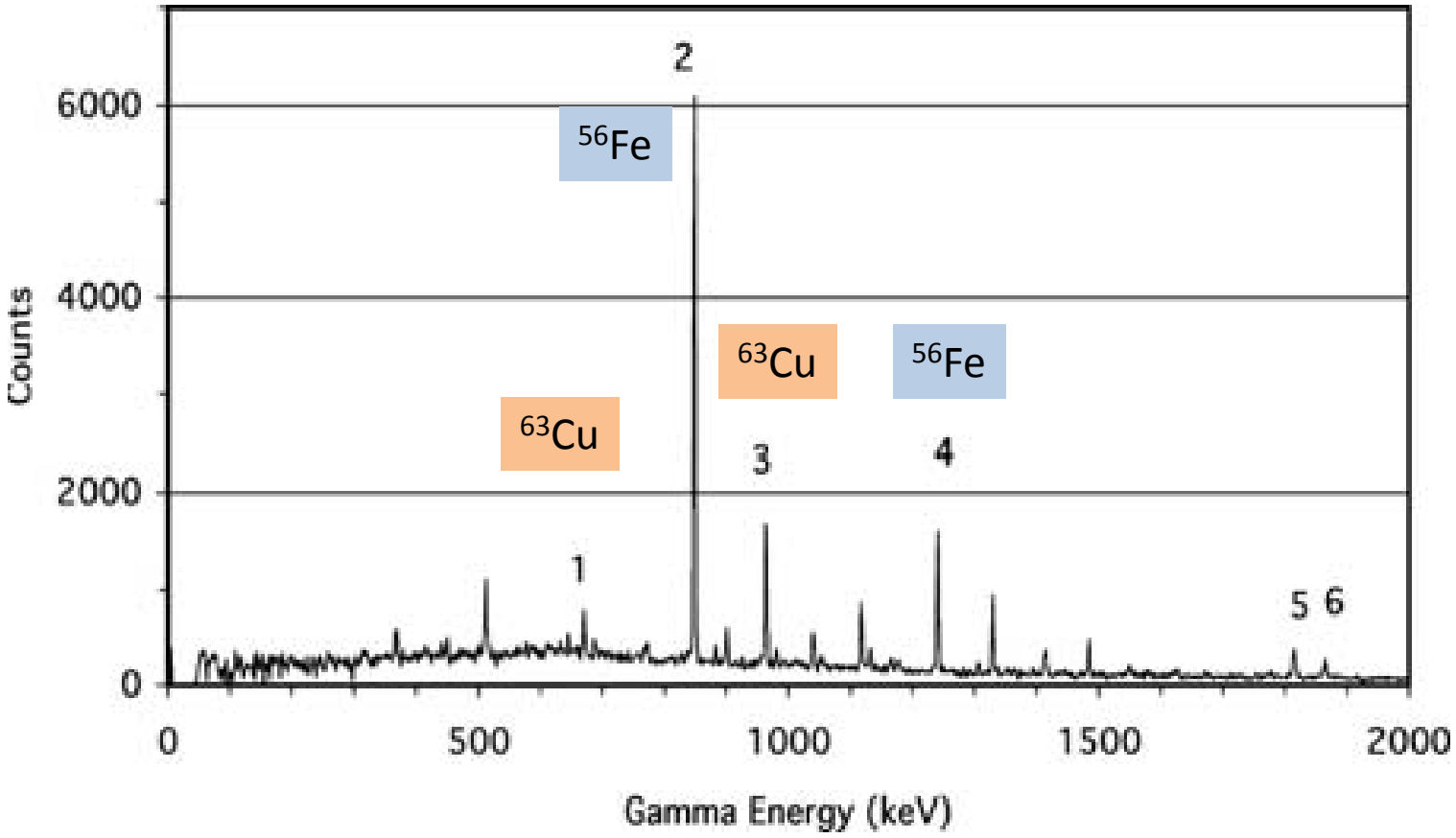
Each bar measures 0.6 cm by 6 cm by 2.5 cm



Reconstructed image from the NSECT acquisition of the sample.

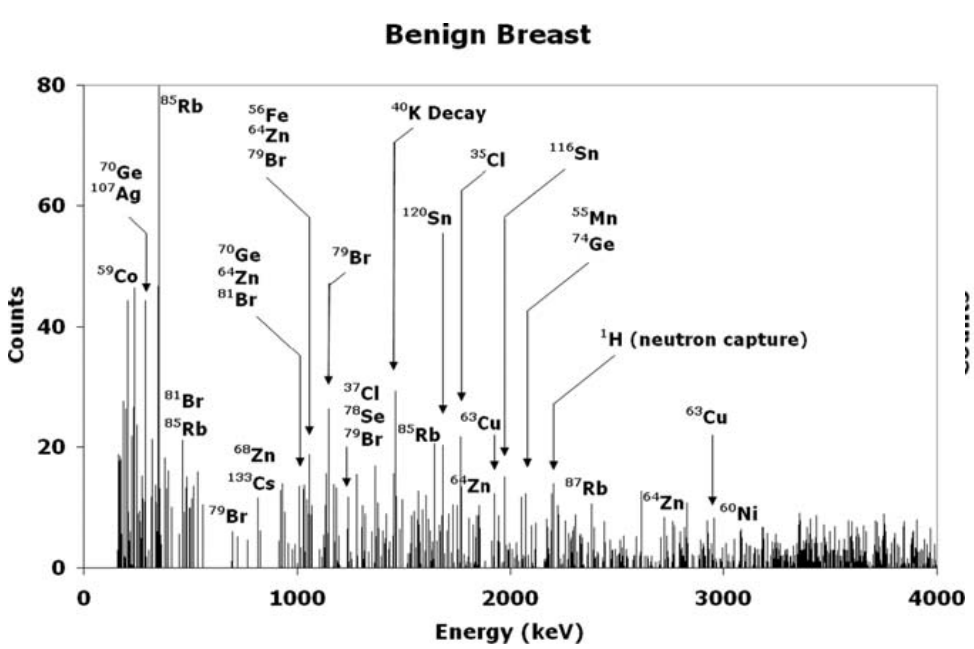
The vertical outer regions represent copper while the diagonal inner region represents iron.

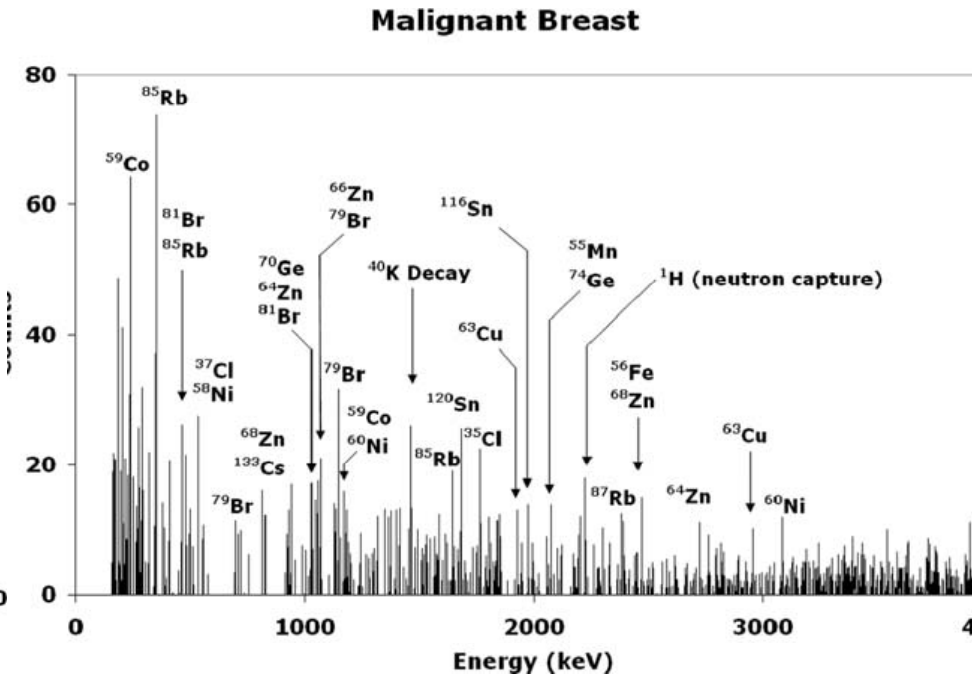
Each element was reconstructed separately and then combined



Gamma energy spectrum from the iron-copper phantom showing spectral lines from six transitions in ^{56}Fe and ^{63}Cu:

1. 63Cu from 1st excited state to ground state; energy 660 keV
2. 56Fe from 1st excited state to ground state; energy 847 keV
3. 63Cu from 2nd excited state to ground state; energy 962 keV
4. 56Fe from 3rd to 2nd excited state; energy 1239 keV
5. 56Fe from 4th to 2nd excited state; energy 1811 keV
6. 63Cu from 6th to 1st excited state; energy 1864 keV





6 MeV Neutron Stimulated Emission Computed Tomography NSECT spectrum of a **benign breast sample** showing elements identified through gamma spectroscopy.

6 MeV Neutron Stimulated Emission Computed Tomography NSECT spectrum of a **malignant breast sample** showing elements identified through gamma spectroscopy.

Table 15.2 List of elements showing statistically significant differences between benign and malignant spectra. Elements with negative differences showed a decrease in concentration in the malignant sample. Statistical significance was calculated using a z-score test for difference of means. (Table from Kapadia et al. [32], pp. 501–509. © 2008 IEEE)

Energy keV	Element match	Counts benign	Counts malignant	Diff	p-val
219	^{79}Br	6	19	13	0.01
397	^{59}Co, ^{79}Br	16	2	–14	0.01
1028	^{81}Br	13	29	16	0.05
1128	^{39}K, ^{68}Zn	0	13	13	0.001
1306	^{56}Fe	10	0	–10	0.01
2299	^{27}Al	0	13	13	0.001
2469	^{37}Cl, ^{56}Fe, ^{66}Zn	5	15	10	0.05
3635	^{35}Cl	3	14	11	0.01

The Dose analysis can be summarized in the following three steps:

(a) a Monte-Carlo simulation is used to estimate two parameters for an incident neutron beam – the number of neutrons that interact in the volume of interest and the average energy deposited per interacting neutron,

(b) the resulting energy deposited in the volume is converted from MeV to J/kg using the knownmass of the volume to give the absorbed energy in Gray (Gy), And

(c) the absorbed energy is multiplied by the quality factor for neutrons (10) and the weighting factor for the organ of interest to give the effective dose equivalent in Sieverts (Sv).

Table 15.3 NSECT dose delivered to organs in the body from NSECT scans

Organ	Spectroscopic scan	Tomography scan
Abdomen	1–2 mSv	1–5 mSv
Liver	0.02–1 mSv	0.5–3 mSv
Breast	0.02–0.5 mSv	0.5–1 mSv

Patient dose was calculated for each gamma spectrum obtained and was found to range from between 0.05 and 0.112 mSv depending on the number of neutrons. This simulation demonstrates that NSECT has the potential to noninvasively detect breast cancer through five prominent trace element energy levels, at dose levels comparable to other breast cancer screening techniques.

NSECT represents an exciting new imaging modality that has the potential for application in both medical and biological research.

At the department of Medical Radiation Physics in Lund we already have a lot of expertise in the different field of knowledge necessary to establish Neutron Stimulated Emission Computed Tomography NSECT in practice.

What we are missing are laboratories for neutron Exposure. A prototype of the NSECT acquisition system has been developed and built at Duke University using a Van-de-Graaff accelerator and HPGe detectors. That would be able to establish in Lund as well, in collaboration with our friends at Nuclear Physics. For furthe establishment at ESS

The use of **nano particles** of iron or other elements labelled with biologically active molecules or antibodies or lymphocytes labelled with nanoparticles in combinations with Neutron Stimulated Emission Computed Tomography NSECT opens up for a completely new field of **Nano-Nuclear medicine.**

This could be one important leg for establishing **Medical Neutron Beam** at ESS