XIV School of Neutron Scattering “Francesco Paolo Ricci” (SoNS)

DESIGNING AND BUILDING A NEUTRON INSTRUMENT, The 2nd Erice School

Compact Accelerator-driven Neutron Sources (CANS)

Chun K Loong
ckloong@gmail.com

Linking neutron applications – R&D and education – among international projects, regional centers, government labs, universities, & industry

Materials characterization PLUS

Outline

1 An Overview

- ✧ CANS: What they are and how they play a role in the neutron sciences & technologies

2 The CANS accelerator structure

- ✧ *Refer to Ken Herwig's talk on linear vs ring, short vs long pulsed structures yet scaling down in power (and cost).*

3 Applications

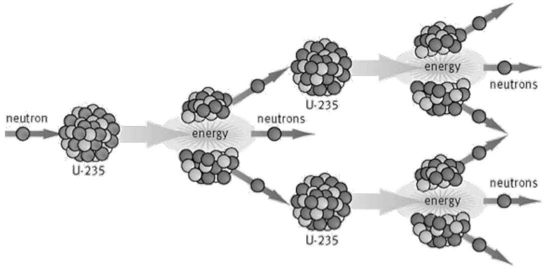
- ✧ The multidisciplinary nature and diverse utilization

4 The community

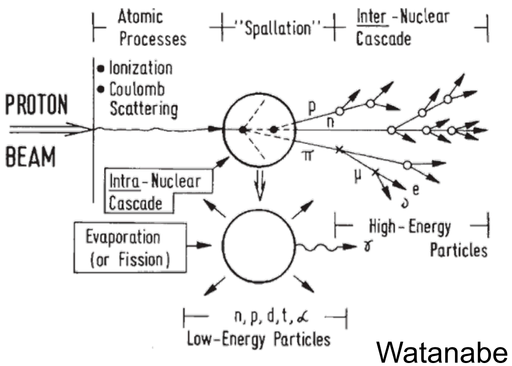
- ✧ Ongoing activities
- ✧ What is next?

Neutron Production Mechanisms

Reactions	Neutron Production Examples
Fission	$^{235}\mathrm{U} + n \longrightarrow \mathrm{A}^* + \mathrm{B}^* + \mathrm{x}n; \quad <\mathrm{x}> \sim 2.5$
Spallation	$p + {}^{184}\mathrm{W} \longrightarrow \mathrm{A}^* + \mathrm{B}^* + \mathrm{x}n, \quad <\mathrm{x}> \sim 20$
Fusion	$d + t \longrightarrow \alpha(3.5\mathrm{MeV}) + n(14.1\mathrm{MeV})$ $d + d \longrightarrow \alpha(0.866\mathrm{MeV}) + n(2.4\mathrm{MeV})$
Photoproduction	$\gamma + {}^{181}\mathrm{Ta} \longrightarrow {}^{180}\mathrm{Ta} + n, \gamma + {}^{2}\mathrm{H} \longrightarrow {}^{1}\mathrm{H} + n$
Charged-particle reaction	$^{9}\mathrm{Be} + p \longrightarrow {}^{9}\mathrm{B} + \mathrm{n}, {}^{2}\mathrm{H} + {}^{3}\mathrm{H} \longrightarrow {}^{3}\mathrm{He} + n$
(n,xn)	$^{9}\mathrm{Be} + n \longrightarrow {}^{8}\mathrm{B}^* + 2n$
Excited-state decay	$^{13}\mathrm{C}^{**} \longrightarrow {}^{12}\mathrm{C}^* + n, {}^{130}\mathrm{Sn}^{**} \longrightarrow {}^{129}\mathrm{Sn}^* + n$

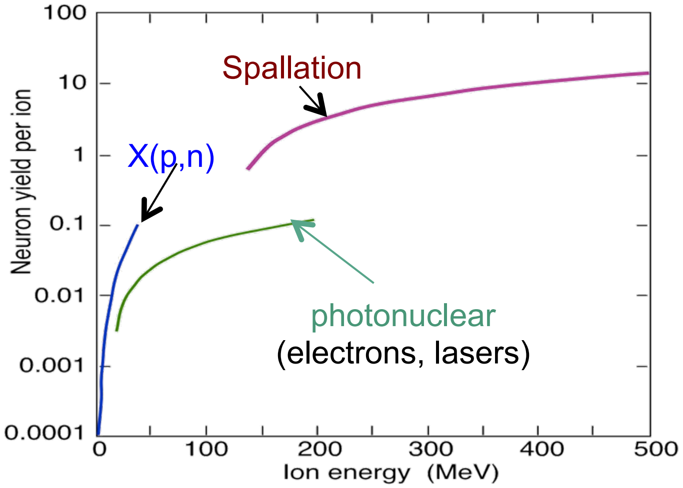


Fission



Watanabe 2003

Spallation



More Neutron Producing Reactions

Reaction types	Examples
(p,n)	^{3}H(p,n)^{3}He, ^{6}Li(p,n)^{6}Be, ^{7}Li(p,n)^{7}Be, ^{9}Be(p,n)^{9}B, ^{10}Be(p,n)^{10}B, ^{10}B(p,n)^{10}C, ^{11}B(p,n)^{11}C, ^{12}C(p,n)^{12}N, ^{13}C(p,n)^{13}N, ^{14}C(p,n)^{14}N, ^{15}N(p,n)^{15}O, ^{18}O(p,n)^{18}F, ^{36}Cl(p,n)^{36}Ar, ^{39}Ar(p,n)^{39}K, ^{59}Co(p,n)^{59}Ni
(d,n)	^{2}H(d,n)^{3}He, ^{3}H(d,n)^{4}He, ^{7}Li(d,n)^{8}Be, ^{9}Be(d,n)^{10}B, ^{11}B(d,n)^{12}C, ^{13}C(d,n)^{14}N, ^{14}N(d,n)^{15}O, ^{15}N(d,n)^{16}O, ^{18}O(d,n)^{19}F, ^{20}Ne(d,n)^{21}Na, ^{24}Mg(d,n)^{25}Al, ^{28}Si(d,n)^{29}P, ^{32}S(d,n)^{33}Cl
(t,n)	^{1}H(t,n)^{3}He
(α,n)	^{3}H(α,n)^{6}Li, ^{7}Li(α,n)^{10}B, ^{11}B(α,n)^{14}N, ^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg

Drosg *et al.* (2002)

Source Characteristics *(Bauer01, Clausen08, Mank et al.01, Zager et al. 05, Nakai et al.10, Elizondo-Decanini et al12)*

Reactions	Neutron Yield	Neutron Production*	Heat Release (MeV/n)	Remarks
Spallation	17-27n/p	10^{14} (n/s/cm^2)	30-55	Expensive, complex, adamant usage
Fission	1 n/fission	10^{13}-10^{15} (n/s/cm^2)	180	Expensive, complex, adamant usage
Giant laser inertial fusion	1 n/D-T pair	> 10^{16} (n/s/cm^2)	Re-stockable D-T pellets	Unattainable?
^{9}Be(D,n)^{10}Be ^{9}Be(p,xn)	1 n/D 5x10^{-3} n/p	10^{13}-10^{15} (n/s/cm^2)	1000 2000	Moderate cost, flexible operation, multipurpose
Photonuclear e-bremsstrahlung	5x10^{-2} n/e	10^{13} (n/s/mA)	2000	Moderate cost, flexible operation, multipurpose
Neutron Generators (D,D) (D,T)	10^7-10^8 n/μC	10^8 -10^{10} (n/s)	3500-10000	Transportable, affordable for tailored commercial applications, need higher flux
Table-top-laser photonuclear	10^6-10^8 n/J	10^8 -10^{10} (per shot)	Ultra-short pulsed lasers	Many debris, neutronics not yet matured
Neutristors solid-state, (D,D) chips	?	?	?	~$2000, tiny, implantable medically, to be developed

*need quantification of neutron spectral distribution and time structure

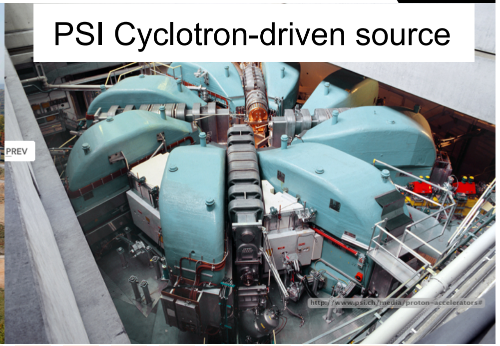
Neutron Sources

Big

FRM-II High Flux Reactor

Spallation Neutron Source

PSI Cyclotron-driven source

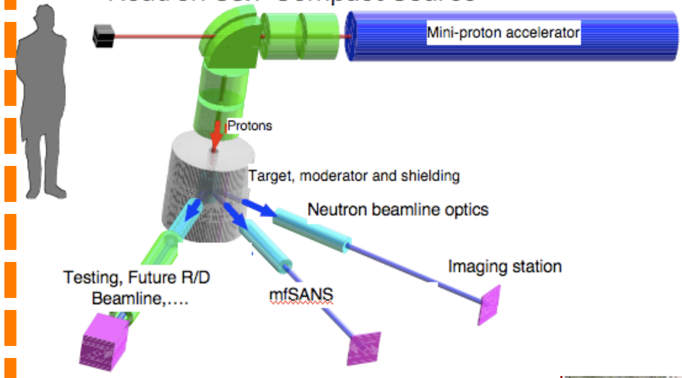


Medium

Small Reactors

Compact Accelerator-Driven Sources <~100kW non-spallation

Neutron S&T Compact Source

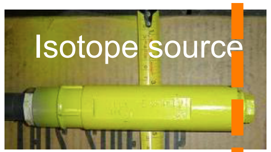


p, d or e^-

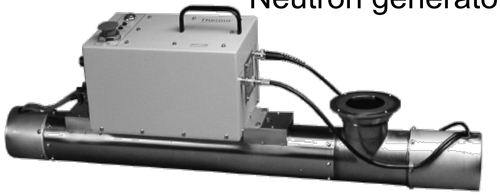
© AccSys Technology, Inc.

Small

Isotope source



Neutron generator



Neutron Interrogation Device

PGNAA

Neutron Sources: Past, Present, & Future

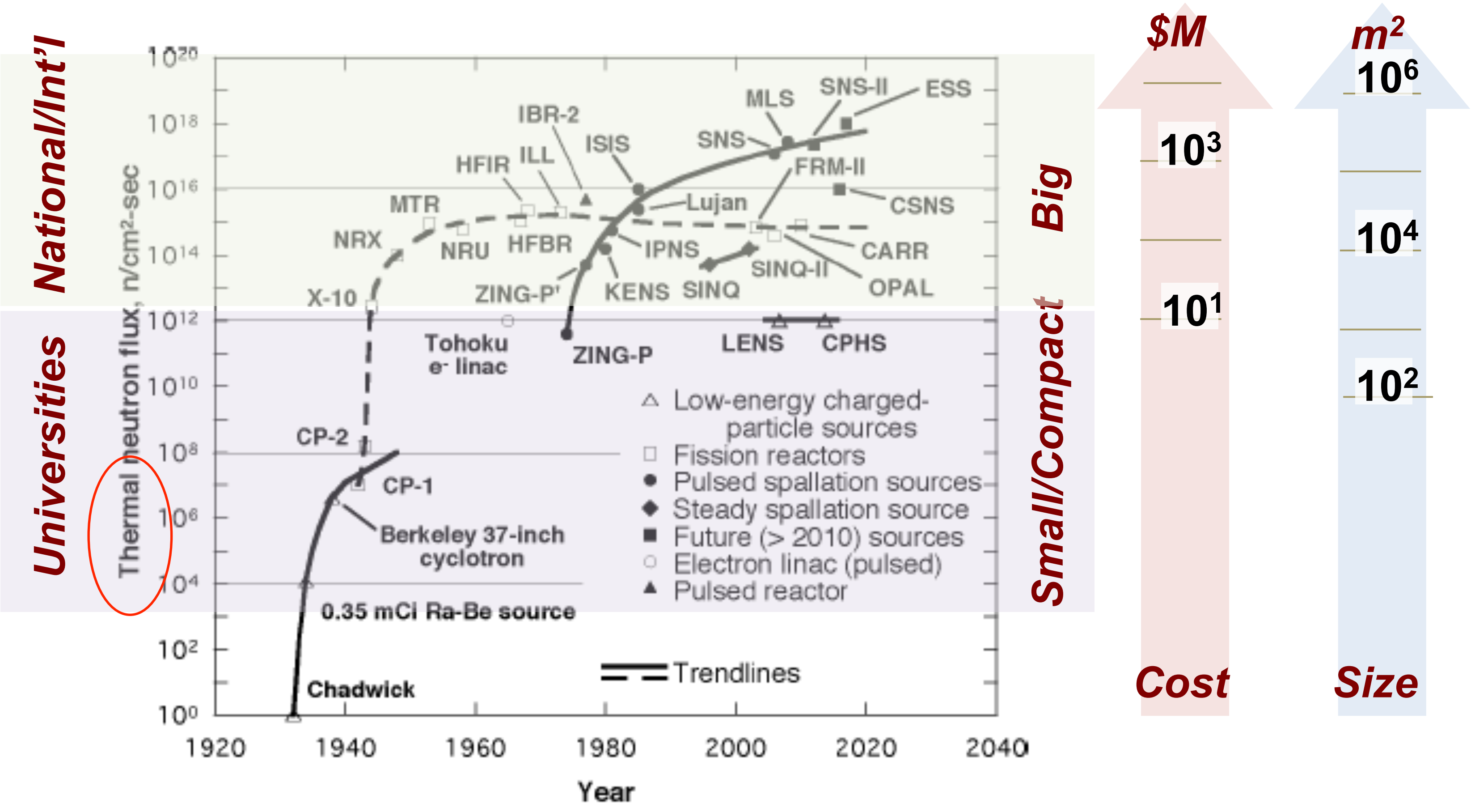
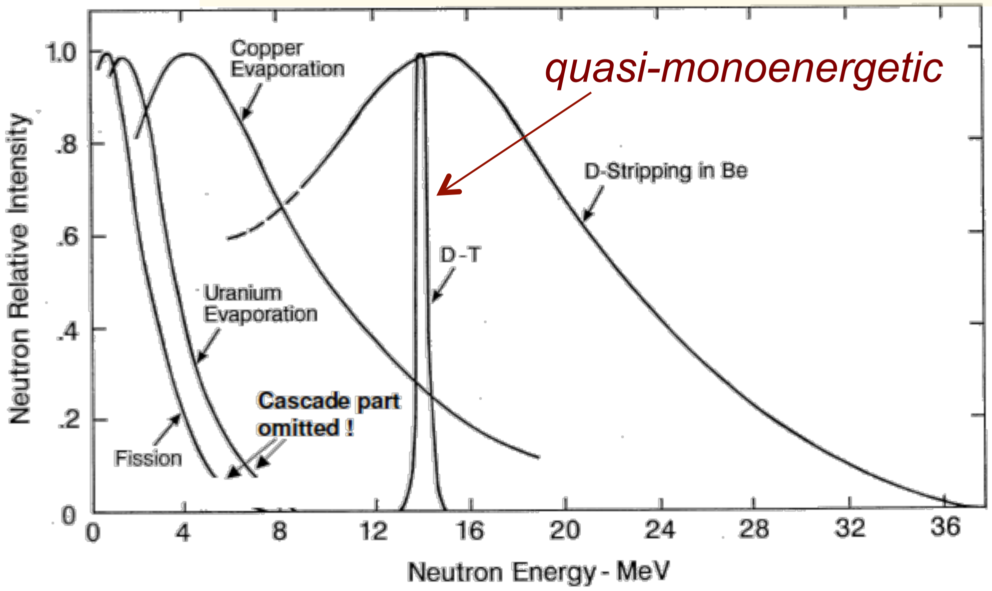


Figure 1. History of development of neutron sources in terms of the effective thermal neutron flux. Carpenter & Lander 2010

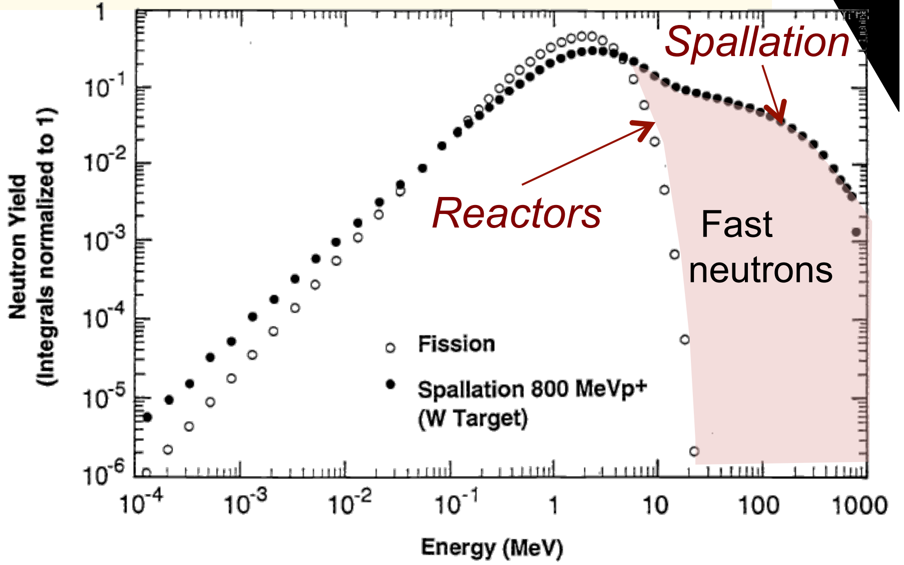
This is not the whole story!

Neutron Energy Spectrum & Time Structure

Accelerator-driven sources generates 10-100 MeV fast neutrons



quasi-monoenergetic



Spallation

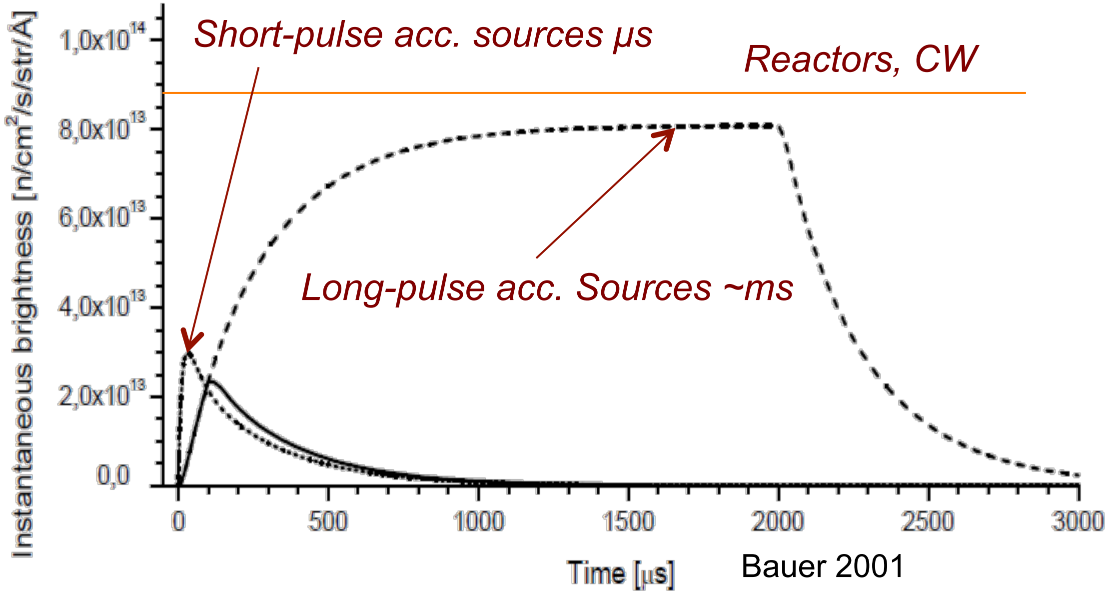
Reactors

Fast neutrons

Accelerator-driven sources generate neutrons with

- *a wide energy spectrum, providing cold, thermal, epithermal, and fast neutrons*
- *A distinct time structure from μs to ms*

Can small accelerator-based sources lend more applications in spite of lower fluxes?



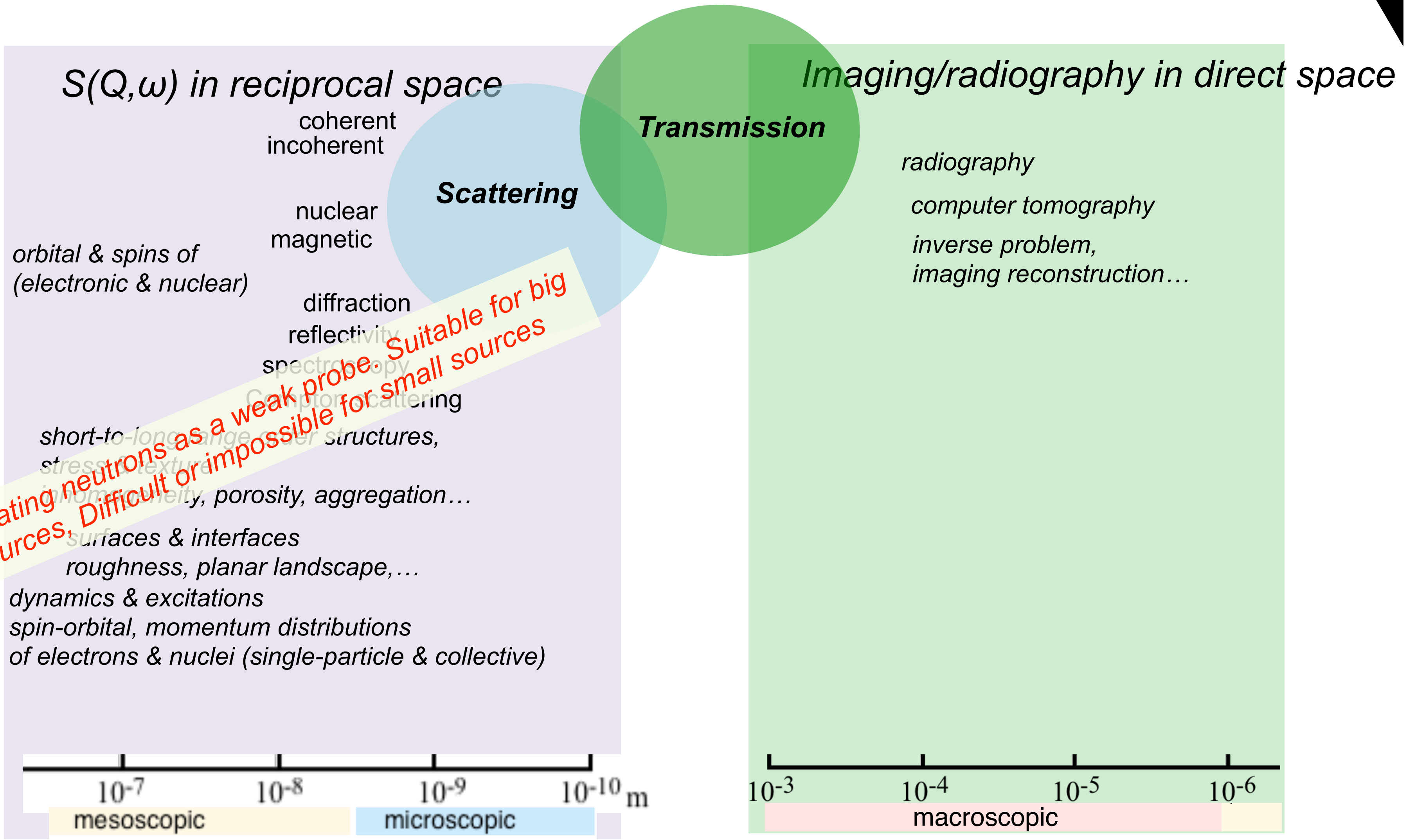
Short-pulse acc. sources μs

Reactors, CW

Long-pulse acc. Sources ~ms

Bauer 2001

Applications of CANS: A Prelude



S(Q,ω) in reciprocal space

coherent
incoherent

nuclear
magnetic

orbital & spins of
(electronic & nuclear)

diffraction
reflectivity
spectroscopy
Compton scattering

short-to-long range order structures,
stress & texture
inhomogeneity, porosity, aggregation…

surfaces & interfaces
roughness, planar landscape,…

dynamics & excitations
spin-orbital, momentum distributions
of electrons & nuclei (single-particle & collective)

Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

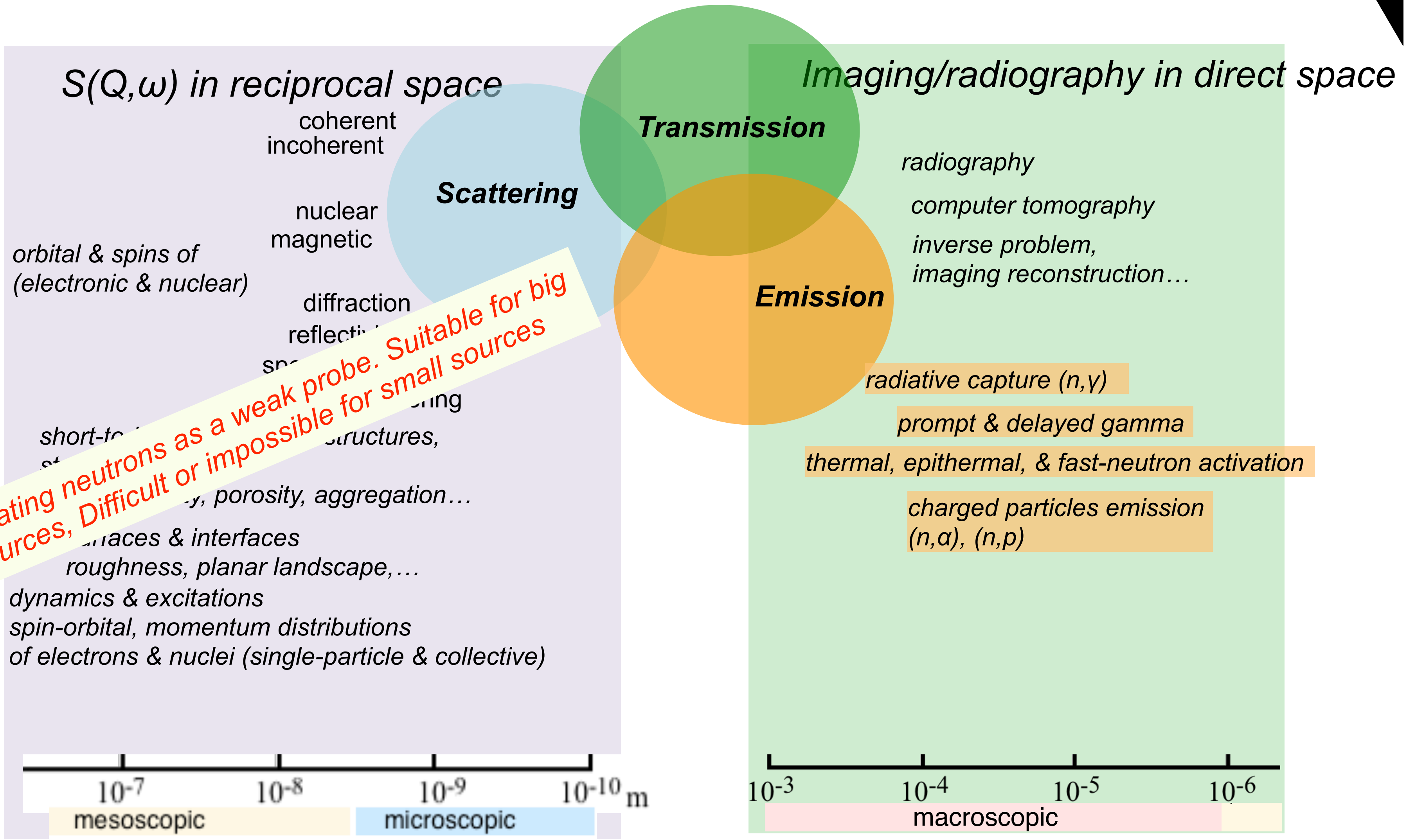
Imaging/radiography in direct space

radiography

computer tomography

inverse problem,
imaging reconstruction…

Applications of CANS: A Prelude



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inverse problem,
imaging reconstruction…

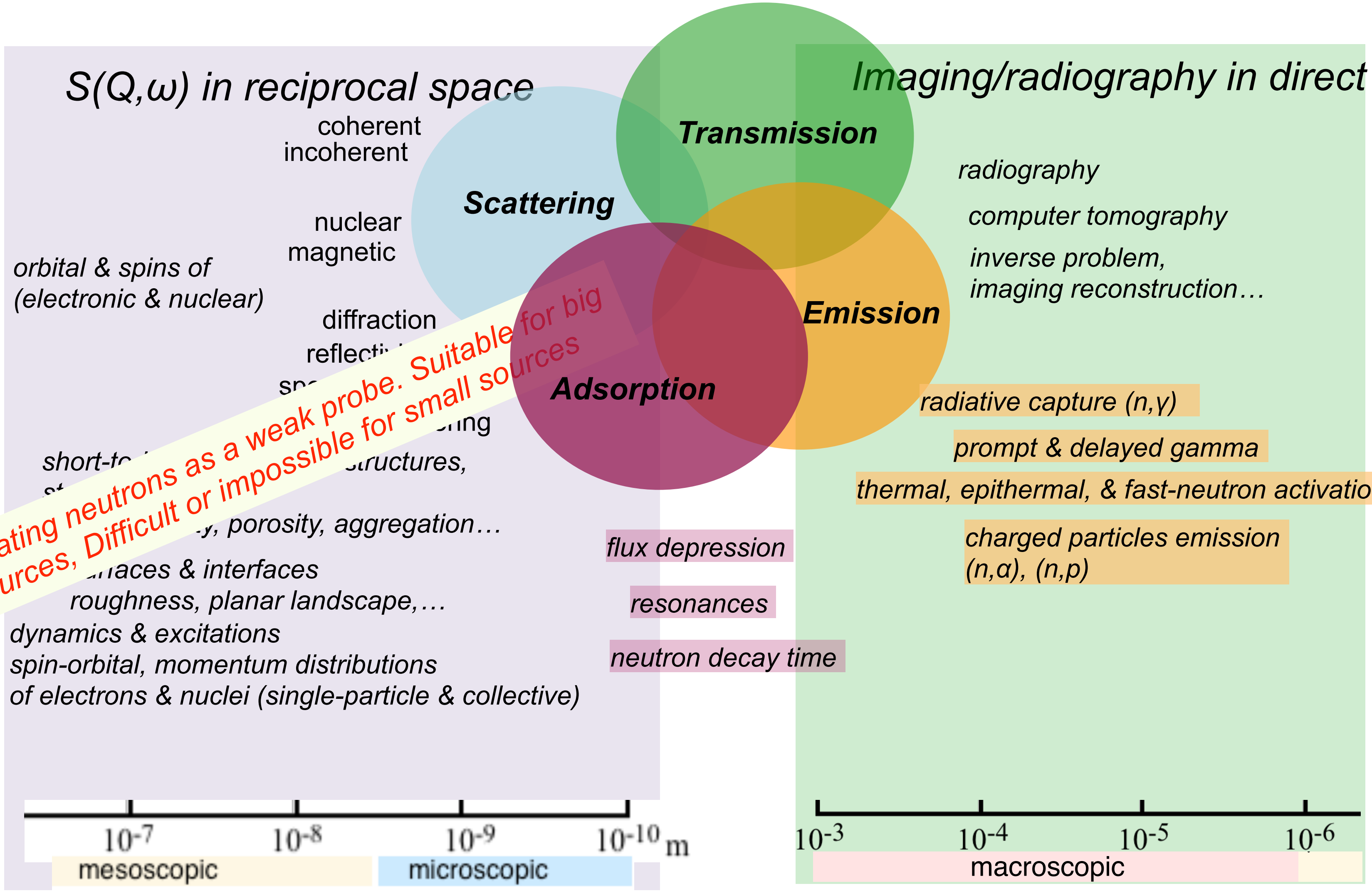
radiative capture (n,γ)

prompt & delayed gamma

thermal, epithermal, & fast-neutron activation

charged particles emission
(n,α), (n,p)

Applications of CANS: A Prelude



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Treating neutrons as a weak probe. Suitable for big sources, Difficult or impossible for small sources

Transmission

Scattering

Emission

Adsorption

flux depression

resonances

neutron decay time

Imaging/radiography in direct space

radiography

computer tomography

inverse problem,
imaging reconstruction…

radiative capture (n,γ)

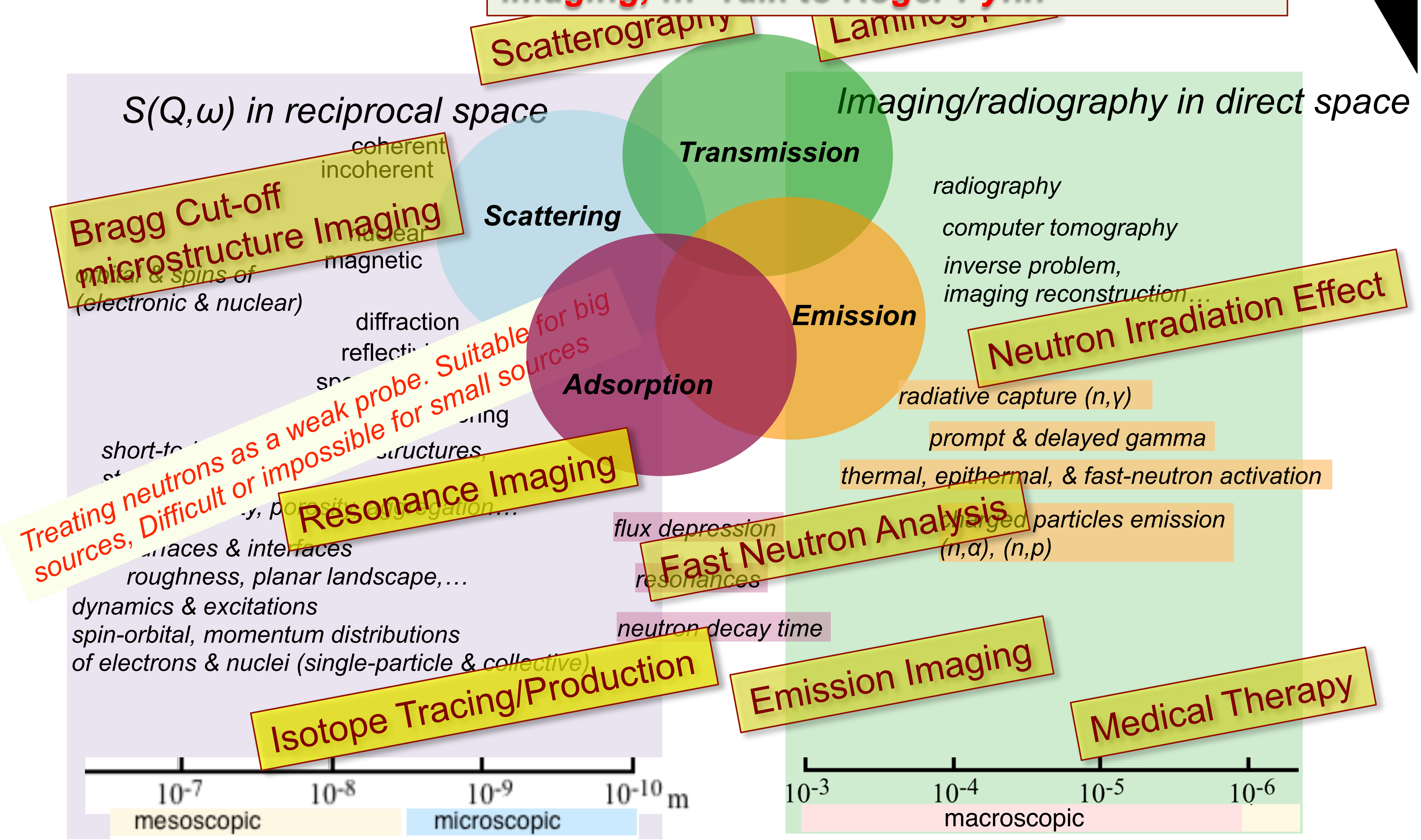
prompt & delayed gamma

thermal, epithermal, & fast-neutron activation

charged particles emission
(n,α), (n,p)

Applications of CANS…

and much More: Magnetic Counterparts e.g., spin-echo resonance, depolarization imaging, … Talk to Roger Pynn



CANS Applications


Applications

Scattering

Experimental Neutronics

Instrumentation & Devices

Detectors

Interrogation

Civil Structures

Cultural Heritage

Detection of Explosives & Landmines

Well-logging & Mineralogy

Irradiation Effects on Electronics

Nuclear Physics

Nuclear Data

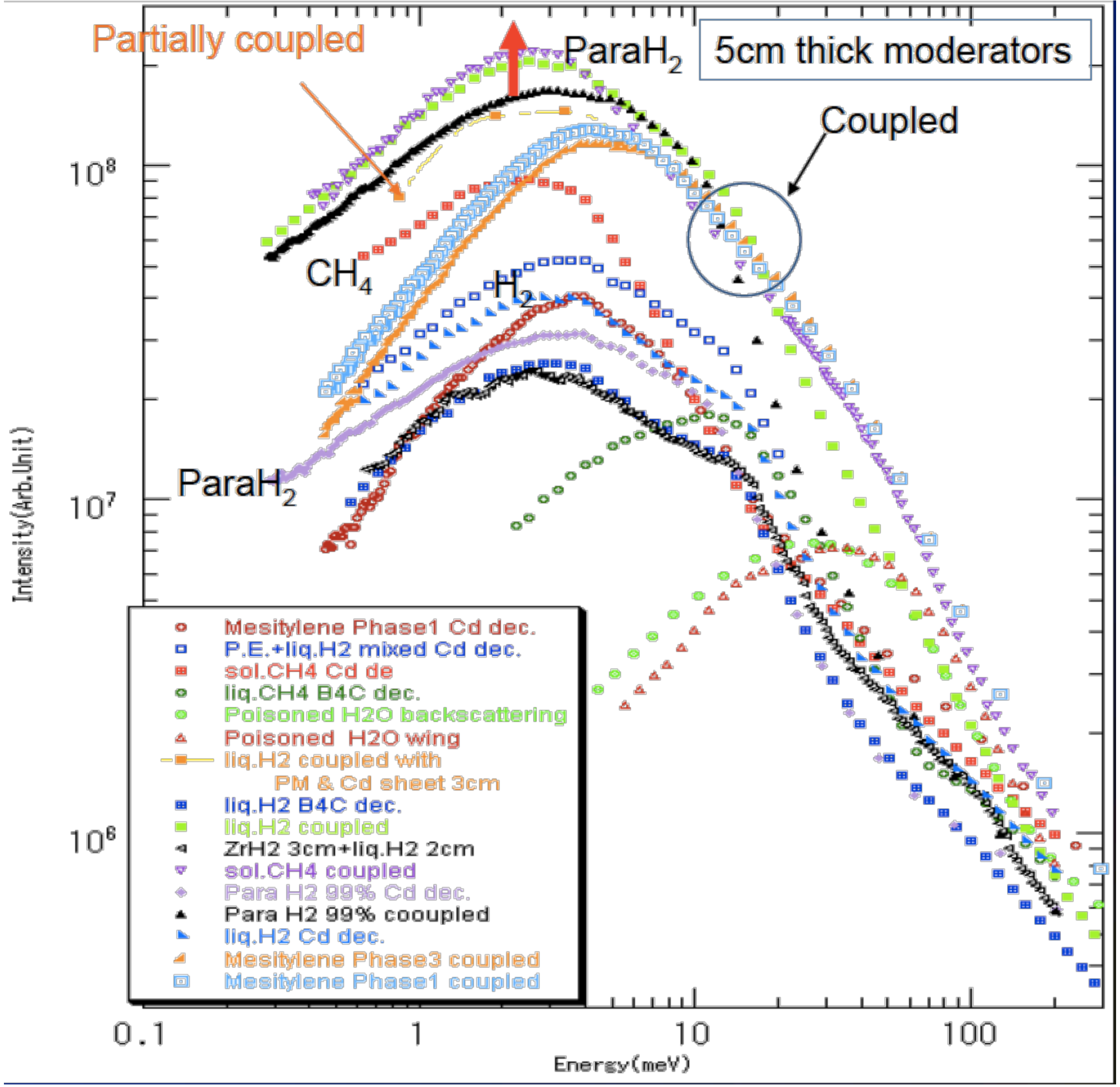
Nuclear Astrophysics

ADS & Energy Amplification

Neutron Capture Therapy

Isotope Production

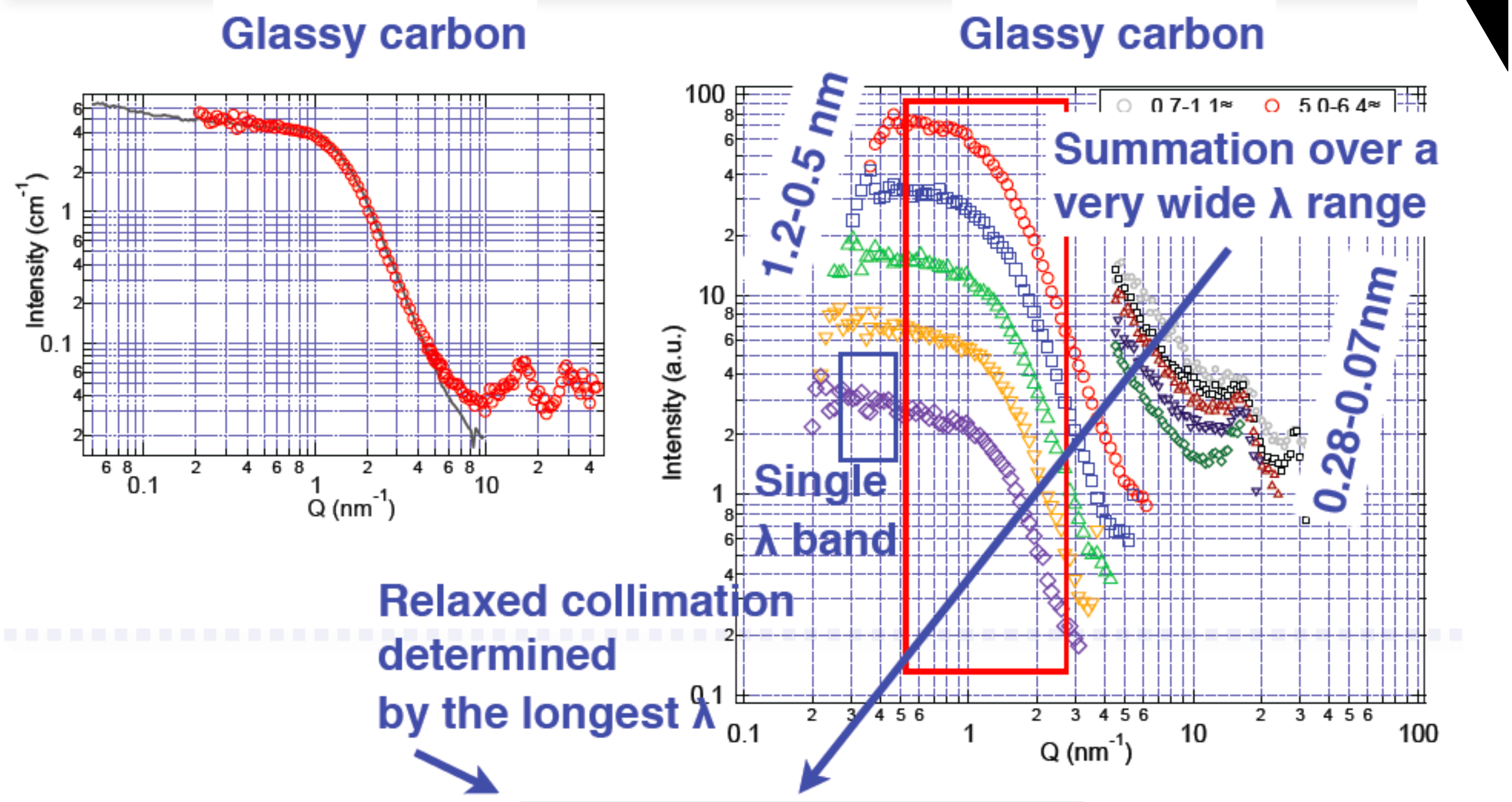
Experimental Neutronics: Moderator Development



Kiyanagi *et al.*

Small-Angle Scattering (SANS): Well Suited for CANS

HUNS@Hokkaido e-linac 6 kW



Summation over a very wide λ range

Single λ band

Relaxed collimation determined by the longest λ

Intensity gain by pulsing

2015.05.14.

Furusaka (2015), UCANS-V

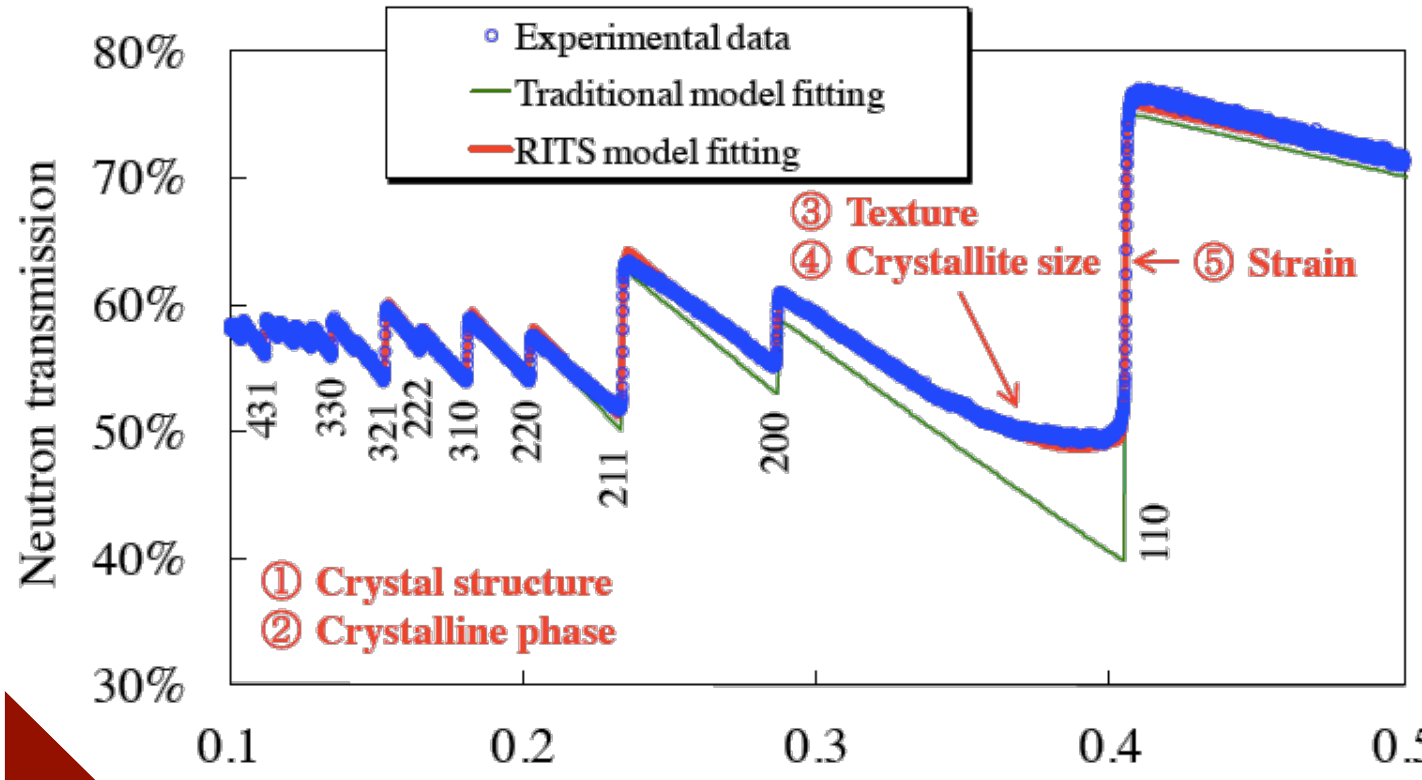
Imaging & Radiography: Short-Pulse CANS

HUNS@Hokkaido e-linac 6 kW

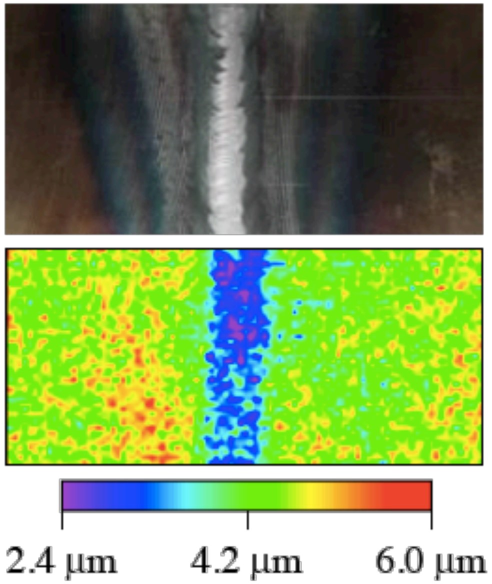
Combine imaging with crystal diffraction: Rietveld imaging transmission spectra (RITS)

Allow concurrent analysis of crystal structures, crystalline phases, crystallite sizes, texture, and strain

Bragg edge transmission of α-Fe



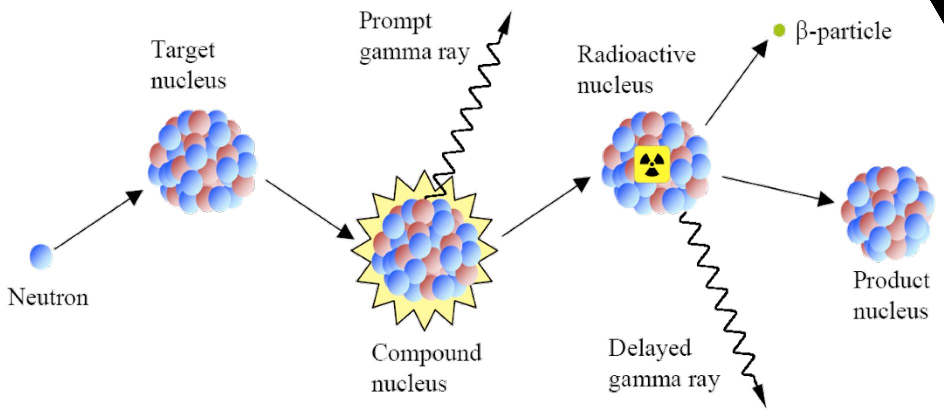
Quantitative imaging of crystallite size by the RITS code



Sato 2011

γ-Ray Imaging & Radiography

Combine tomography with thermal-neutron-induced γ-ray imaging (PGA-CT):
Allow 3D elemental analysis



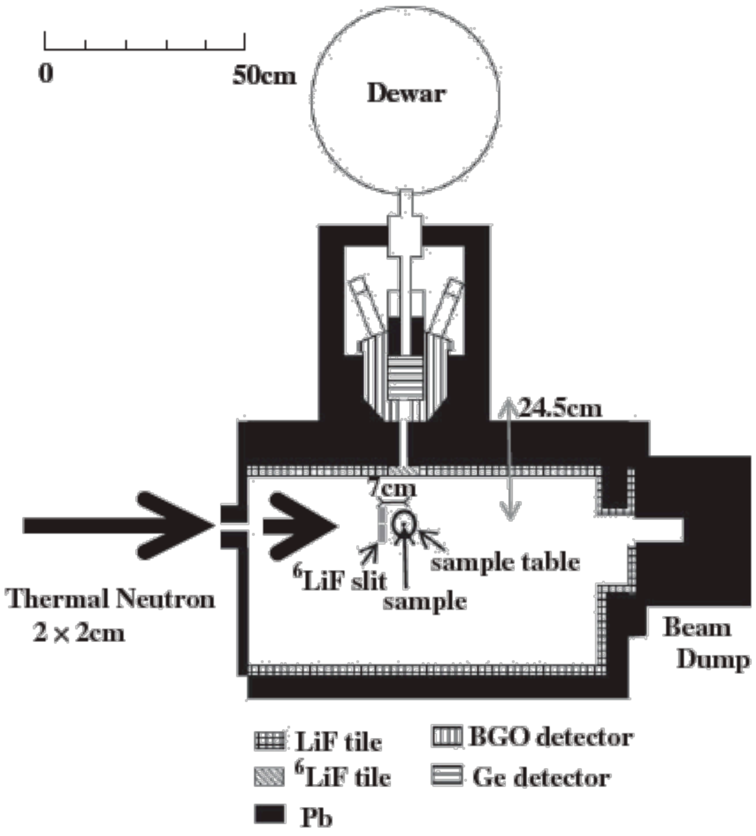


Fig. 1. Schematic view of experimental setup.

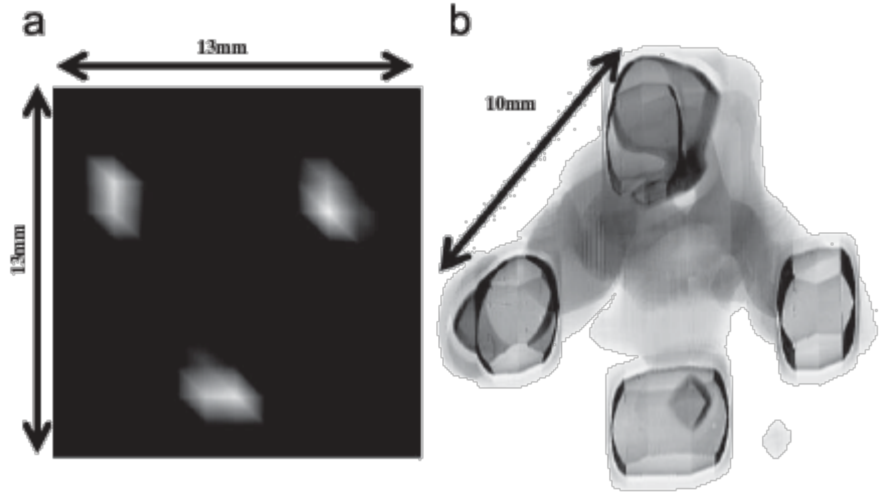
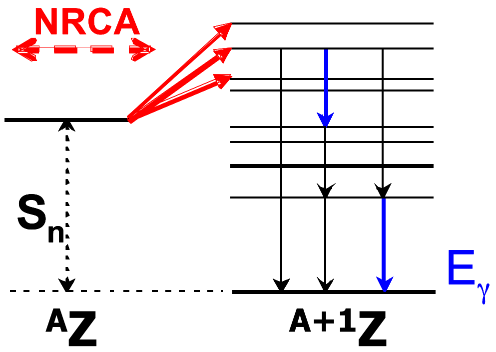


Fig. 5. The reconstruction images for a Cd sample in the form of a three-sided pyramid of 1 cm using the computerized tomography program "NIPPON". (a) A slice figure on the bottom of the sample in the *X–Z* plane. (b) A 3-D elemental image made by accumulations of slice figures.

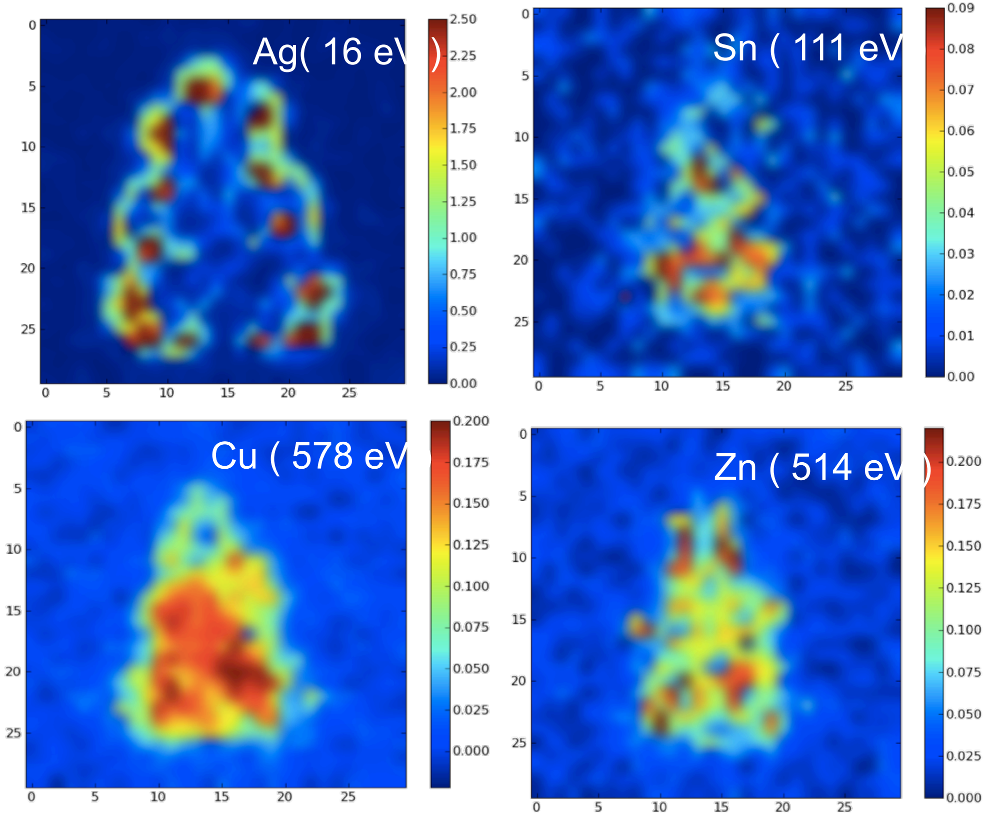
Segawa 2009

Imaging & Radiography: Beyond Conventional Approaches

Combine imaging with epithermal neutron resonance capture analysis (NRCA):
Allow elemental analysis, significant to archaeometry: high sensitivity to Cu, Sn Zn, As, Sb, Ag, Au, Pb,…



Original belt mount
Hungarian National
Museum, Budapest

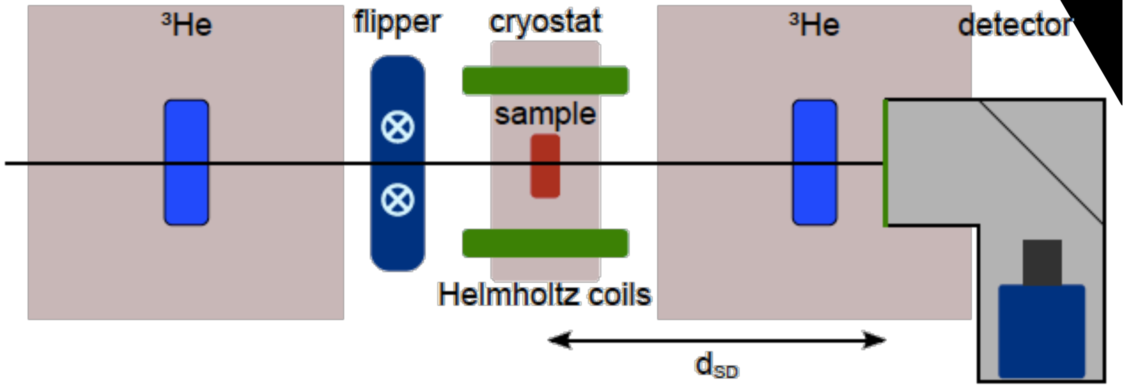


Andreani 2012
ISIS data

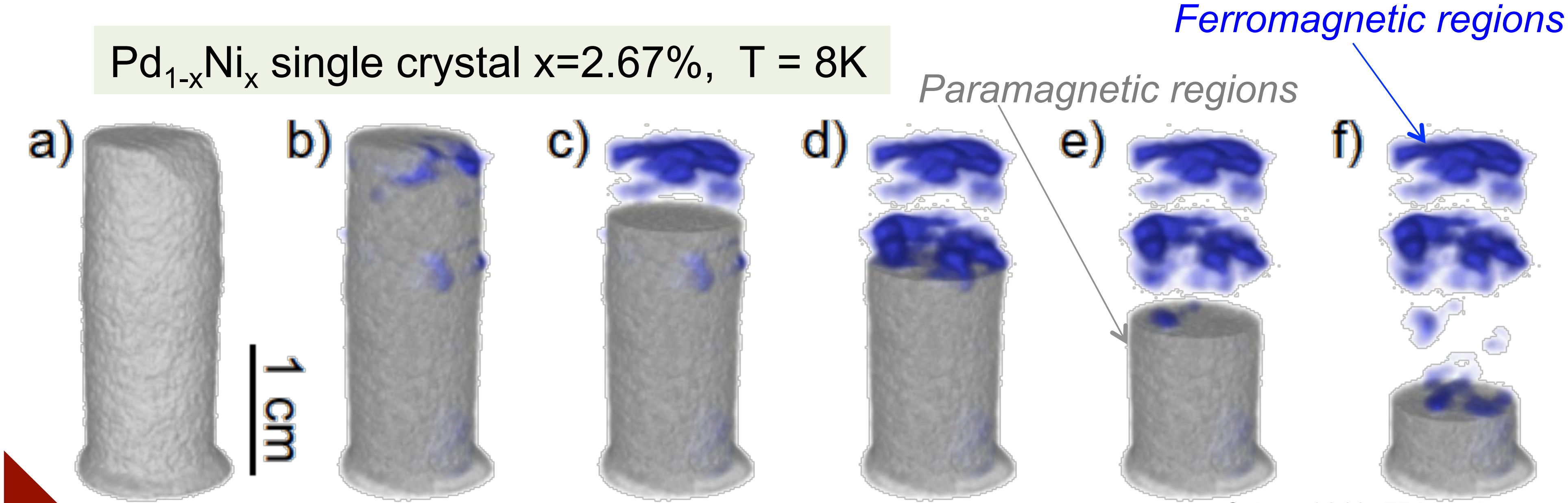
Magnetic Structures: Beyond Conventional Approaches

Combine imaging with polarization analysis of magnetic diffraction using polarized neutrons

Allow fundamental studies of quantum criticality, magnetic inhomogeneity in single crystals by depolarization imaging

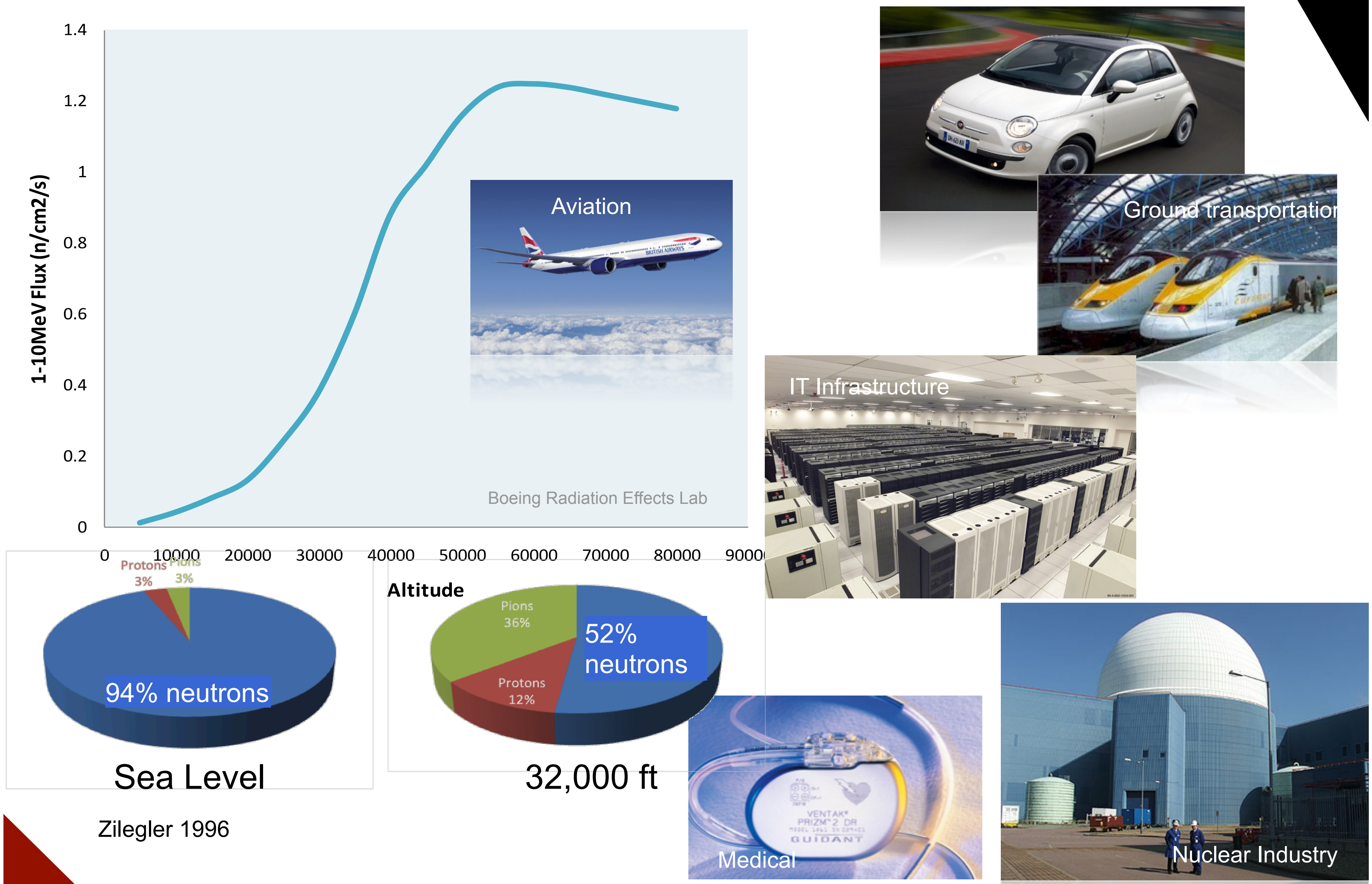


$Pd_{1-x}Ni_x$ single crystal x=2.67%, T = 8K



Schulz 2010 FRM-II data

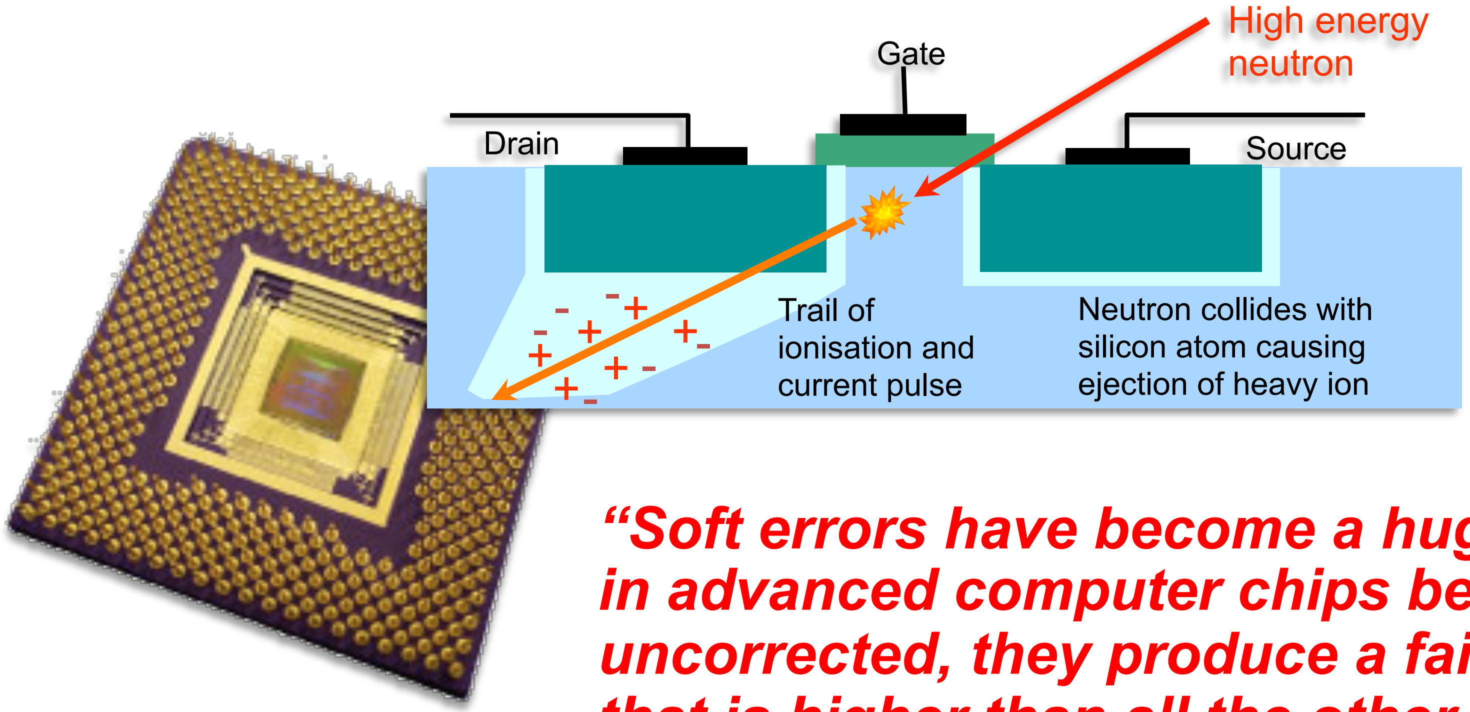
Neutron SEE is a Serious Threat at High Altitude & at Sea Level



Zilegler 1996

Neutron Impact on Industry and Life

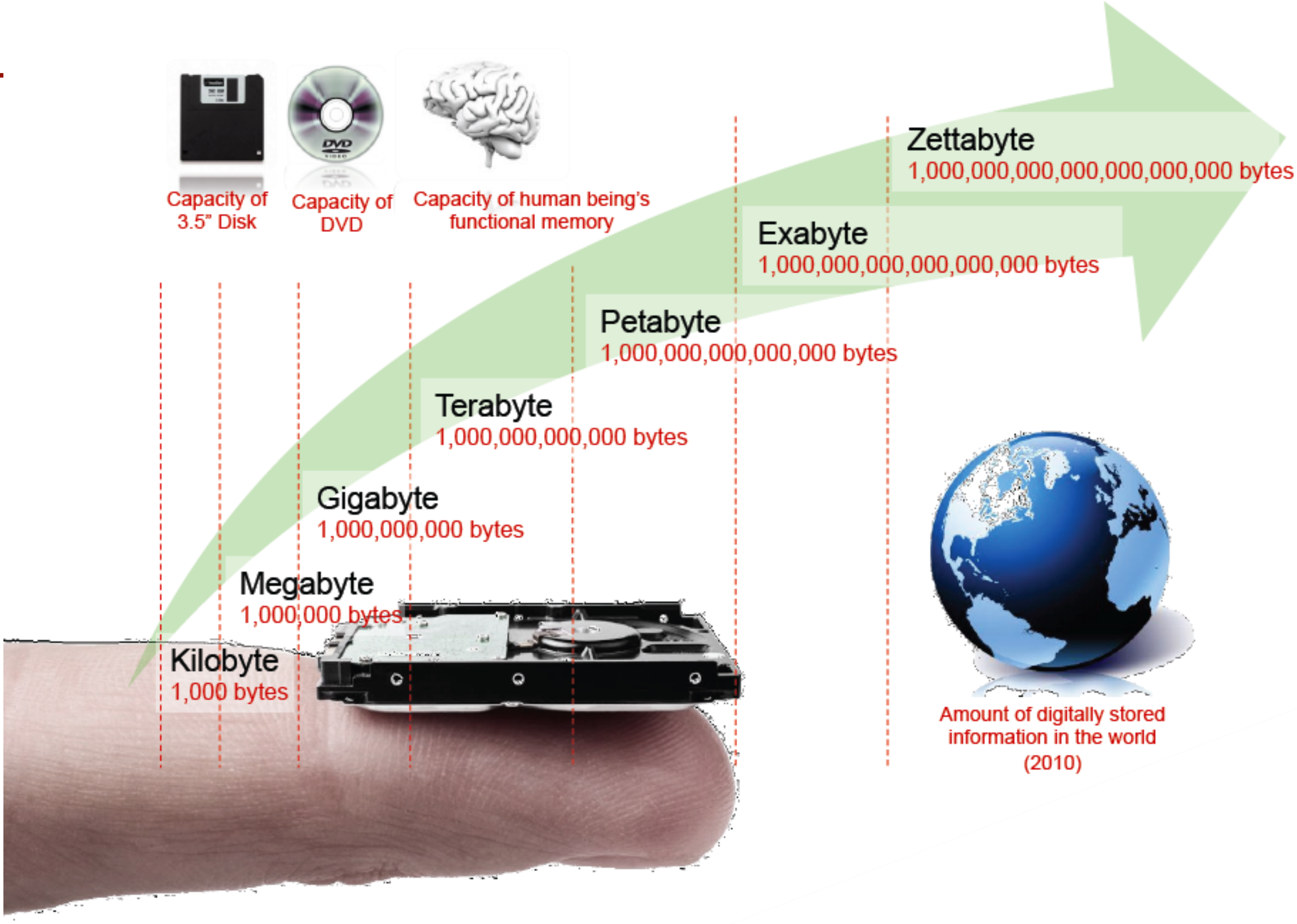
Single Event Effects (SEE): A single energetic particle (neutron) strikes sensitive regions of an electronic device, e.g., logic or support circuitry, memory cells, registers, etc., disrupting its normal function, usually causing non-destructive soft errors.



"Soft errors have become a huge concern in advanced computer chips because, uncorrected, they produce a failure rate that is higher than all the other reliability mechanisms combined!"

.......R. Baumann, IEEE-TDMR, 2005

Frost 2011



Capacity of 3.5” Disk

Capacity of DVD

Capacity of human being’s functional memory

Zettabyte
1,000,000,000,000,000,000,000 bytes

Exabyte
1,000,000,000,000,000,000 bytes

Petabyte
1,000,000,000,000,000 bytes

Terabyte
1,000,000,000,000 bytes

Gigabyte
1,000,000,000 bytes

Megabyte
1,000,000 bytes

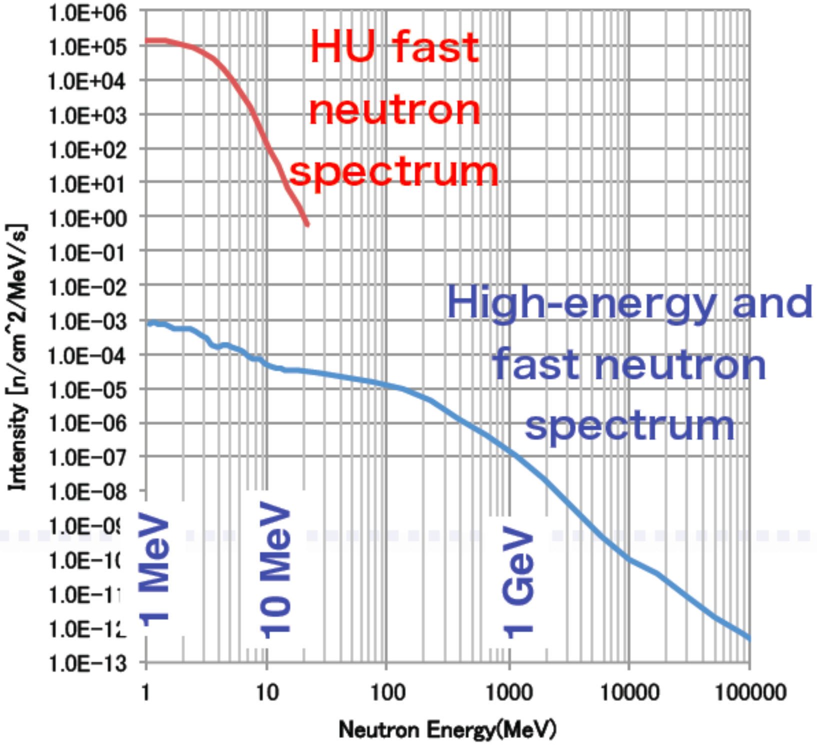
Kilobyte
1,000 bytes

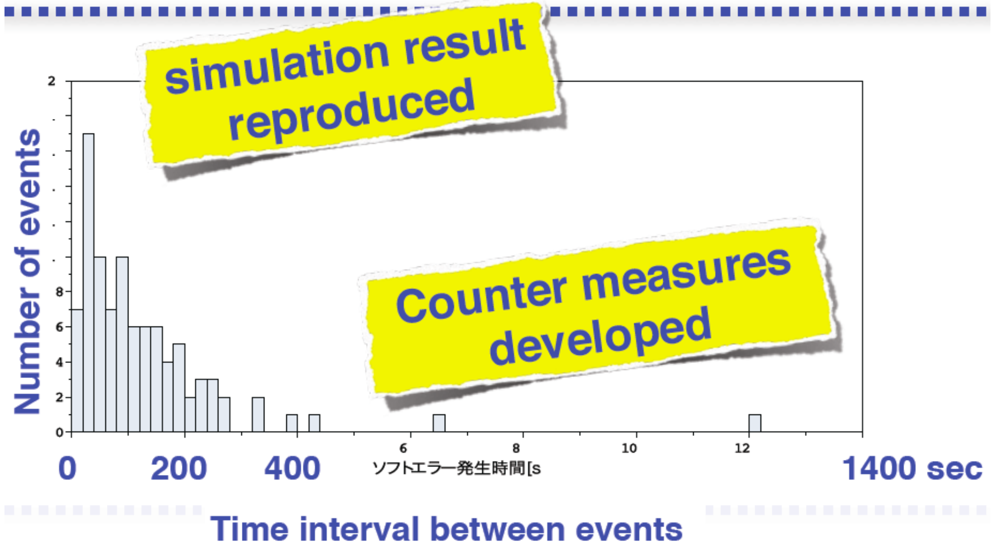
Amount of digitally stored information in the world (2010)

Source: Cisco

Measurements of Soft-Error Counts in Electronics At HUNS

HUNS@Hokkaido e-linac 6 kW





simulation result reproduced

Counter measures developed

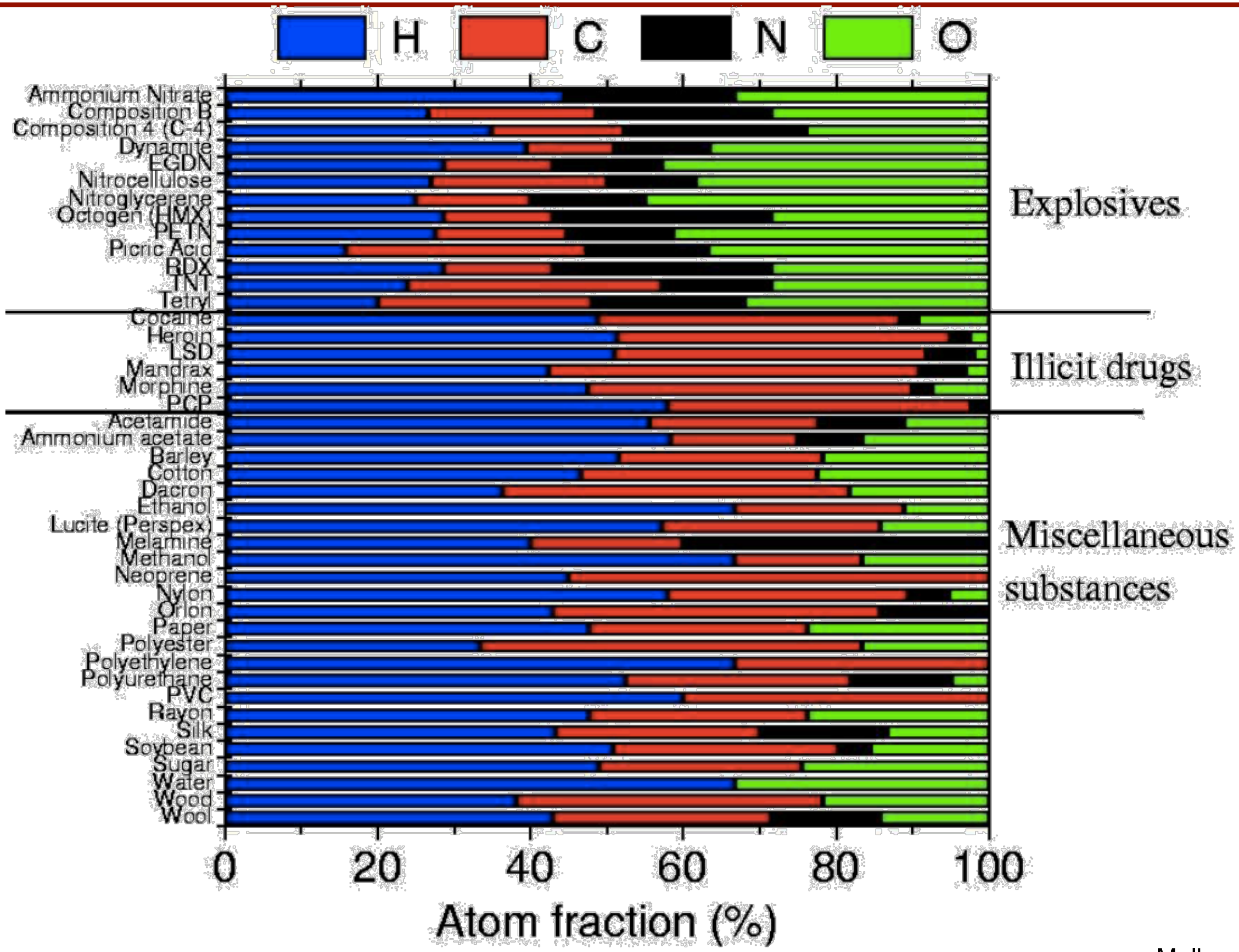
Furusaka (2015), UCANS-V

Neutron Interrogation of Concealed Substances: Explosive

Desirable capabilities

- ✧ Remote detection
- ✧ Non-intrusive
- ✧ High sensitivity (chemical density, 3D volumetric rendering)
- ✧ Materials specific (precise, minimize false alarms)
- ✧ Rapid
- ✧ Flexible (portable, on-site deployment,…)
- ✧ Automatic

Chemical Composition of Different Materials



Mulhauser

Aim to be More Quantitative Than N/C Ratio Detection

	Materials	C	H	N	O	P	F	Cl	S	N/H	N/C
Explosives	C4	21.9	3.6	34.4	40.1	0	0	0	0	10	2
	TNT	37	2.2	18.5	42.3	0	0	0	0	8	1
	PETN	19	2.4	17.7	60.8	0	0	0	0	7	1
	AN	0	5	35	60	0	0	0	0	7	∞
Chemical agents	Sarin	34.3	7.1	0	22.9	22.1	13.6	0	0	0	0
	VX	49.5	9.7	5.2	12	11.6	0	0	12	1	0
	CA	44.5	3.7	51.8	0	0	0	0	0	14	1
	HD	30.2	5	0	0	0	0	44.6	0	0	0
	Phosgene	12.1	0	0	16.2	0	0	71.7	0	NA	0
Benign	Water	0	11.1	0	88.9	0	0	0	0	0	0
	Paper	44	6	0	50	0	0	0	0	0	0
	Plastic	86	14	0	0	0	0	0	0	0	0
	Salt	0	0	0	0	0	0	60	0	NA	NA

Explosives are rich in N and O but poor in H and C

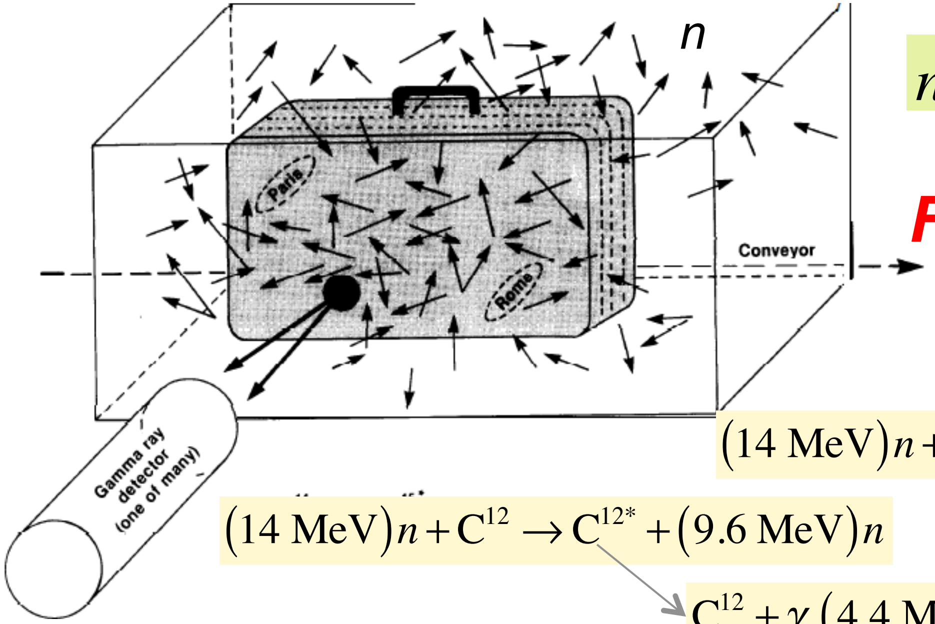
Gozani 2005

"Neutron in Gamma Out" Methods (1)

Thermal Neutron Analysis (TNA): In TNA the object is irradiated by slow (thermal) neutrons, which produce gamma-rays in reactions of radiative capture with the nuclei of chemical elements constituting ES. e.g. N: 10.8 MeV H: hydrogen 2.23 MeV Cl: 7.50 and 6.11 MeV, etc.

Fast Neutron Analysis (FNA): The object is irradiated with a continuous flux of fast neutrons with energy above 8 MeV, which produce characteristic gamma-rays in inelastic scattering reactions with nuclei of C: 4.44, O: 6.13,.. N: 5.1 MeV. Detection of these secondary gamma-rays provides information about relative concentrations of carbon, oxygen and nitrogen in molecules of the inspected substance.

Neutron Resonance Attenuation (NRA): A neutron radiography technique measuring the areal density (density times thickness) of elements present in the interrogated object.



TNA

$$n + \mathrm{N}^{14} \to \mathrm{N}^{16*}$$

$$\mathrm{N}^{15} + \gamma\,(10.8\ \mathrm{MeV})$$

FNA

$$(14\ \mathrm{MeV})n + \mathrm{N}^{14} \to \mathrm{N}^{14*} + (8.9\ \mathrm{MeV})n$$

$$\mathrm{N}^{14} + \gamma\,(5.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})n + \mathrm{O}^{16} \to \mathrm{O}^{16*} + (7.9\ \mathrm{MeV})n$$

$$\mathrm{O}^{16} + \gamma\,(6.1\ \mathrm{MeV})$$

$$(14\ \mathrm{MeV})n + \mathrm{C}^{12} \to \mathrm{C}^{12*} + (9.6\ \mathrm{MeV})n$$

$$\mathrm{C}^{12} + \gamma\,(4.4\ \mathrm{MeV})$$

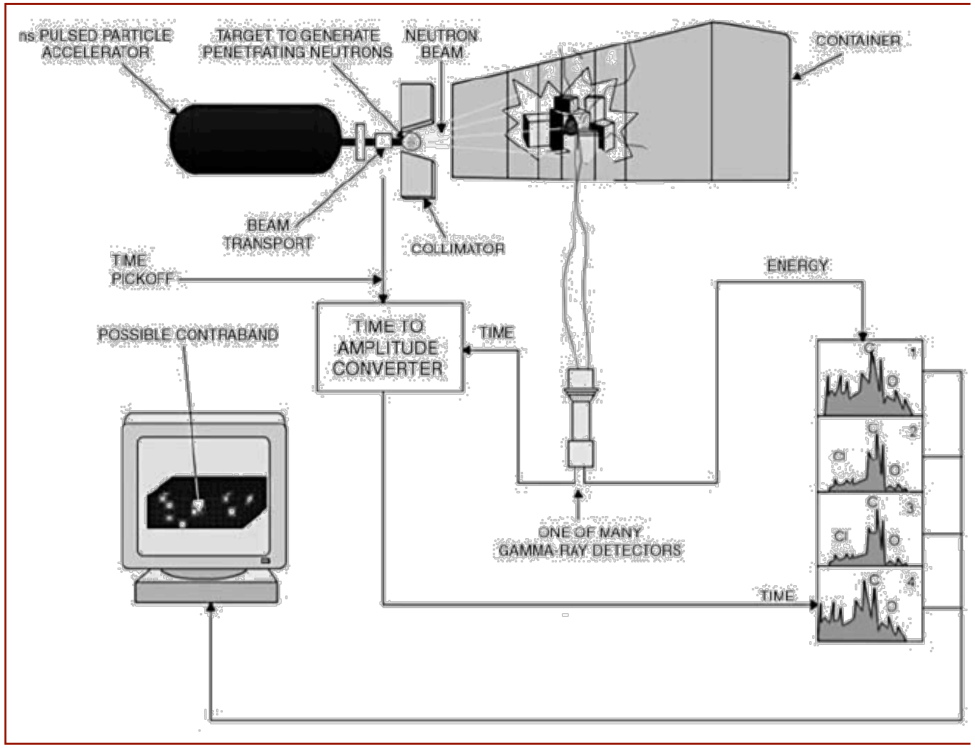
Grodzine 1990; Schubert 2006

“Neutron in Gamma Out” Methods (2)

Pulsed Fast Neutron Analysis (PFNA): Use pulsed neutron flux (with pulse duration of severa nanoseconds) to irradiate the inspected object. This allows one to use time of flight information to determine the location of the ES inside the inspected volume. By using collimators for the neutron beam one can get a 3D distribution of carbon, oxygen and nitrogen in the investigated object.

Pulsed Fast and Thermal Neutron Analysis (PFTNA): PFTNA is a combination FNA and TNA.

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with α to discriminate secondary γ. Background γ-rays that are not correlated in time with “tagged” neutrons are rejected by the data acquisition system. Use of position sensitivity of the α-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.

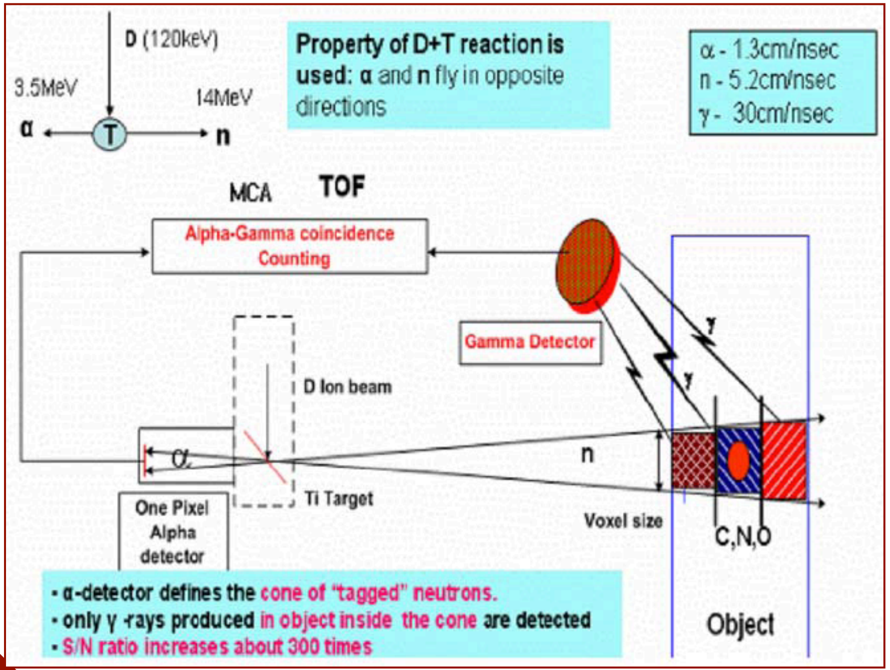


PFNA

Gozani 2005

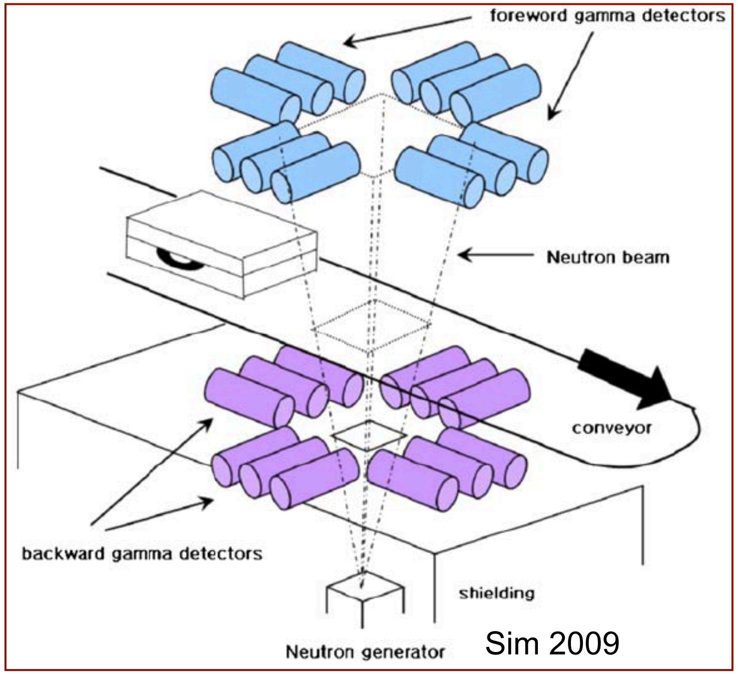
Associated-Particle Imaging (API)

Nanosecond Neutron Analysis / Associated Particles Technique (NNA/ APT): Use d(t,α)n to produce fast neutrons in portable neutron generators, mono-energetic neutrons (E = 14 MeV) and α-particles (E = 3 MeV) are emitted simultaneously in opposite directions. Tag *n* with alpha to discriminate secondary γ. Background γ-rays that are not correlated in time with "tagged" neutrons are rejected by the data acquisition system. Use of position sensitivity of the γ-detector and time-of-flight analysis allow one to obtain 2D spatial distribution of chemical elements in the examined object.

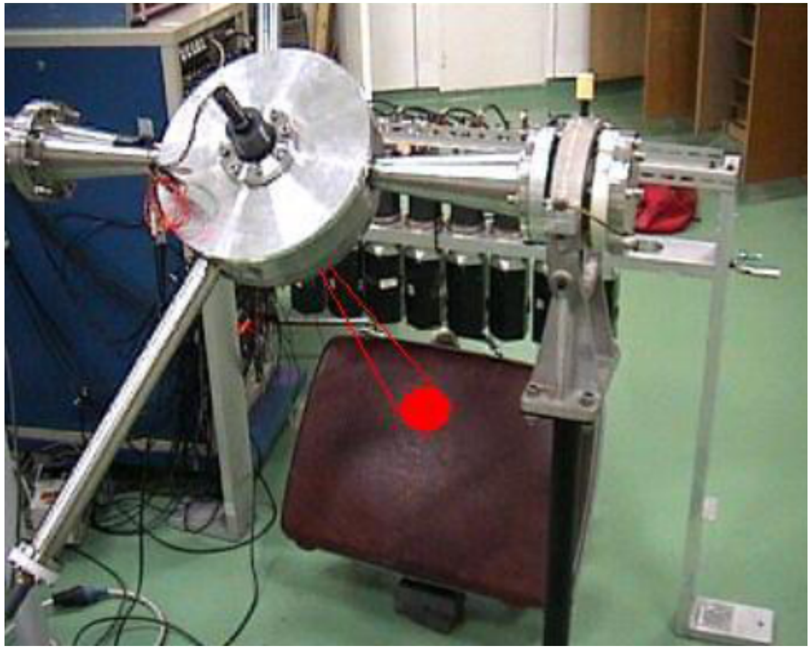


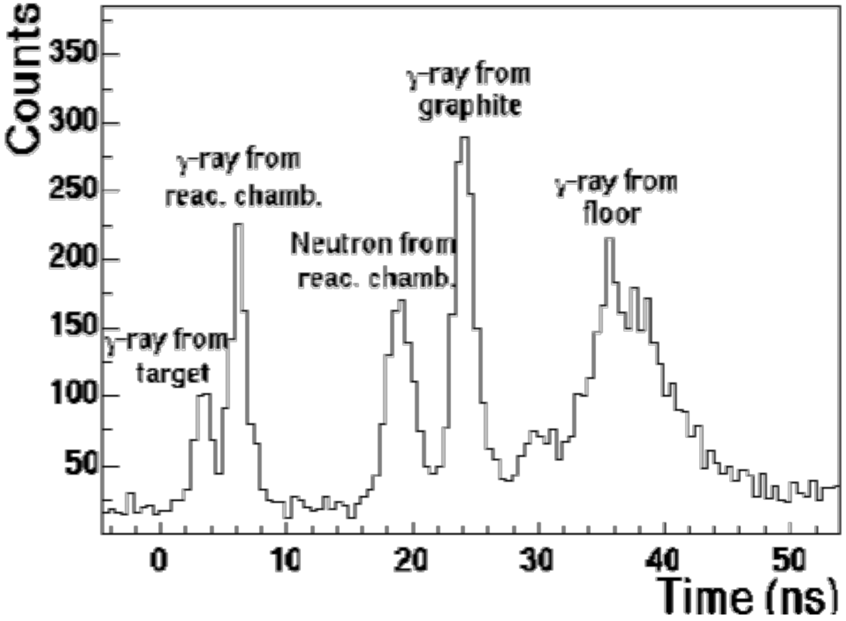
Property of D+T reaction is used: α and n fly in opposite directions

- α-detector defines the cone of "tagged" neutrons.
- only γ -rays produced in object inside the cone are detected
- S/N ratio increases about 300 times



Sim 2009




Counts
350
300
250
200
150
100
50
γ-ray from target
γ-ray from reac. chamb.
Neutron from reac. chamb.
γ-ray from graphite
γ-ray from floor
0
10
20
30
40
50
Time (ns)

Mulhauser

First Commercial Scanner – Nuctech AC6015XN

Needing improvement in order to be practical

Mulhauser

Automated Cargo-Container Inspection System

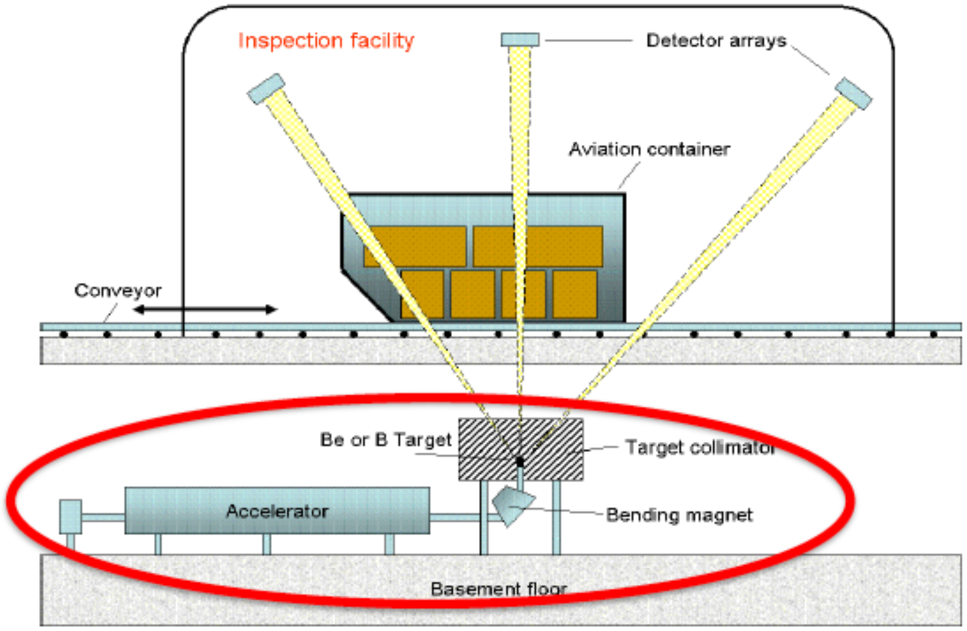
$^{11}B(d,n+\gamma)^{12}C$ – Deuteron Energy 3-8 MeV

4.43, 15.1 MeV γ-rays

Dual **D**iscrete **E**nergy
Gamma **R**adiografie
=> SNM detection

0-17 MeV neutron spectrum

Fast **N**eutron
Resonance **R**adiografie
=> Explosives detection



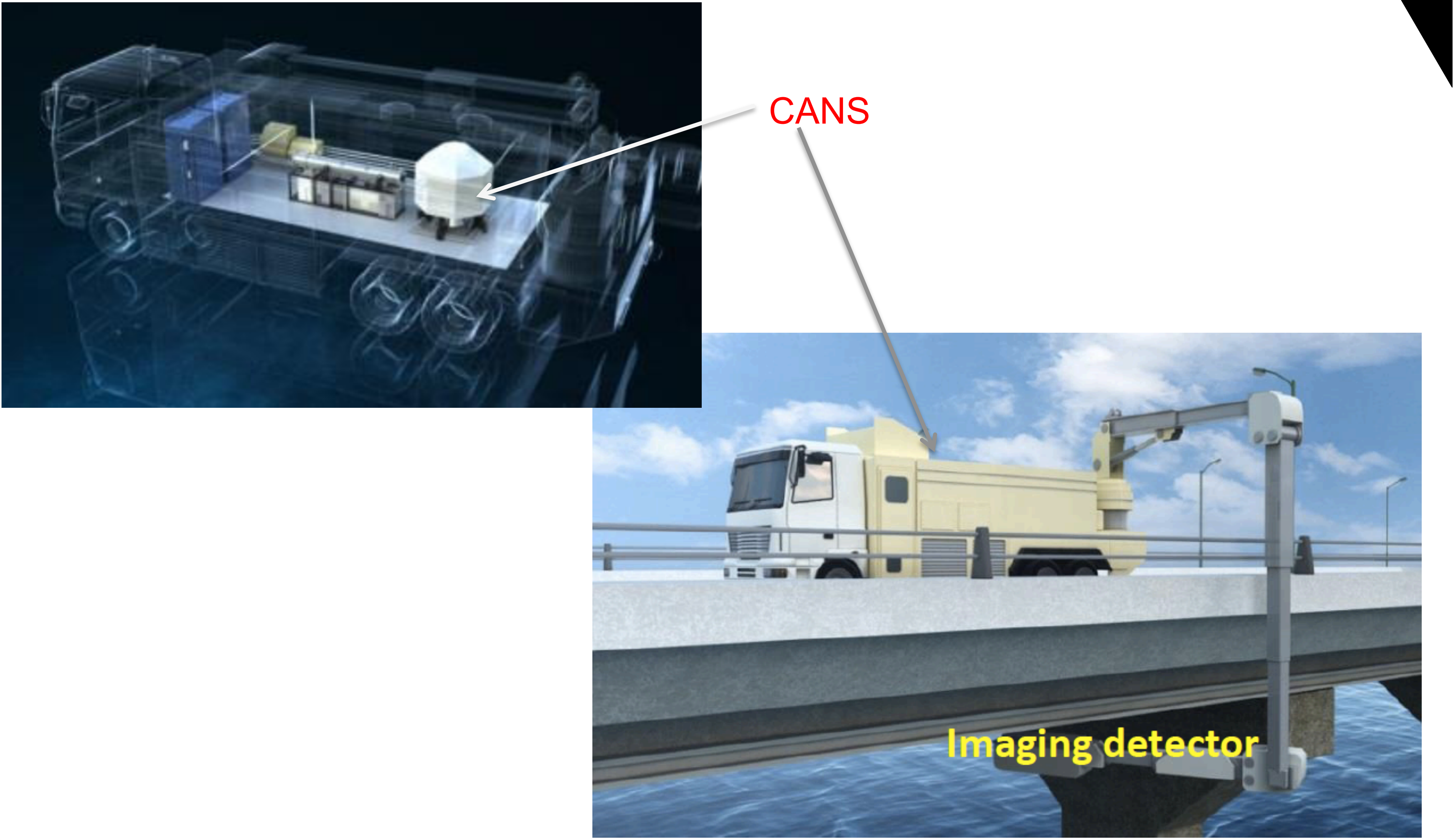
- (Semi-) Automatic Inspection
- Isotope specific Detection
- Combined Explosives & SNM Detection

Bromberger (2015), UCANS-V

Landmine Detection: An Ongoing Effort

Mulhauser

A Goal to be Fulfilled: Neutron Interrogation Using CANS, To Complement Other Methods

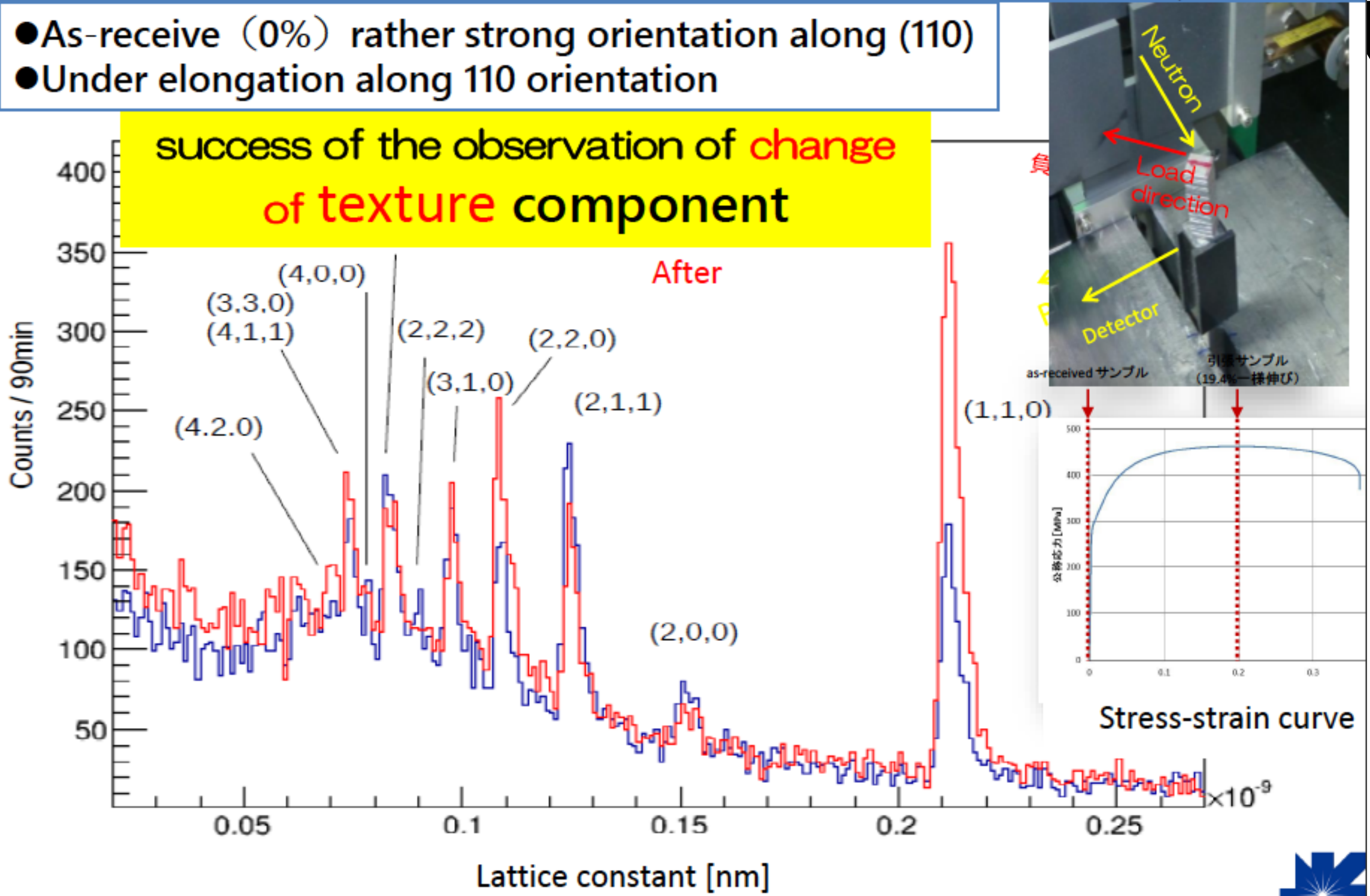


Otake (2013)

Success of the observation of texture @ RANS

JAEA H. Suzuki,
RIKEN Takamura,
Y.IKEDA

- As-receive（0%）rather strong orientation along (110)
- Under elongation along 110 orientation



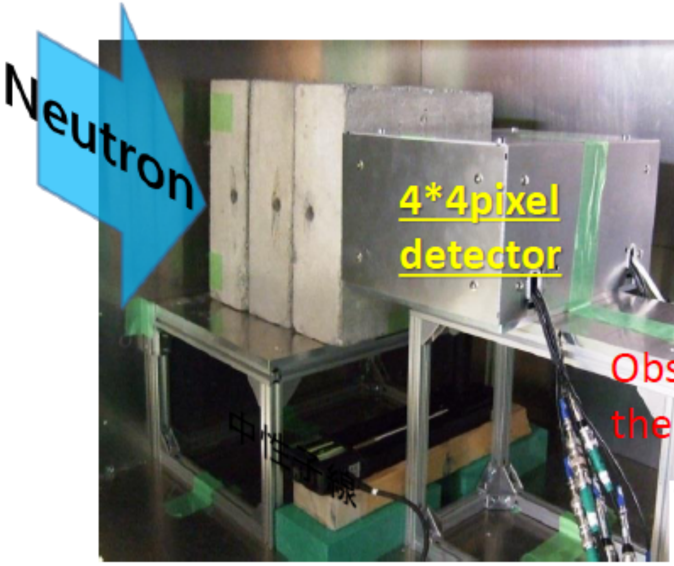
success of the observation of change of texture component

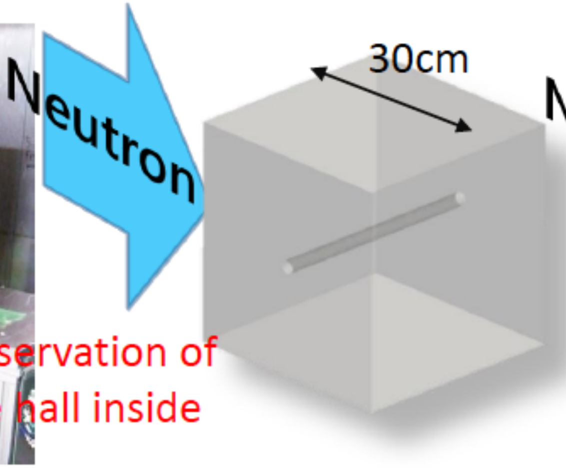
Stress-strain curve

Otake (2015), UCANS-V

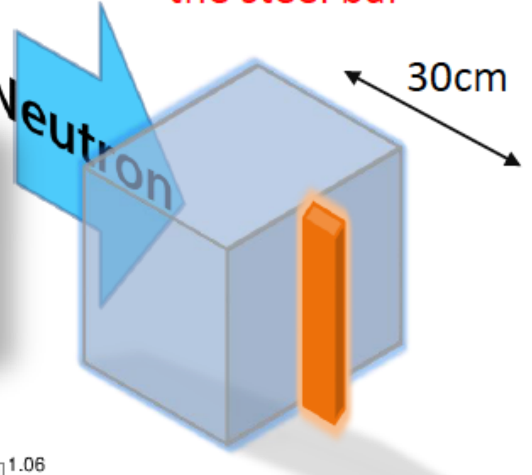
Fast neutron imaging through 30cm concrete block

(>1MeV) Non-destructive inspection

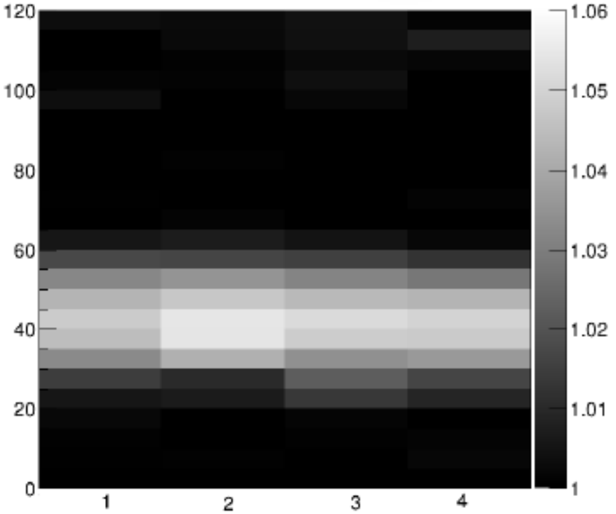


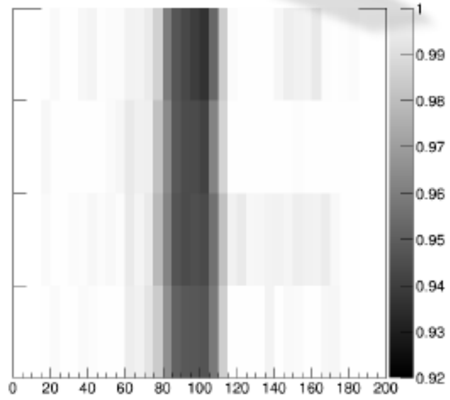


Observation of the hall inside



Observation of the steel bar



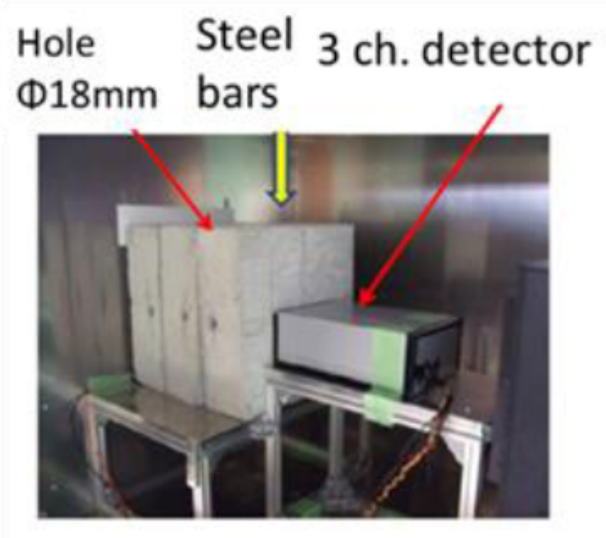


Proton linac

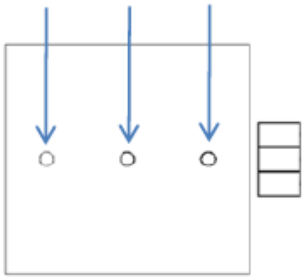
Proton energy: 7 MeV
Beam current: 11 μA (avg.)
Rep. rate: 20 Hz
Pulse width: 100 μs

Otake (2015), UCANS-V

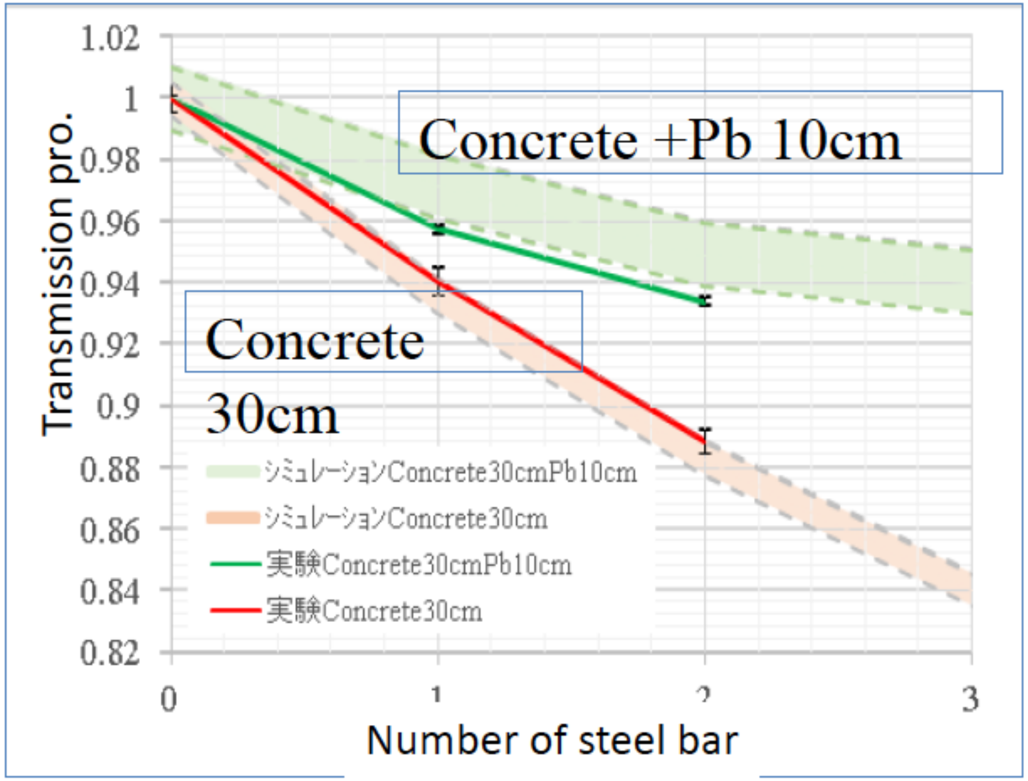
Success of observation difference of steel bar in the concrete



Insert ion bars
into concrete
0, 1, 2, 3



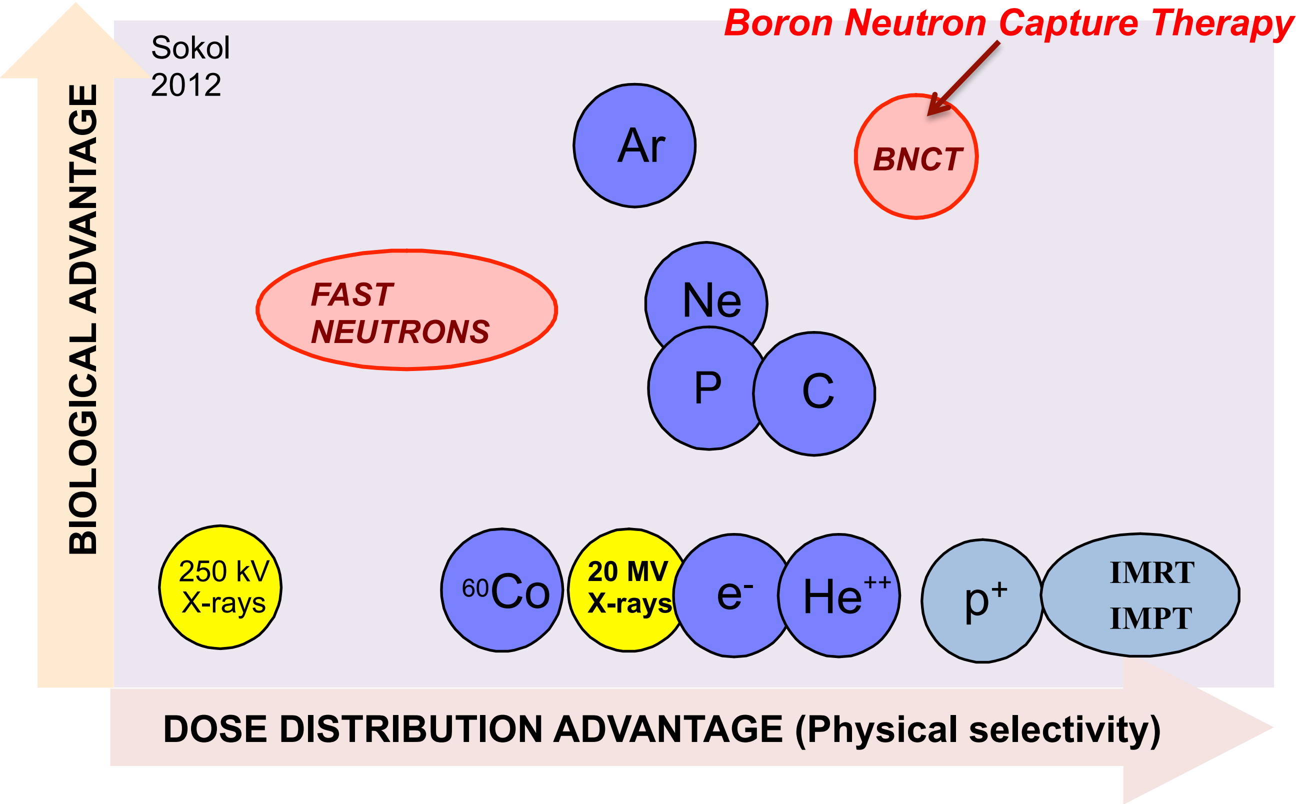
・comparison with the experimental results and simulation by GEANT4.



2015/5/20

Otake (2015), UCANS-V

Neutron Therapy: Superior Biological advantage & Selectivity



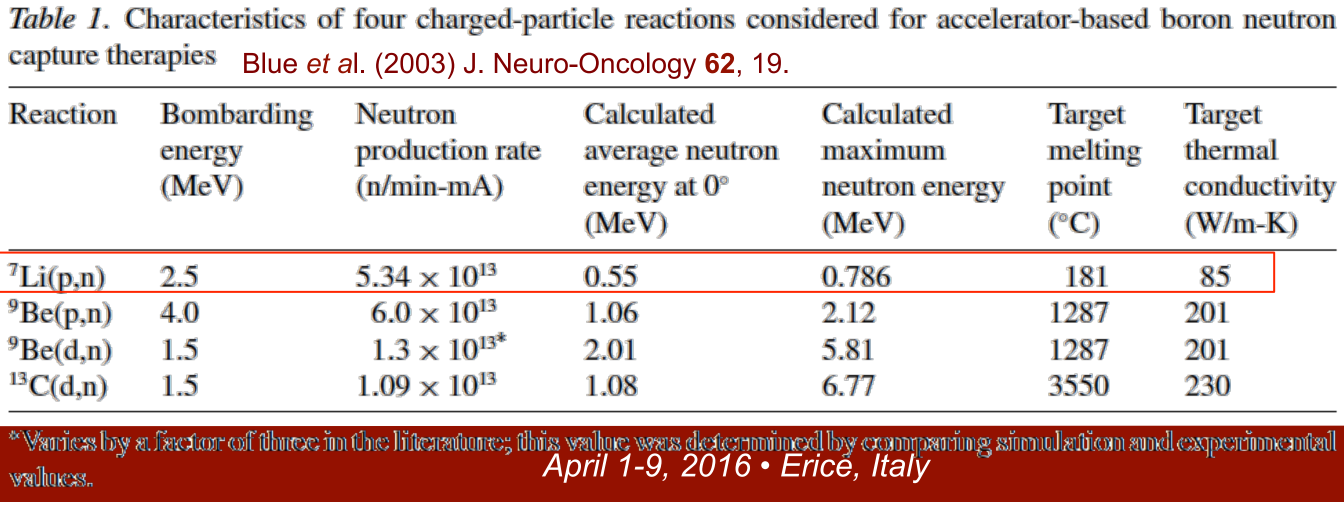
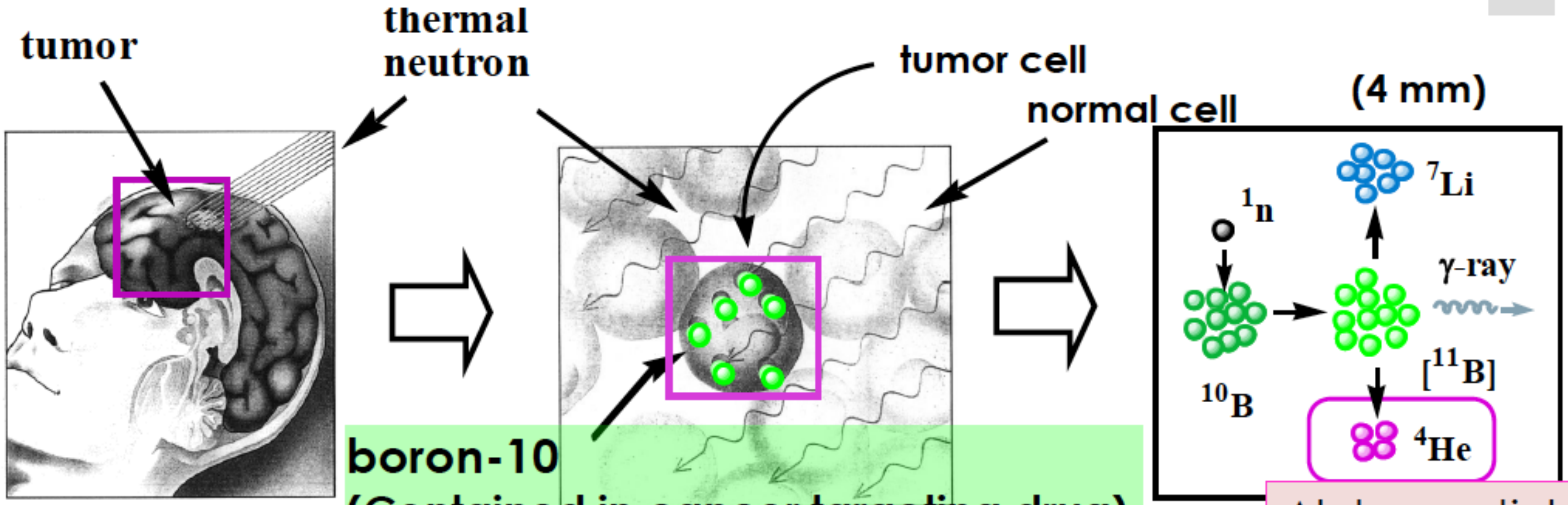


Table 1. Characteristics of four charged-particle reactions considered for accelerator-based boron neutron capture therapies

Blue *et al*. (2003) J. Neuro-Oncology **62**, 19.

Reaction	Bombarding energy (MeV)	Neutron production rate (n/min-mA)	Calculated average neutron energy at 0° (MeV)	Calculated maximum neutron energy (MeV)	Target melting point (°C)	Target thermal conductivity (W/m-K)
^{7}Li(p,n)	2.5	5.34×10^{13}	0.55	0.786	181	85
^{9}Be(p,n)	4.0	6.0×10^{13}	1.06	2.12	1287	201
^{9}Be(d,n)	1.5	$1.3 \times 10^{13*}$	2.01	5.81	1287	201
^{13}C(d,n)	1.5	1.09×10^{13}	1.08	6.77	3550	230

*Varies by a factor of three in the literature; this value was determined by comparing simulation and experimental values.

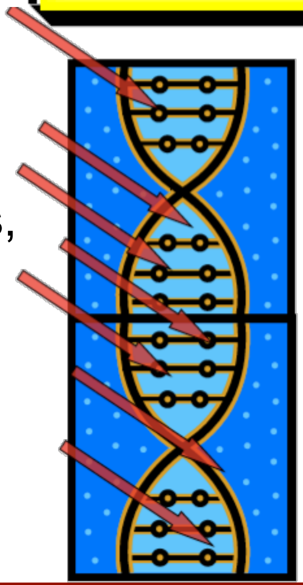


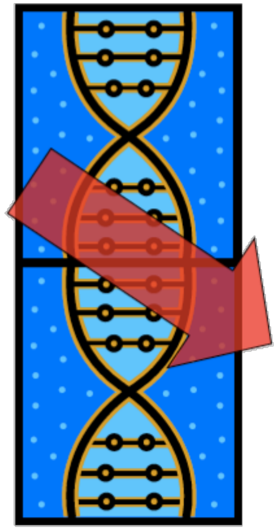
boron-10
(Contained in cancer targeting drug)

Alpha particle
Path length :10
micron

$$^{10}B + {}^{1}n \rightarrow [^{11}B] \rightarrow {}^{7}Li + {}^{4}He + 2.79\ MeV$$

X-rays, ϒ-rays,
LE protons

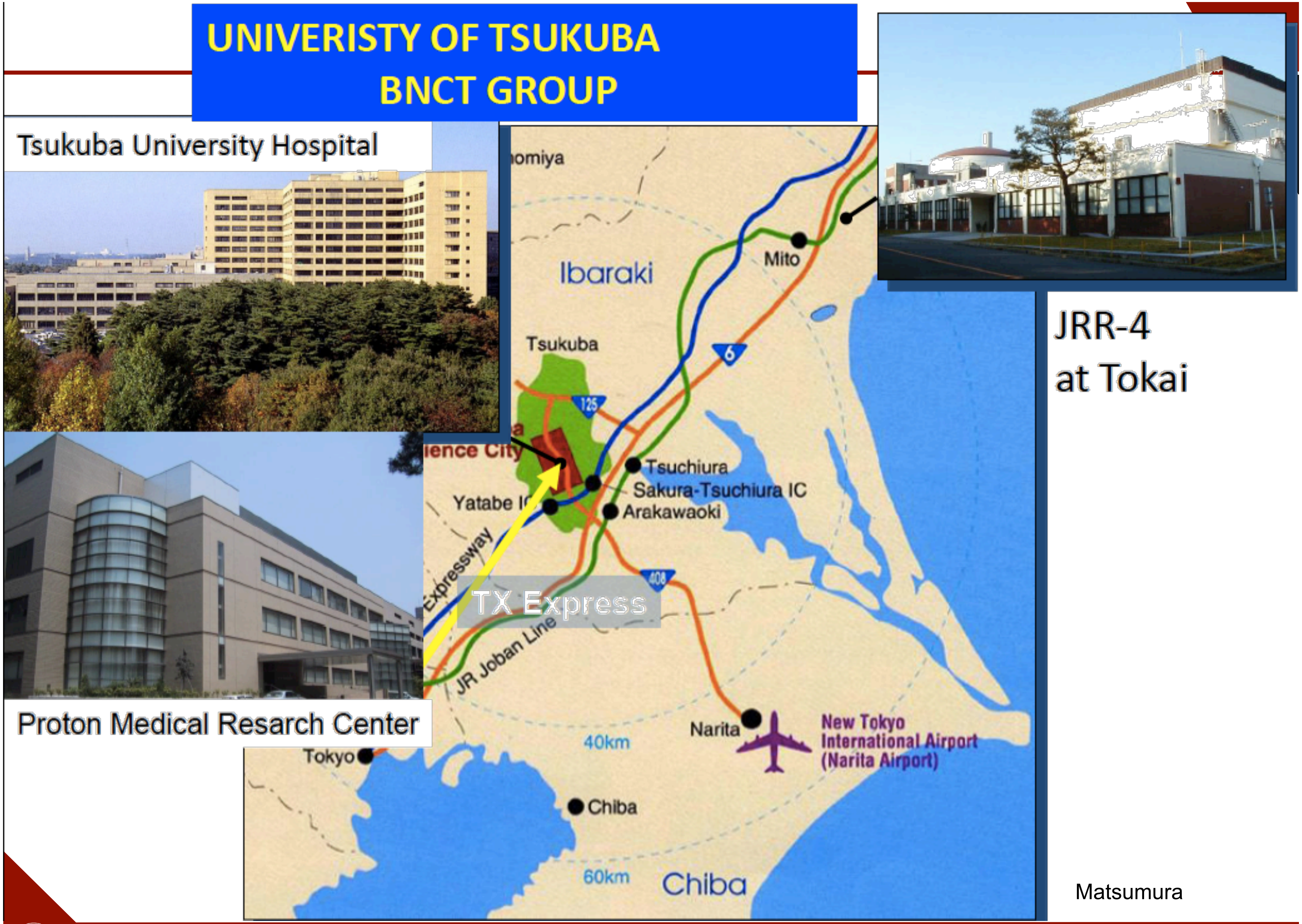




α particles & ^{7}Li nuclei from *boron neutron capture therapy* cut both DNA strands of the tumor cells

Matsumura

UNIVERISTY OF TSUKUBA BNCT GROUP



Tsukuba University Hospital

Proton Medical Resarch Center

JRR-4
at Tokai

Matsumura

Weekly Asahi, Special Issue on new treatment

Modalities (0ct,2010) issued on top page

週刊朝日
増刊号
定価650円

最新治療20

現代の最新治療2011

患者をどこまで救えるのか！

最新治療は実験的な側面がある。だから、最新は「最良」だとは限らない。しかし、「患者を苦しみから解放したい」と熱い志を持った医師たちは、日々、挑戦的な治療に臨んでいる。未来の標準治療の現場を歩いた。

進化する放射線治療

ホウ素中性子捕捉療法

原子炉を利用した新しいがん治療

膠芽腫は脳腫瘍の一種。神経膠腫（グリオーマ、▼192㌻）の中でももっとも悪性度が高いとされている。この病気の治療に期待がかかるのが「ホウ素中性子捕捉療法」だ。患者の体内にあらかじめがん細胞にだけ集まる「ホウ素化合物」を投与する。その後、医療照射用の原子炉から発生させた中性子を患部に照射するとホウ素化合物との核反応が起こり、がん細胞を標的にして強力な放射線が発生する。

治療を実施する松村明医師（筑波大学病院副病院長）はこう話す。

「膠芽腫は脳の中に深く入り込んでいるので、標準的な放射線治療（X線）などでは再発例が少なくないため、効果的な治療法が期待されています。この病気では2年生存率が有効性の一つの指標になりますが、薬剤や照射法を工夫して実施した最先端の中性子捕捉療法では2年生存率が57.1%という結果（X線では21.1%）が出ています」

正常細胞には放射線がほとんどあたらないため、再発した場合も2度目の照射が可能。1度目の治療がX線や陽子線（▼170㌻）だった場合も症例によっては対象となる。現在、研究段階だが、頭頸部がんや皮膚がん、肝臓がん、肺がんなどにも実施されており、次世代のがん治療法として世界から注目されている。

照射室。壁の奥に炉心があり、ビーム孔から中性子が患部に向けて照射される

治療は茨城県東海村の日本原子力研究開発機構（原子力科学研究所）で実施している

中性子が水の中を通過するときに発生する青い光。「チェレンコフ放射光」と呼ばれる

松村 明医師
筑波大学病院
脳神経外科教授
茨城県つくば市
天久保2-1-1
029-853-3900

■ホウ素中性子捕捉療法の治療の仕組み

ホウ素中性子捕捉療法の原理。正常細胞を傷さずがん細胞を狙い撃ちにする

医師たちは原子炉稼働中の照射室に長時間入れないため、別室で照射の位置決めをする

7 週刊朝日

新「名医」の最新治療 2011 6

Matsumura

Sample cases of BNCT Treatment
(High effectiveness & preservatoin of normal tissue)

Prof.Kato,Osaka University

Recurrent Parotid Cancer

Pre BNCT

Recurrent tumor after Surgery, Chemotherapy and Radiotherapy. Skin erosion and infection is evident

After 2nd BNCT

Marked shrinkage of the tumor and regeneration
of the skin

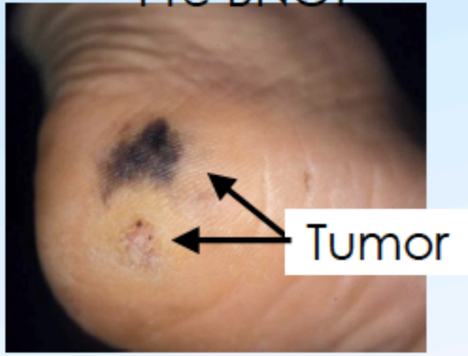
5M after 3rd BNCT

Complete cure by BNCT. The patient was alive 5 yrs without cancer recurrence

Malignant Melanoma at foot

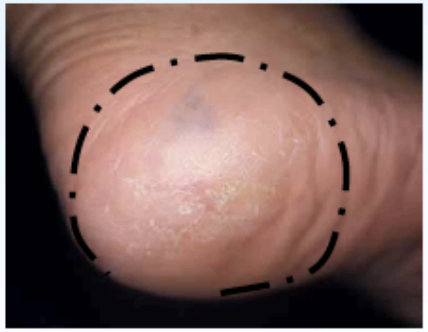
Corutsey of Kawasaki Medical University

Pre BNCT



3M after BNCT

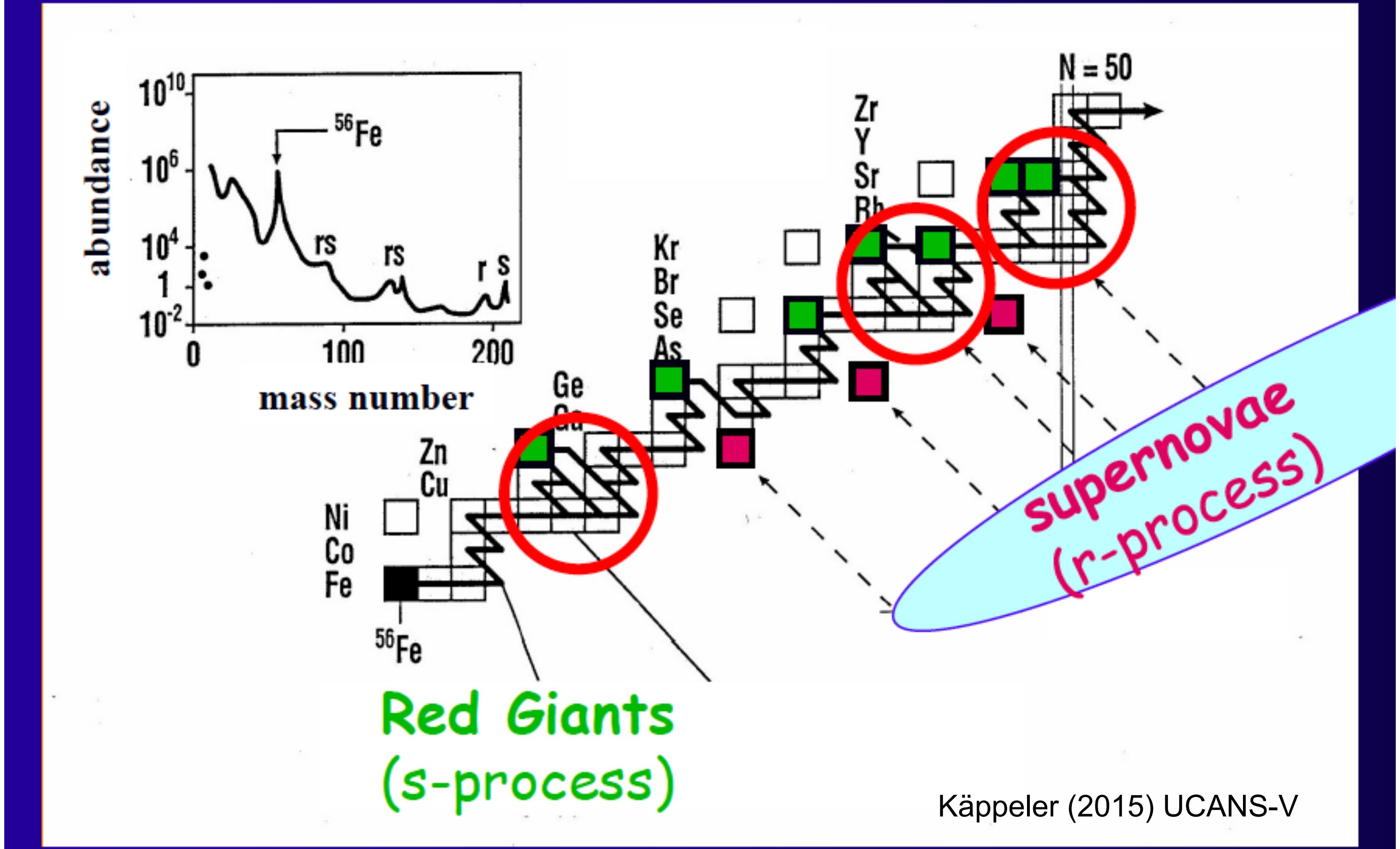
6M after BNCT



Fast Neutron Therapy (FNT)

- Fast neutrons damage cells through high linear-energy-transfer (HLET); kill cancer cells by cutting both cords of the chromosome helix.
- HLET reduces the numbers of treatment by >50% compared with other LLET therapies.
- Under hypoxic conditions (reduced oxygen supply) at the tumor tissue neutrons are more effective than x-rays.
- Currently FNT is only available at a handful facilities in Germany, Russia, USA and South Africa, mainly based on cyclotrons and reactors. Reactors need special beamlines to extract fast neutrons from the reactor core.

Fe to U: s- and r-process



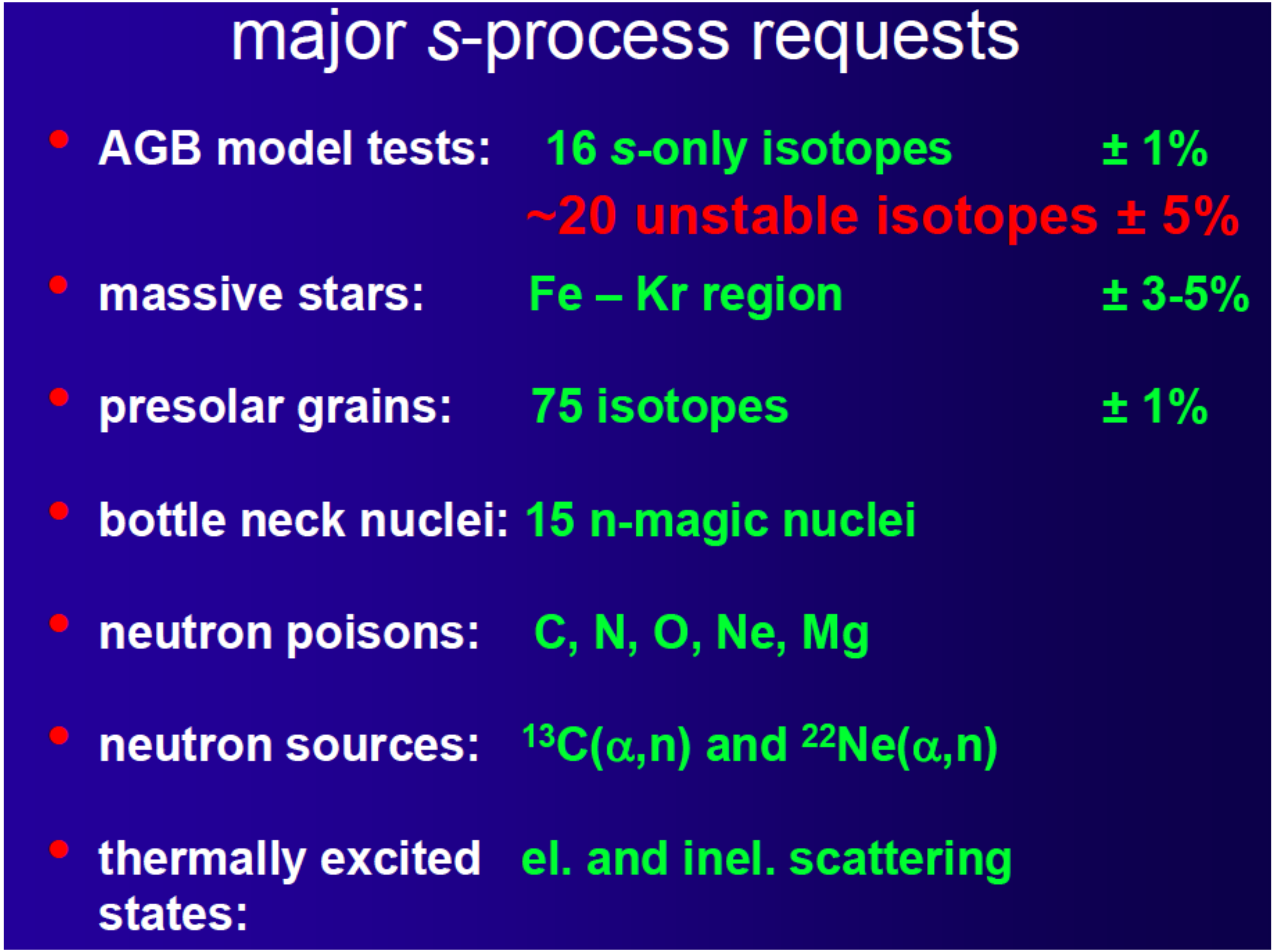
supernovae (r-process)

Red Giants (s-process)

Käppeler (2015) UCANS-V

s-abundance × cross section = $N_s \sigma$ = constant

The Neutron-related Needs

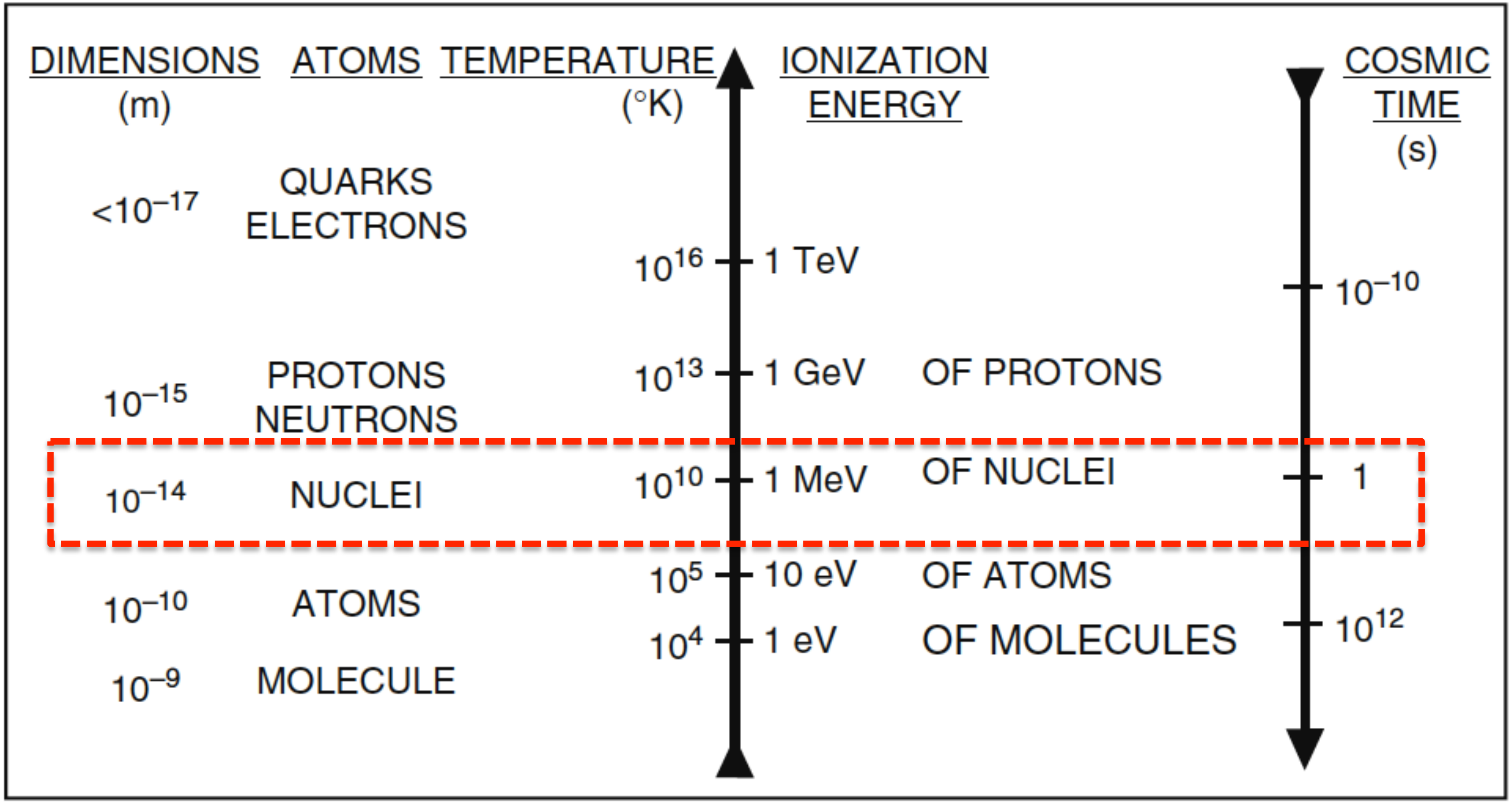


major *s*-process requests

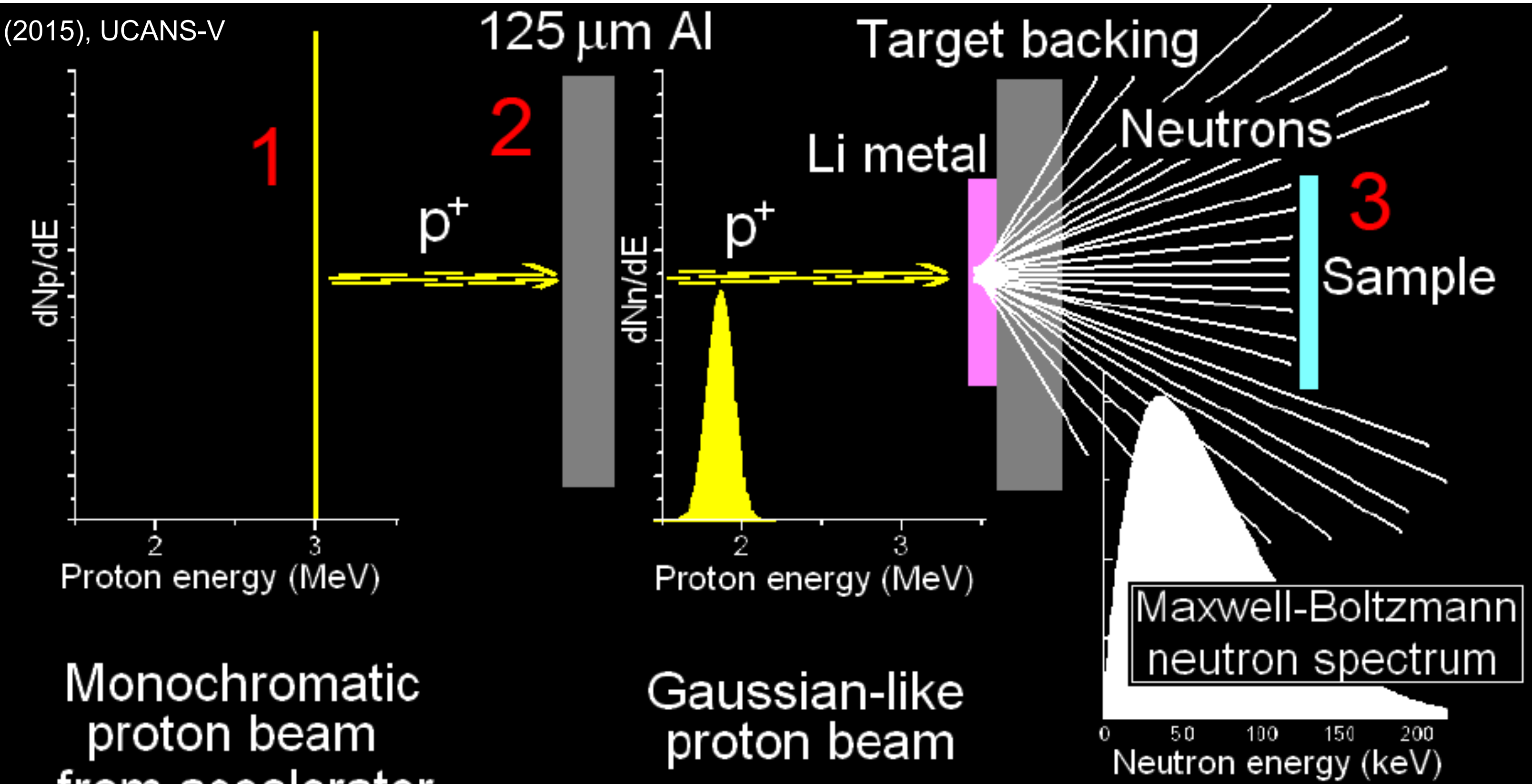
AGB model tests:	**16 *s*-only isotopes**	**± 1%**
	~20 unstable isotopes	**± 5%**
massive stars:	**Fe – Kr region**	**± 3-5%**
presolar grains:	**75 isotopes**	**± 1%**
bottle neck nuclei:	**15 n-magic nuclei**	
neutron poisons:	**C, N, O, Ne, Mg**	
neutron sources:	**$^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$**	
thermally excited states:	**el. and inel. scattering**	

Käppeler (2015) UCANS-V

CANS provides neutrons of energies (~MeV) comparable to the temperatures of the sun and supernova explosion.



Mastinu (2015), UCANS-V



Monochromatic proton beam from accelerator

Gaussian-like proton beam

Mastinu (2015), UCANS-V

$$\frac{d^2Y}{d\Omega dE_n}(\theta,E_n) = N_{7_{Li}}\frac{d\sigma_{pn}}{d\Omega'}\frac{d\Omega'}{d\Omega}\frac{dE_p}{dE_n}\left(\frac{dE_p}{dx}\right)^{-1}$$

$$\left\langle \frac{d^2Y}{d\Omega dE_n}(\theta,E_n)\right\rangle = \frac{1}{\sigma_p\sqrt{2\pi}}\int_0^\infty e^{-\frac{(E_p-E_p^m)^2}{2\sigma_p^2}}\frac{d^2Y}{d\Omega dE_n}(\theta,E_n)dE_p$$

$$\frac{dY}{dE_n}(E_n) = 2\pi\int_0^{\theta_{max}}\left\langle \frac{d^2Y}{d\Omega dE_n}(\theta,E_n)\right\rangle \sin\theta\, d\theta \quad \longleftarrow$$

The neutron spectrum at the sample

Applied Radiation and Isotopes 70 (2012) 1583–1589

Contents lists available at SciVerse ScienceDirect

Applied Radiation and Isotopes

journal homepage: www.elsevier.com/locate/apradiso

Temperature-tuned Maxwell–Boltzmann neutron spectra for *kT* ranging from 30 up to 50 keV for nuclear astrophysics studies

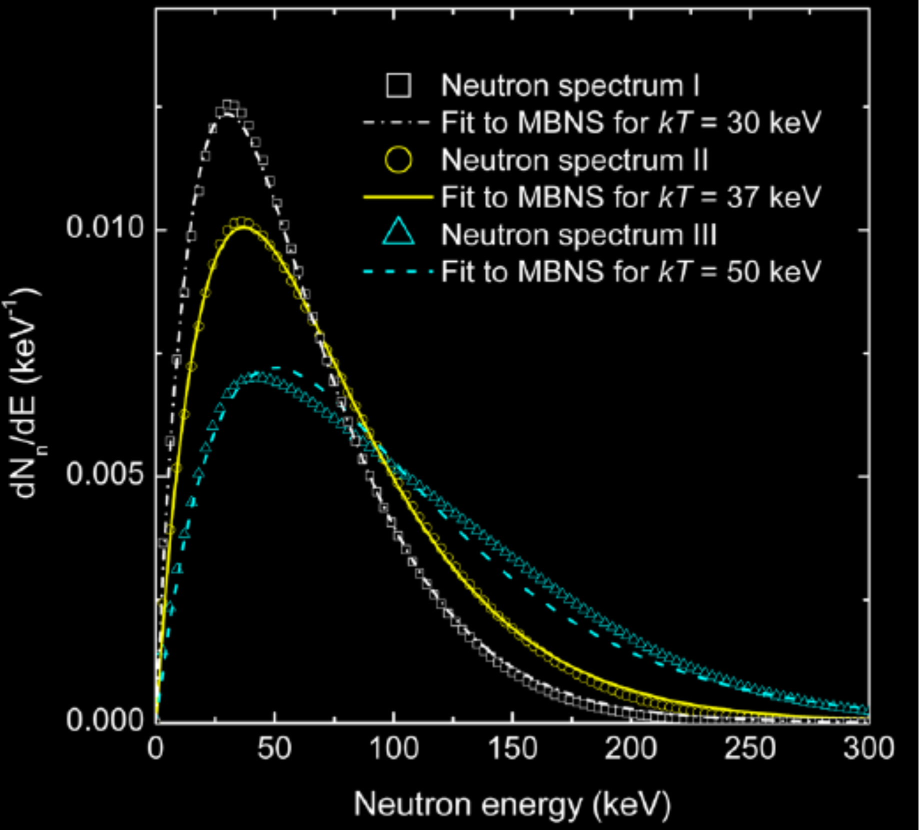
G. Martín-Hernández [a,*], P.F. Mastinu [b], J. Praena [c], N. Dzysiuk [b], R. Capote Noy [d], M. Pignatari [e]

[a] *Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear, 5ta y 30, Playa, La Habana, Cub*
[b] *INFN, Laboratori Nazionali di Legnaro, Viale dell'Università 2, 35020 Legnaro, Italy*
[c] *Universidad de Sevilla, CNA, Spain*
[d] *NAPC-Nuclear Data Section, International Atomic Energy Agency, A-1400 Vienna, Austria*
[e] *Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerl*

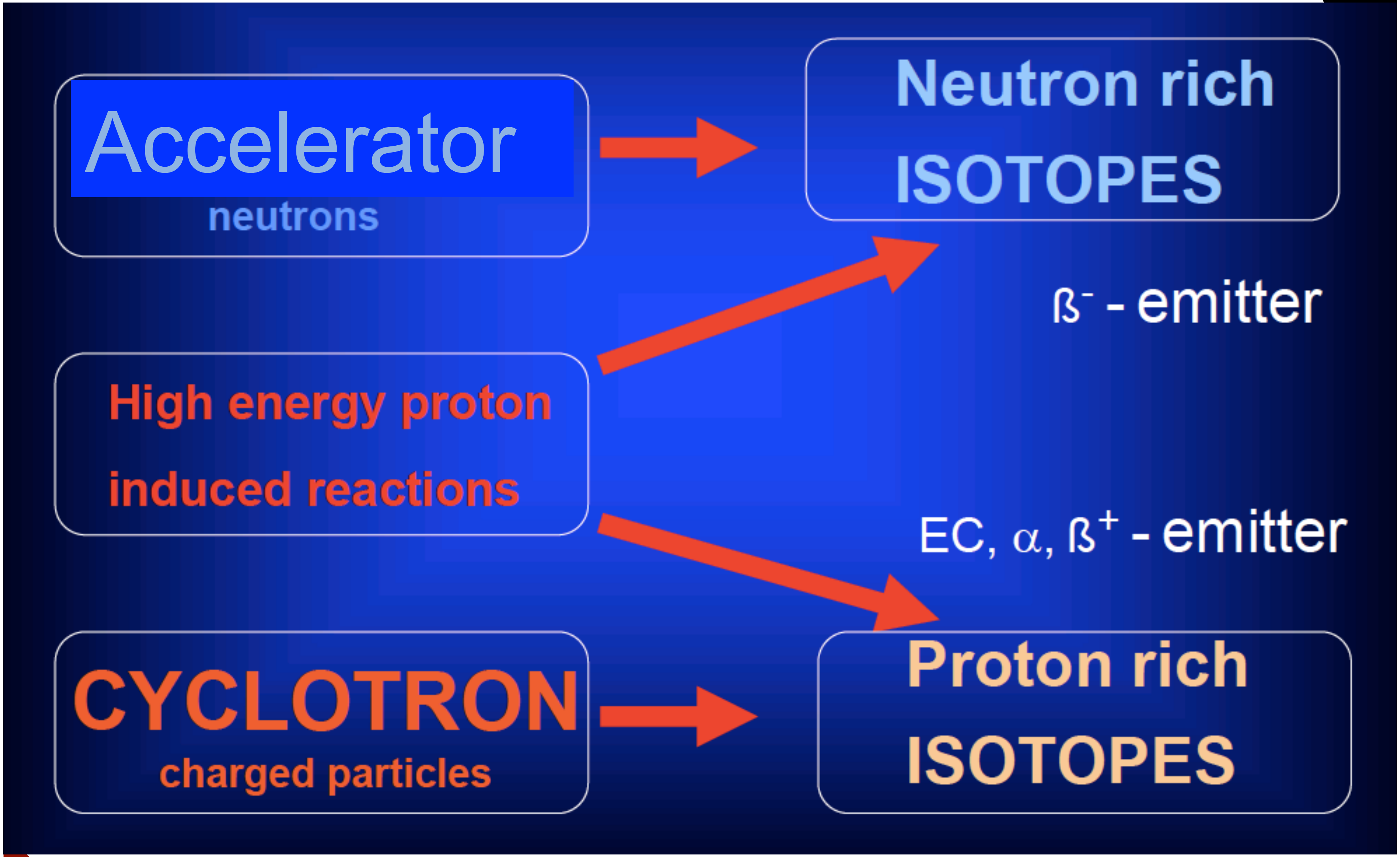
HIGHLIGHTS

- We expand the use of the accelerator-based ^{7}Li(p,n)^{7}Be reaction for astrop
- High-quality stellar (Maxwell-Boltzmann) neutron spectra are calculated.
- Easy control of the proton beam shape can produce the desired neutron sp
- Weighted fit increases accuracy in settling on the neutron spectrum temp

Spectrum	E_p (keV)	E_p (keV) after foil	θ_{max} (degree)	kT (keV)	R^2	Neutron yield (n/pC)
I	4510	1795 ± 79	90	30	0.9995	4.3
II	4547	1865 ± 78	63	37	0.9998	16.4
III	4604	1973 ± 76	43	50	0.9975	37.7



Other Applications: Isotope Production



Accelerator

neutrons

Neutron rich ISOTOPES

β^- - emitter

High energy proton induced reactions

EC, α, β^+ - emitter

CYCLOTRON

charged particles

Proton rich ISOTOPES

Supply Problem of ^{99M}Mo/^{99}Tc Isotope for Medical Use

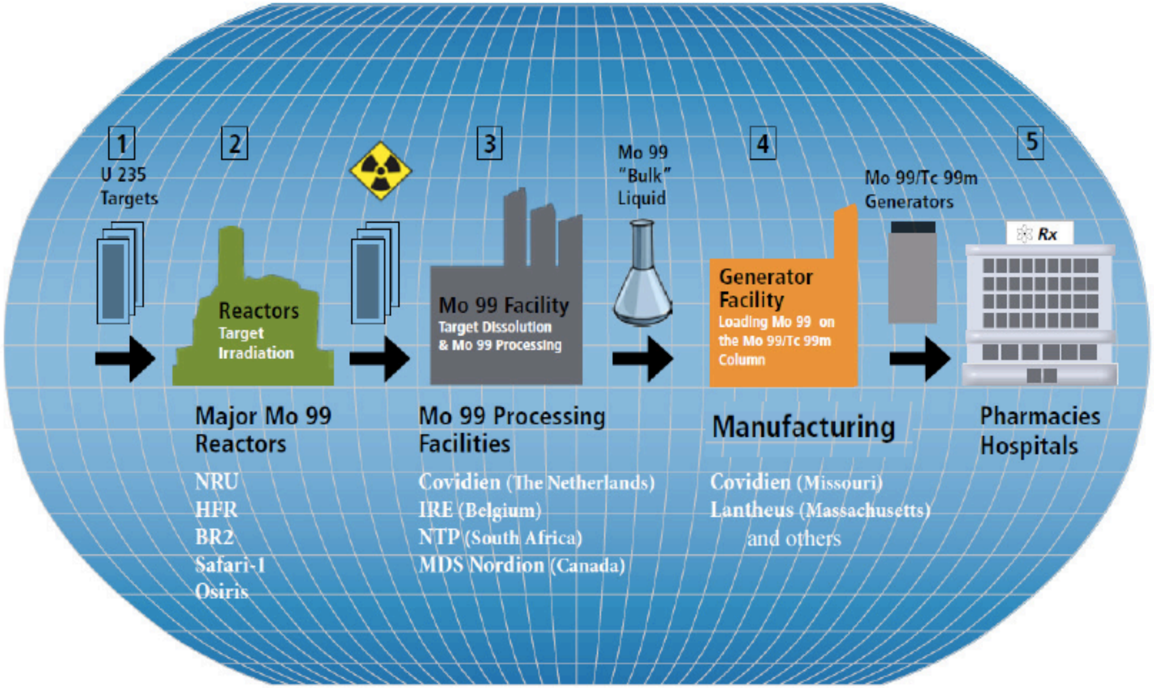


FIG. VII-1: Global supply chain of ^{99}Mo and subsequent utilization schematics. Source: www.covidien.com (October 2009)

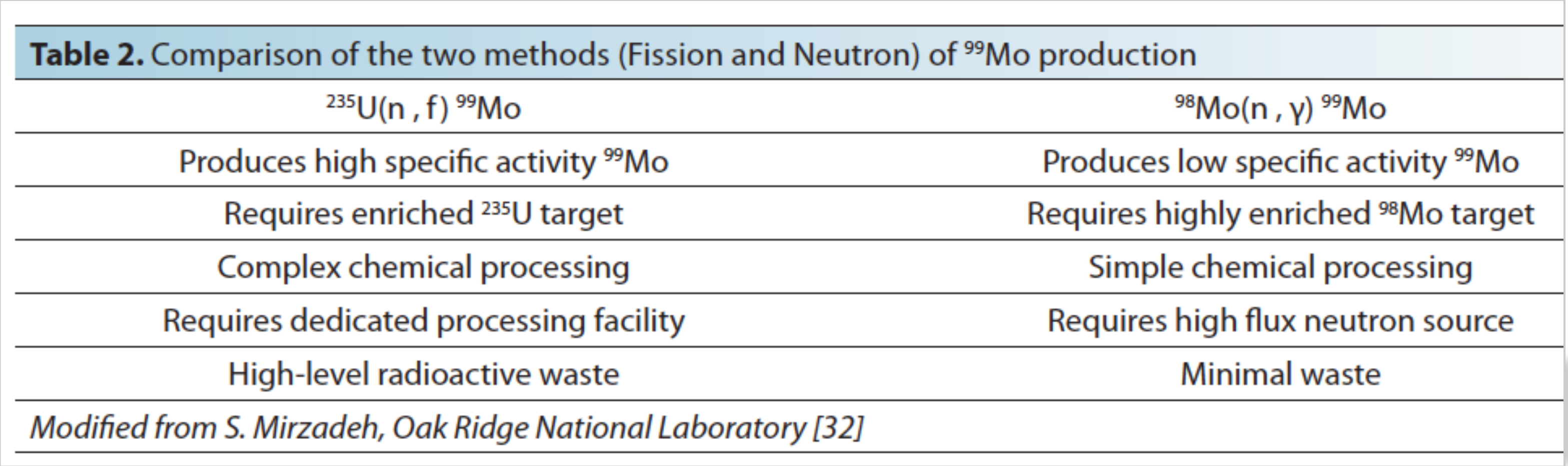


Table 2. Comparison of the two methods (Fission and Neutron) of ^{99}Mo production

^{235}U(n , f) ^{99}Mo	^{98}Mo(n , γ) ^{99}Mo
Produces high specific activity ^{99}Mo	Produces low specific activity ^{99}Mo
Requires enriched ^{235}U target	Requires highly enriched ^{98}Mo target
Complex chemical processing	Simple chemical processing
Requires dedicated processing facility	Requires high flux neutron source
High-level radioactive waste	Minimal waste

Modified from S. Mirzadeh, Oak Ridge National Laboratory [32]

CANS Facilities

Operational

Name	Country	Accelerator type/reaction type
Bariloche Linac	Argentina	Electron linac
CPHS—Compact Pulsed Hadron Source of Tsinghua University	P. R. China	Proton linac
CYRIC: Quasi-monoenergetic neutron beam facility at CYRIC	Japan	Azimuthal varying field cyclotron
FNG: the Frascati Neutron Generator	Italy	Deuteron electrostatic accelerator
Gaerttner linear accelerator at Rensselaer Polytechnic Institute	USA	Electron linac
GELINA: Geel Electron Linear Accelerator Facility	Belgium	Electron linac
HUNS: the Hokkaido University Neutron Source	Japan	Electron linac
iThemba	South Africa	Proton cyclotron
KOMAC-NST, **KIRAMS-MC-50**, and **PAL-PNF**	Korea	Tandem accelerator, cyclotron, electron linac
KUANS: Kyoto University Accelerator-driven Neutron Source	Japan	Proton radio frequency quadrupole (RFQ)
KURRI-LINAC: Kyoto University Research Reactor Institute, Electron Linear Accelerator	Japan	Electron linac
LENS: the Low-Energy Neutron Source	USA	Proton RFQ + 2 linacs
n_TOF: n_time-of-flight facility at CERN	Switzerland	Proton synchrotron
PKUNIFTY	P. R. China	RFQ linac
RANS: RIKEN Accelerator-driven Neutron Source	Japan	Proton RFQ+ linac
TSL neutron facility	Sweden	Proton and H_2^+ cyclotron

Under Development

Name	Country	Accelerator type/reaction type
ESS Bilbao Project	Spain	Proton linac
FRANZ: Frankfurt Neutron Source at the Stern-Gerlach-Zentrum	Germany	Proton linac
LENOS: Legnaro Neutron Source	Italy	Proton RFQ
n@BTF:The Frascati electron-driven source	Italy	Electron linac
nELBE: Time-of-flight facility at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR)	Germany	Superconducting electron accelerator
NEPIR: NEutron and Proton IRradiation	Italy	Proton cyclotron
NUANS: Nagoya University Accelerator-driven Neutron Source	Japan	DC accelerator (dynamitron)
UTCANS, University of Tokyo	Japan	Electron linac
Van de Graaff @IRMM, Institute for Reference Materials and Measurements	Belgium	Tandem

Education and Mentoring

1. Interactions among scientists (e.g., accelerator & neutron physicists), engineers, and students
2. Include CANS in neutron schools and workshops
3. Books about CANS:

   Neutron Scattering Applications and Techniques (Springer)
   Series Editors: Ian Anderson, Alan Hurd, & Robert McGreevy

Upcoming volumes:

Compact Accelerator Driven Neutron Sources: Physics, Technology and Applications
Editors: David V. Baxter (Indiana U), Michihiro Furusaka (Hokkaido U),
& Chun Loong

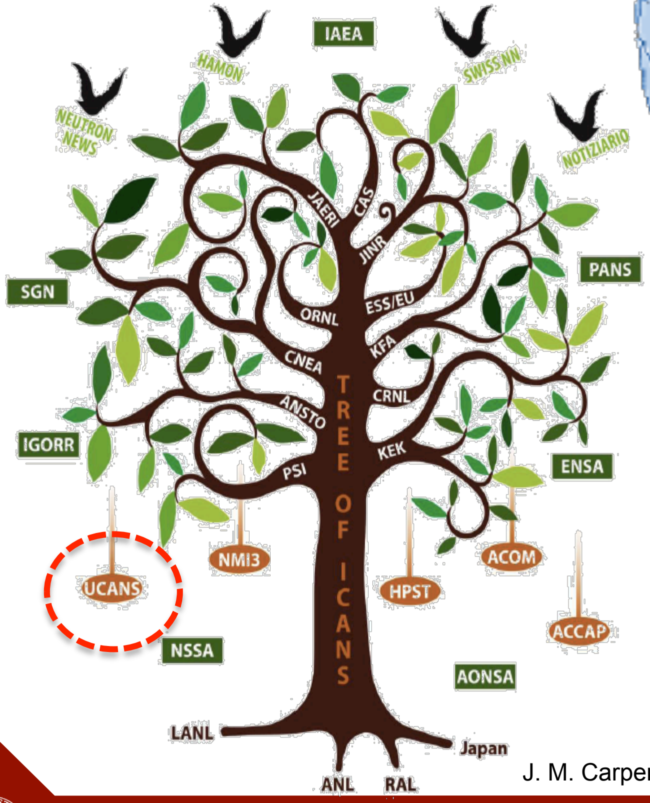
Neutron Experimental Methods in Cultural Research
Editors: Nikolay Kardjilov (Helmholtz-Zentrum Berlin) and
Giulia Festa (U Rome)

Union for Compact Accelerator-driven Neutron Sources (UCANS)

Established in 2008

UCANS

- ✧ Established in 2008
- ✧ 14 members in Americas, Asia and Europe, encompassing
  - ✧ Academia
  - ✧ Government labs
  - ✧ Industry



J. M. Carpenter (2012)

Neutron News, **25**(2), 12 (2014); *ibid* **22**(1), 7 (2011)

Collaborative & Complementary: Capability vs Capacity

➔UCANS-VI, China, Nov 2016

➔Workshops on Neutron Scattering Landscape in Europe - 2015

➔JCANS - 2014

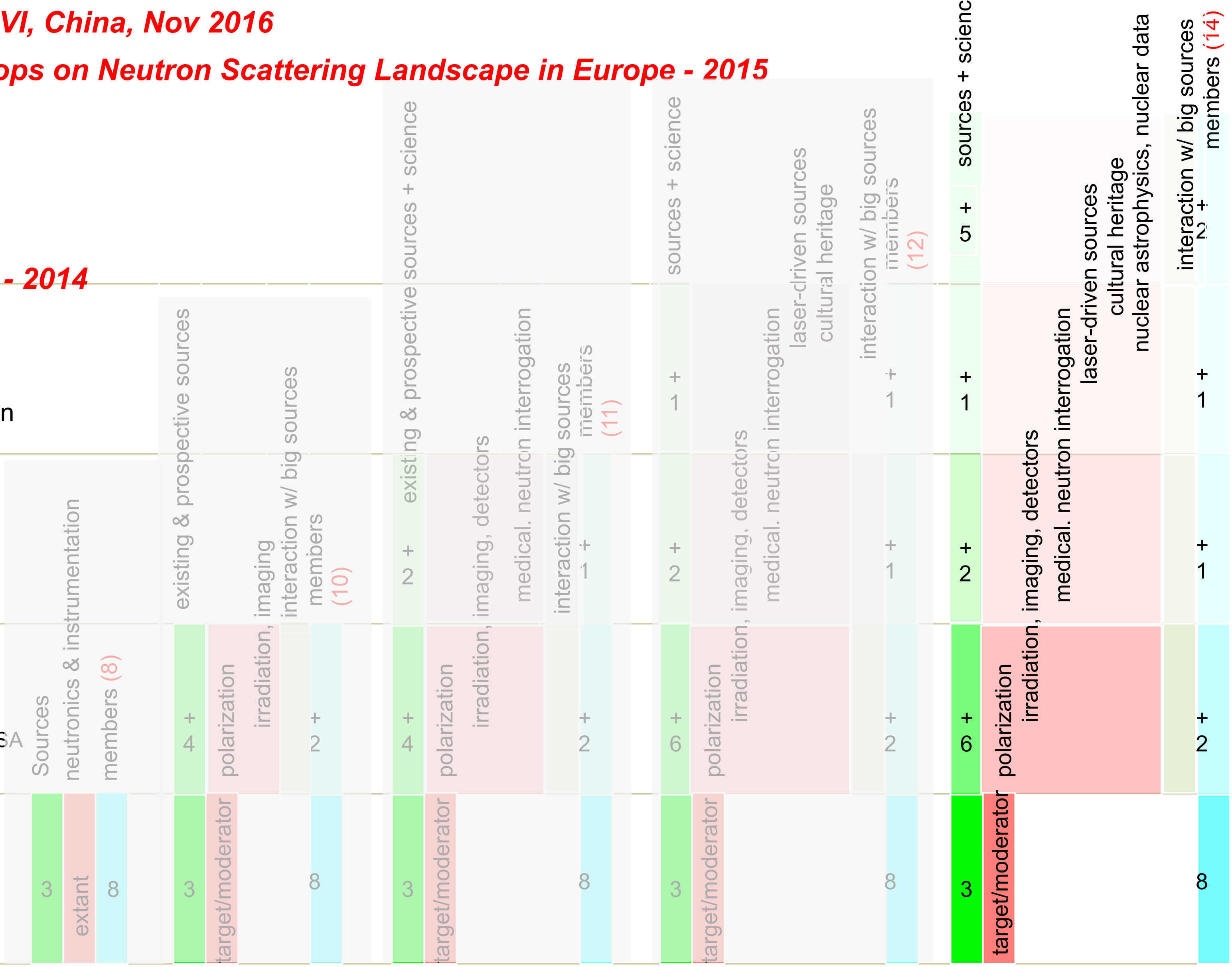
UCANS-V
2015
Padova, Italy

UCANS-IV
2013
Sapporo, Japan

UCANS-III
2012
Bilbao, Spain

UCANS-II
2011
Bloomington, IN USA

UCANS-I
2010
Beijing, China



Concluding Remarks

- ✧ CANS have demonstrated their cost-effectiveness & usefulness in continuing development of high-power neutron sources, instrumentation and in user training

- ✧ CANS are expanding rapidly to cross-disciplinary applications spanning fundamental research and industrial development

- ✧ Historically, many CANS were spinoffs from legacy accelerator projects. But in view of the need for networking the communities (materials, nuclear, medical,…) and for maintenance of a healthy neutron-scattering capacity for the future, perhaps it is time to contemplate new ‘medium-flux’ neutron sources – the ***ABC neutron sources***.

Accelerator-driven Brilliant & Compact

Thank you

ABC NS
Thank You

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Questions