



Ionizing Radiation

SPEAKER

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- Ionizing Radiation
- MWG6
- Radioactivity
- Dosimetry
- Neutron

Ionizing Radiation





Ionizing vs. Non-Ionizing Radiation

- Ionizing radiation has enough energy to break an electron away from an atom
- It has the ability to change the chemical composition of the material it interacts with.

- Non-ionizing radiation is described as a series of energy waves composed of oscillating electric and magnetic fields traveling at the speed of light.
- Non-ionizing radiation includes the spectrum of ultraviolet (UV), visible light, infrared (IR), microwave (MW), radio frequency (RF)

Ionizing Radiation

Unstable nucleus ejects particles to become more stable.

The three main types of ionizing radiation are **alpha particles, beta particles, and gamma rays**.

- alpha particles
- beta particles

• gamma rays



Alpha Particle Radiation



Alpha decay is a radioactive process in which a particle with two neutrons and two protons is ejected from the nucleus of a radioactive atom. The particle is identical to the nucleus of a helium atom.

Alpha decay only occurs in very heavy elements such as uranium, thorium and radium. The nuclei of these atoms are very "neutron rich" (i.e. have a lot more neutrons in their nucleus than they do protons) which makes emission of the alpha particle possible.

Beta Particle Radiation



Beta decay is a radioactive process in which an electron is emitted from the nucleus of a radioactive atom, along with an unusual particle called an antineutrino. The neutrino is an almost massless particle that carries away some of the energy from the decay process. Because this electron is from the nucleus of the atom, it is called a beta particle to distinguish it from the electrons which orbit the atom.

Gamma-Ray Radiation



Gamma rays are often produced alongside other forms of radiation such as alpha particles or beta particles. When a nucleus emits an α or β particle, the daughter nucleus is sometimes left in an excited state. It can then jump down to a lower level by emitting a gamma ray. Gamma rays are not particles and do not have any charge.

Penetration Ability



MWG6 Ionizing Radiation









Chair: Lizbeth Laureano Perez, NIST Co-Chair: Raphael Galea, NRC





Members of MWG6 – IR

Country	Institution (*DI)	Capabilities		
Country		Dosimetry	Radioactivity	Neutrons
Argentina	* Comisión Nacional de Energía Atómica	v	Y	
	(CNEA)	X	X	
Brazil	*National Metrology Laboratory of Ionizing	×	Y	X
	Radiation (LNMRI)	X	X	X
Canada	(National Research Council (NRC)	x	x	х
Chile	*Comisión Chilena de Energía	x	x	x
	Nuclear (CCHEN)			
International	International Atomic Energy Agency (IAEA)			
organisation		X		
Mexico	*Instituto Nacional de Investigaciones			x
	Nucleares (ININ)	X	X	
St. Kitts and	*St. Kitts and Nevis Bureau of	Developing capabilities		
Nevis	Standards (SKNBS)			
Uruguay	*Ministerio de Industria, Energía y Minería			
	-Dirección Nacional de Aplicaciones de la	x	x	
	Tecnología Nuclear (MIEM-DINATEN)			
USA	National Institute of Standards and		x	x
	Technology (NIST)	X		

Quantities of Interest

Neutron Measurements

- Absorbed dose and dose rate to graphite, tissue, water, other
- Ambient dose equivalent and rate
- Emission anisotropy
- Emission rate
- Fluence and fluence rate
- Personal dose equivalent and rate
- Dosimetry
 - Absorbed dose/rate to air, graphite, tissue, water, other
 - Air kerma area product
 - Air kerma length product
 - Air kerma/rate
 - Ambient dose equivalent/rate
 - Directional dose equivalent/rate
 - Personal dose equivalent/rate, penetrating or superficial
 - Reference Kerma Rate
 - X-ray tube voltage

- Radioactivity
 - Activity
 - Activity per unit area, mass, volume
 - Efficiency of contamination monitors
 - Efficiency of gamma-ray spectrometers (versus energy)
 - Efficiency of ionization chambers
 - Emission rate, rate per unit solid angle
 - Surface emission rate, rate per unit area

Radioactivity Radionuclide Metrology





Radioactivity

When the particles or photons are emitted (decay of the nuclei) they release energy. This spontaneous emission of energy and subatomic particles from individual, unstable nuclides is called Radioactivity.

- It is naturally occurring, or artificially produced
- SI unit is the Becquerel (Bq) number of decays per second
- Natural background ranges up to 10's of millions of Bq's per kg
- Uses in health, environmental studies, industry, scientific research
- Good measurements are crucial to meet safety and regulatory concerns







Decay and Nuclear Data

• Activity (A_t) at time *t* is related to the initial activity (A_0) at time 0 (t_0) as a function of the half life ($T_{1/2}$) by

•
$$A_t = A_{(0)} e^{-\Delta t \lambda}$$

- Uncertainties are lowest closest to t₀
- Activity values must have stated reference time
- Can measure T_{1/2} over several half-lives (tougher for the longer-lived)
- Photon or particle energies measured (spectrometry) provide identification for both radionuclide of interest and possible impurities.







Nuclear Data

Key physics to be considered in radionuclide metrology

- Type of particle/energy
- Half-life (T_{1/2})
- Energy value(s)
- Emission probabilities
- Mode of production
- Some 150+ possibilities



Types of Sources Considerations

- Physical nature: gas, liquid, solid
- Single versus multinuclide sources
- Source preparation
 - Instrumentation availability
 - Ease of quantitative extraction (if needed)
 - Scattering, self-absorption



Impurities

- Act as a mixed source
- Naturally co-occurring (e.g., radium decay), or co-produced
- Can interfere with detection or quantification
- Spectroscopic methods (gamma and alpha)
- Half-life differences can also be used



Primary Measurement Methods

- Direct detection (Bq)
- Accurate, precise, independent
- Specialized (defined solid angle; high geometry; coincidence methods)
- Assumptions, i.e "boot strap"
- Errors investigated and corrected
- Some potential aspects common to all (background; self-absorption; uncertainty budgets; in-growth, impurities)
- How to choose the best (better?)
 - Physics (half life, energies)
 - Chemistry
 - Source preparation

Corrections and Complications

- Source geometry
- Half-life and decay scheme
- Impurities and daughters ("mixed" sources)
 - Gamma and alpha spec
 - Evaluating differences in half life
- Activity level (dead time, pile up)
- Calculational approaches (Monte Carlo)
 - Step-by-step
 - All possible trajectories, interactions
 - Input include energy, material density, mean free path





High Geometry (Efficiency) Methods

- Catching all the decays
- 4π or 2π geometry possibilities
- Loss corrections
- Ionization capacity of decay
- Examples: internal gas counting and liquid scintillation counting (LSC)



(Length-Compensated) Internal Gas Counting

- Gas sources (nobles, ³H)
- Set of cylindrical proportional counters
 - Different lengths
 - Identical diameters, central wires, end insulators
 - Each with given uniform region of *E*
- Volume difference measurement is key
- Ionization cascade



Ref: M. Unterweger, *Metrologia* **44**, 4, S79-S81 (2007).

(Length-Compensated) Internal Gas

- Original ionizing particle instigates avalanche of ion-pair formations
- Voltage set-up so that pulse height is proportional to energy
- Largest uncertainty component is from pressure (directly related to mass)
- Activity based on average N₀ among three counters



Liquid Scintillation Counting

- Liquid matrix (well-mixed)
- Energy transfer (α and β)
 - Decay energy to fluor
 - 10% excited state, emits light
- PMTs set-up for coincidence
- Efficiencies of concern
 - Scintillation (transfer and range)
 - Detector (light collection)
- Quenching
 - Color, chemical, physics
 - Issues for very low energies (<1 keV)



Activity (A_{nuc}) = $R_{nuc}/(\epsilon_{nuc} m)$

Ref and Review: R. Broda, et al., Metrologia 44, 4, S36-S52 (2007).

Liquid Scintillation Counting CIEMAT/NIST Method – Efficiency Tracing

- Tracer (usually ³H)-based, 2 PMTs in coincidence
- Relation between $\varepsilon_{\text{nuclide}}$ and $\varepsilon_{\text{tracer}} \rightarrow$ "efficiency curve"
- Calibration curve (ε_{tracer}) determined from measured quenched tracer samples (QIP measured automatically)
- Uncertainty of counting efficiency related to non-efficiency (so, when detection efficiency is low, the uncertainty on the tracer is more important)



- R = count rate
- M = free parameter
- QIP = quench indicating parameter
- ε = counting efficiency
- a_{nuclide} = activity concentration
- m = mass of solution (in sample)

Efficiency: $\varphi(\lambda) = \int_{0}^{E_{max}} S(E) P(E, \lambda) dE$

Liquid Scintillation Counting TDCR Method (in an ideal world)

- 3 PMTs (A, B, and C), $\varepsilon_A = \varepsilon_B = \varepsilon_C$
- Series of quenched measurements Filters
- Double (AB, AC, BC) & triple (ABC) coincidences
- Normalized energy spectrum needed
 - for β, integration over entire energy spectrum
 - for electron capture, sum over entire spectrum



Defined Solid Angle

- Solid sources (alphas)
- CsI(TI) scintillation counter
 - Radiation in solid angle subtended by detector
 - Scintillation proportional to energy
 - Pulse-height analysis of amplified electrical pulse
- Backscatter
 - Minimized for alpha
 - Approach initiated to avoid issues with 2π





Ref: J.M.R. Hutchinson, et al., *Int'l J. App. Rad. Isot.*, 19 , 517-522 (1968).

Defined Solid Angle

- "Sampling" approach allows for higher source activities
- Also requires higher activities (background)
- Activity (in counts)
 - Determined from integrated sums from resulting spectra (R)
 - Geometry factor ($\Omega/4\pi$) gives the efficiency



Activity (
$$A_{nuc}$$
) = R/ ($\Omega/4\pi$)

Coincidence/Anticoincidence Methods

- Dependent on multiple detection (decay-specific)
- High efficiency less critical
 - Detection of coincidence versus single event
 - Time is only standard needed
- Same considerations for corrections (dead time, half life, background)
- Additional consideration ("accidental" coincidence, etc.)



Ref: C. Bobin, *Metrologia* **44**, 4, S27-S31 (2007).

4-π Beta-Gamma Coincidence

Large variety of radionuclides

- Simple in simple decay
- Improved detectors and thorough considerations allow wider range
- Event in 2 different detectors within a given time interval



- Random coincidences:
 - $N_{ran} = N_{\beta}N_{\gamma}(2\tau)$ [minimized with 2τ]
- Complex situations
- Uncertainties predominated by counting stats



Uncertainties in Radionuclide Measurements

- Final answer ≡ approximation
- Error ≠ uncertainty
- Statistical (e.g., counting) versus other (e.g., judgment) estimates
 - Instrument calibration
 - Any reference sources used
 - Decay corrections (half life)
 - Gravimetric (mass)
 - Live-time determination
 - Pile-up ('dead time'')
 - Detection limits for impurities

Usual coverage factor, k=2, and normal distribution



Table 2. Uncertainty evaluation for the massic activity for SRM 4927F

	Uncertainty component		Relative standard uncertainty contribution on massic activity of ³ H (%)
1	Massic count rate of SRM 4927E, corrected for background and decay; standard deviation of the mean for 23 sets of gas counting measurements (see Note 6)	А	0.18
2	LS intercomparison of SRM 4927F and SRM 4927E; standard deviation of the mean for 7 sets of LS measurements	А	0.06
3	Decay corrections for ³ H; (for half-life uncertainty of 0.18%)	А	0.002
4	Gram-mole determinations based on pressure, volume and temperature measurements	В	0.20
5	Livetime determinations	В	0.10
6	Extrapolation of count-rate-versus-energy to zero energy	В	0.20
7	Limit for radionuclidic impurities	В	0.05
Rel	ative combined standard uncertainty	0.36	
Rel	ative expanded uncertainty $(k = 2)$	0.72	

 † = (A) denotes evaluation by statistical methods: (B) denotes evaluation by other methods.

Comparisons in Radioactivity

- Currently, 168 comparisons in measurement of radionuclides (radioactivity) are listed in the Key Comparison Database (KCDB)
- Comparisons include
 - Key and Supplemental
 - SIM, EURAMET, COOMET, APMP, CCRI(II), BIPM (including SIR and SIRTI)
 - Planned, in progress, measurements complete, Draft B, approved/published, equivalence
 - A variety of radionuclides for health, security, environmental protection, metrology; single and multiple
 - Many matrices (from solution to soils)



Comparisons in Radioactivity

To establish equivalency of activity standards with national metrology institutes (NMIs) participation in comparisons is required

- Participating in Key Comparisons
- Participation in Supplemental Comparisons
- Submitting Source to BIPM SIR for gamma-emitting radionuclides
- NEW Submitting Source to BIPM ESIR for beta- emitting radionuclides using TDCR
- For short lived radionuclides schedule to received SIRTI









TDCR at BIPM



Recent Comparisons in Radioactivity

Comparison	Description	SIM Participants
CCRI(II)-K2.Cd-109	Activity of Cd-109 Solution	NIST, NRC, ININ and LNMRI
SIM.RI(II)-K2.Zn-65	Activity of Zn-65 Solution	NRC, NIST, ININ, CNEA, LNMRI pilot
CCRI(II)-S15	Cs-137 and K-40 in mushrooms	NIST
APMP Supplementary	Large Area Sources, Surface Emission Rate Measurements	NIST
CMCs in Radioactivity

- Radioactivity CMCs are nuclide specific
- Currently in 2627*different* combinations (quantity/nuclide/matrix) in CMCs
- Comparison results (quantity/nuclide/matrix) valid for "limited" time (eventually will be 10 years)
- Need to cover more than 1 quantity/nuclide/matrix with each comparison
- Primary methods of radionuclide metrology can be grouped according to nuclide characteristics and behavior
- In principle, one comparison could support dozens of CMCs at a time

Measurement Methods Matrix

- Categorized by
 - Radiation-type
 - "Primary" measurement method
- Degree of difficulty color-coded
 - Red: most difficult
 - Yellow: moderately difficult
 - Green: least difficult
- In general, CMCs can be supported by comparisons results
 - If red: all red, yellow and green nuclides in method
 - If yellow: all yellow and green nuclides in method
 - If green: only all green nuclides in method
- In general, results using one primary method can not support claims (for the same nuclide) by another method
- Secondary methods not grouped
- Uncertainties are NOT benchmarks, but are "reasonable" to expect (for CMC reviewers' aid)



Dosimetry





Dosimetry for Ionizing Radiation

Dosimetry: the measurement of quantities that describe the effects of ionizing radiation (x rays, gamma rays, neutrons and charged particles) on matter. The SI unit for Dosimetry is the Gray (Gy) = Joule/Kg



Absorbed Dose



Absorbed dose is a dose quantity which is the measure of the energy deposited in matter by ionizing radiation per unit mass. Absorbed dose is used in the calculation of dose uptake in living tissue in both radiation protection, and radiology.

Air Kerma

- kerma is an acronym for "kinetic energy released per unit mass"
- defined as the sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation in a sample of matter, divided by the mass of the sample.
- Simply the amount of energy that was deposited in the air when the photon passed through it
- Radiation beam intensity is represented by this value.

Determination of Air Kerma and Absorbed Dose

- Air Kerma and absorbed dose generally apply to any absorbing medium,
- Dosimetry standards are centered on air kerma and absorbed dose to water
 - Absorbed dose to water from suitable 60Co beams: direct realization by a water calorimeter.
 - Air kerma from suitable 192Ir, 137Cs, and 60Co beams: **direct realization by graphite walled, air-filled ionization chambers**.
 - Air kerma from suitable x-ray beams with maximum energies from 10 keV to 300 keV: **direct realization by free-air ionization chambers**.
 - Absorbed dose to water from suitable beta emitters: direct realization of absorbed dose to air by an air-ionization extrapolation chamber, then corrected to absorbed dose to water.

Medical Physics Applications

- Knowledge of **absorbed dose** allows safe and effective use of ionizing radiation in medical diagnostic (mammography) and therapeutic (external beam cancer therapy) procedures
- The traceability of radiation dose to clinical end users ensure safety and efficacy of diagnostic and therapeutic procedures that involve ionizing radiation.
 - X-ray and Gamma-ray Calibrations
 - Seed and Electronic Brachytherapy Calibrations
 - Water Calorimetry Research
 - Remote Sensing Dosimetry Research



Air Kerma Rate by Free-Air Chambers



- Correction usually applied
 - Correction for air attenuation
 - Correction for the effects of temperature, pressure, humidity
 - Correction for ionization produced by scattered photons
- Uncertainty at NMI ~0.9 %
 - End User ~ 1-4 %

Air-Kerma Rate (Gy/s) Measurement













The SI unit of dose, Gy, Air-Kerma Rate (Gy/s) as Realized by Free-Air Chambers

$$\dot{K} = \frac{I}{\rho_{\text{air}}V} \frac{W_{\text{air}}}{e} \frac{1}{1 - g_{\text{air}}} \prod_{i} k_{i}$$

- K is the air-kerma rate at a given distance in air.
- $I / (\rho_{air} V)$ is the measured ionization current divided by the mass of air in the measuring volume.
- W_{air} is the mean energy expended by an electron of charge *e* to produce an ion pair in dry air. The value used at NIST is $W_{air}/e = 33.97$ J/C.
- g_{air} is the fraction of the initial kinetic energy of secondary electrons dissipated in air through radiative processes, which is 0.0 (negligible) for x rays with energies less than 300 keV.
- $P K_i$ is the product of various correction factors.



Range of corrections: 0.983-1.13 Air attenuation: 1.005-1.05

NIST technical support for the Mammography Quality Standards Act (MQSA)

Quantity	MQSA Final Regulation Citation	Regulation or Action Levels		NIST Support
Pean quality (H)(L)	000 10(a)/5)/a)	Operating Voltage (kV) 20	Minimum HVL (mm Al) 0.20	17 reference beam qualities between
Beam quality (HVL)	900.12(e)(5)(<i>W</i>)	25 30	0.25 0.30	. 23 kVp and 40 kVp
Dose	900.12(e)(5)(vi)	Cannot exceed 3.0 mGy (0.3 rad) per exposure		Air-kerma calibration
Instrument calibration	900.12(e)(12)	Instruments used by medical physicists in their annual survey to measure the air kerma or air kerma rate from a mammography unit shall be calibrated at least once every 2 years and each time the instrument is repaired. The instrument calibration must be traceable to a national standard and calibrated with an accuracy of ±6 percent (95 percent confidence level) in the mammography energy range.		Air-kerma calibration and technical support to calibration facilities
Radiation output	900.12(e)(5)(x)	Minimum output of 4.5 mGy/s using Mo/Mo28 at any SID where the system is designed to operate with the detector center located 4.5 cm above the breast support surface with compression paddle in between. After October 28, 2002, the system, under the same measuring conditions shall be capable of producing a minimum output of 7.0 mGy/s.		Air-kerma calibration
Traceability	900.2(xx)	Instrument must be calibrated at either NIST or at a calibration laboratory that participates in a proficiencytest with NIST at least once every 2 years and the agreement must be within +/-3 % of the NIST value.		NIST proficiency test
КVр	900.12(e)(5) <i>ii</i>	Cannot exceed +/- 5%	of indicated kVp	Proposed calibration service

Absorbed dose based on water calorimetry

- All clinical absorbed dose measurements for radiation beam therapy are traceable to the gray.
- Used to determine the ΔT from as a results of ionizing radiation
- Absorbed Dose is calculated

$$D_{w} = c_{p,w} \cdot \Delta T_{w} \cdot k_{hd} \cdot k_{ht} \cdot k_{p} \cdot k_{dd} \cdot k$$

where $c_{p,w}$ = specific heat capacity of water

• Dominant uncertainty was the non-linear temperature drifts





Examples of probe format calorimeters developed by (a) McGill University, and (b) NPL



Air-Kerma Rate for Electronic Brachytherapy

- Electronic brachytherapy sources are miniature, low-energy x-ray tubes for clinical applications
- The electronic brachytherapy calibration range determine the air-kerma of miniature x-ray sources
 - Lamperti free-air chamber (FAC),
 - Well-ionization chamber,
 - High-purity germanium (HPGe) spectrometer to



Electronic Brachytherapy Source Lab/Lamperti Free-Air Chamber



Electronic Brachytherapy Source

Radiation Protection Applications

- **Absorbed dose** monitoring of radiation workers prevents exceeding safe limits to minimize potential adverse health effects
- Traceability of radiation dose to radiation workers.
- Nearly 4 million occupational workers are monitored annually for radiation dose NCRP 160 (2006) Table 7.1, page 201
- Some Users
 - Manufacturer of Instruments
 - Radiation Workers and HAZMAT teams
 - Emergency Responders (Federal, State, Local,)
 - Coast Guard, TSA, CBP, etc
- X-ray and Gamma-ray Calibrations
- Beta Source and Instrument Calibrations

Use of Detectors Calibrated with 137Cs: " A Few examples...





Radiation workers at Nuclear Power plants monitor surroundings for radiation levels using detectors calibrated with ¹³⁷Cs

Radioactive shipments arrive at **ports of entry by cargo ships, rail and trucks**. Measurements are made with Radiation Detector instruments tested with ¹³⁷Cs



Soldiers and Military personnel wear electronic and passive dosimetry to measure potential exposure to radiation

Use of Detectors Calibrated with 137Cs: " A Few examples...



Radiation monitoring is essential at medical facilities to ensure safety of patients and medical staff. Safety is ensured by health physics staff who use **area monitors, personnel dosimetry, survey meters**, all calibrated with ¹³⁷Cs





Emergency responders monitoring radiation levels w. Radiation Detectors calibrated with ¹³⁷Cs

At Fukushima Nuclear Reactor incident

Potential radiation incident



¹³⁷Cs Irradiator Unique Properties



- ¹³⁷Cs sources provide a monoenergetic photon beam at 662 keV.
- Irradiator output: Outstanding reproducibility (~ 0.1 % over periods of months to years)
- Enable low uncertainty measurements Broad range of air kerma rates
- Long half life of 30 years.
- Practically no maintenance costs after installation. Small footprint.

Calibration of cavity chambers in ¹³⁷Cs beams

An <u>air kerma</u> calibration coefficient N_{κ} is determined for a given chamber at NIST as:

NIST reference air kerma rate from ¹³⁷Cs irradiator

lonization current produced in the chamber



The end user of the chamber can later use the value of N_{κ} (provided by NIST) to measure the air kerma rate, \dot{K}_{user} (in Gy/s) of a radiation field as:

$$\dot{K}_{user}(\frac{Gy}{s}) = N_{K}(\frac{Gy}{C}) \cdot I_{user}(C/s)$$

 $N_{K}(\frac{Gy}{C}) = \frac{\dot{K}_{NIST}(\frac{Gy}{S})}{I_{NIST}(\frac{C}{S})}$



¹³⁷Cs Irradiator



Consider for Uncertainty Analysis

- Wall and collector thickness
- Total thickness
- Ionization current
- Chamber orientation
- Volume determination
- saturation, scatter

Rodriguez et al., Health Physics, 85, 2003

Reproducibility provided by ¹³⁷Cs Irradiators

It is important for **measurement uncertainties** provided by primary calibration facilities to be low to minimize propagation down the traceability chain. For this, the output of the irradiator source needs to be reproducible over long periods of time (months, years)

1.0 Percentage difference relative to first measurement (%) 0.5 0.0 -0.5

Jan-03

-1.0

Jan

-97

Jan-00

 N_{K} measured over years for a given reference chamber

Jan-06

Jan-09

Jan-12

Jan-15

Reproducibility of the ¹³⁷Cs irradiators is reflected in the reproducibility observed over years of the air kerma coefficient N_K of reference class chambers calibrated in these gamma-ray beams

Radiation Processing Applications

- Measurement of **absorbed dose** in radiation processing plants ensures adequate sterilization of medical devices while avoiding product damage
- Traceability of radiation dose to industrial processing.



Radiation com



Radiation Sterilization Materials Modification Food Irradiation

Alanine Dosimeters

- Alanine dosimeters are used to measure absorbed doses of ionizing radiation.
 - Crystalline material
 - Absorbed energy is bonded
 - Measured in an EPR spectrometer.
 - Energy recovered
- Used in gamma, electron beam, or X-ray applications that require a dose range from <10Gy to 150kGy,
- Used in industrial processes such as medical device sterilization, and food irradiation.



Electron Paramagnetic Resonance

Electron paramagnetic resonance (EPR) or electron spin resonance (ESR) spectroscopy

- detect atoms and molecules containing unpaired electrons
- Provides in-situ and non-destructive information on electron spins, orbitals, and nuclei at the microscopic scale.



Homeland Security Applications

 Develop and validate standards for technical performance and radiation safety for detection of bulk-explosives and other contraband.



Meeting Executive and Legislative requirements for 100 % screening of baggage, cargo, and airline passengers



Scope:

Consensus documentary standards, test methods, and test artifacts for technologies for all venues that employ screening for bulk explosives & other contraband: checkpoints, checked baggage, cargo/vehicle, human-subject, and bomb-squad applications.

<u>**Deliverables:**</u> Development, validation, revision of a standards infrastructure

Comparisons in Dosimetry

- Currently, 78 comparisons in x and gamma rays, and electrons measurements (dosimetry) are listed in the Key Comparison Database (KCDB; Appendix B)
- Comparisons include
 - SIM, EURAMET, COOMET, APMP, CCRI(I), BIPM, AFRIMETS, GULFMET
 - Planned, in progress, measurements complete, Draft B, approved/published, equivalence
 - Absorbed dose to water, absorbed dose rate for beta, air kerma (low and med energy, Co-60), personal dose equivalent



Recent Comparisons in Dosimetry

Comparison	Description	SIM Participants
EURAMET.RI(I)-S16	Comparison of personal dose equivalent at 0.07 mm and 3 mm depth, Hp(0.07) and Hp(3), for beta radiation	NIST, ININ, NRC
BIPM.RI(I)-K2, K7	Low energy x rays, mammography x-ray energies with tungsten anode	NIST
SIM-RI(I).K1,K4	Air Kerma and Absorbed Dose to Water in Co-60 Fields	CNEA(2019), ININ(2020), LNMRI- IRD(2022), MIEM(withdrew) CCHEN (next) then NIST
BIPM.RI(I)-K6	MV x-ray absorbed dose to water	NIST

Neutrons Measurements







Neutrons



The neutron is a subatomic particle, symbol n or n^o, which has a neutral charge, and a mass slightly greater than that of a proton. They predominantly interact via the strong interaction.

Definitions

- **Equivalent Dose** is a dose quantity representing the stochastic health effects of low levels of ionizing radiation on the human body
- **Fluence** is the radiant energy *received* by a *surface* per unit area. The SI unit of radiant exposure is the joule per square meter (J/m²)
- **Spectral fluence** is the radiant exposure per unit frequency or wavelength. The SI unit in frequency is the joule per square meter per hertz (J·m⁻²·Hz⁻¹) in wavelength is the joule per square meter per metee (J/m³)

Neutron Physics Scope



Neutron interferometry

Calibrations and Metrology:

- Neutron source calibrations
- Neutron meter calibrations
- High dose irradiations
- Absolute neutron fluence
 Standard cross sections



High dose irradiation of DNA se

Basic Physics Research:

• Fundamental neutron physics (lifetime, decay correlations, hadronic parity violation)

- Neutron interferometry
- Reactor and solar neutrinos
- Ultracold neutrons

5 Ultracold neutron production in superfluid He-4

Applied Research/Services:

- Neutron imaging
- Polarized He-3 spin filters
- Neutron detection/spectroscopy



Photon Assisted Neutron Detection

- Incident neutrons are absorbed in the ¹⁰B(n, α)⁷Li reaction.
- The daughter particles travel out of the boron thin film into a gas volume
- They excite xenon to form a short-lived excimer state which releases a far ultraviolet photon upon relaxation.
- The photon is detected by a silicon photomultiplier.
- Multiple films are used to create an optical cavity for higher photon detection efficiency.
- The number of photons produced is a function of the energy deposited by the α and ^7Li



Fast Neutrons Detection

- Technologies often infer neutron energy indirectly through effective attenuation or thermalization
- Extract incident neutron energy are complicated by the non-linear response of detection media
- Can correct for this non-linear response by segmenting the detector such that neutrons typically scatter in a single segment
- And Integrating an appropriate neutron capture isotope into the detector can provide a unique event tag and provide powerful background rejection



IllustrationoftheFaNS-1detector. Blue - scintillator, grey - lucite light guide, red -3He proportional tubes, PMTs on cylindrical light guides

T.J. Langford et al./Nuclear Instruments and Methods in Physics Research A771(2015)

Neutrons Source Emission Rate

- The emission rates (n/s) of neutron sources are measured relative to that of the National Standard Neutron Source (NBS-1) by comparison of activation of manganese in a totally absorbing manganese bath.
- NBS-1 is known from absolute beta-gamma coincidence counting of induced manganese activity with corrections for neutron capture





Personnel Protection Instrumentation

- For the dose-equivalent rate from a D2O moderated 252Cf source, the spectral fluence is based on an evaluation of Monte Carlo calculations
- Calibrations are performed in a large, mostly empty room as far from all walls as possible to minimize room return corrections.
- The emission rates of the 252Cf sources are known by comparison to NBS-I.



Californium Neutron Irradiation

- The dose-equivalent rate from a bare 252Cf source is based on the spectral fluence rate from the source and fluence-to-dose conversion factors
- The spectral fluence is known from an evaluation of experimental data.




Neutron Imaging

- Neutrons and X-rays are complementary, nondestructive, penetrating probes of matter.
- X-rays interact with the electron cloud of atoms and therefore see increasing attenuation with atomic number
- Neutrons interact with the nuclei resulting in a very scattered pattern with atomic number.



Neutrons see material differently than x-rays and other common probes

Comparisons in Neutrons

- Currently, 34 comparisons in neutron measurements (fluence, fluence rate, emission rate, ambient dose and survey meter) are listed in the Key Comparison Database (KCDB; Appendix B)
- Comparisons include
 - SIM, EURAMET, COOMET, APMP, CCRI(II), BIPM; generally fewer labs
 - Planned, in progress, measurements complete, Draft B, approved/published, equivalence
 - A variety of neutron energies reflecting various applications



Recent Comparisons in Neutrons

Comparison	Description	SIM Participants
CCRI(III)-K9.Cf.2016	Emission rate comparison of the neutron emission rate from a ²⁵² Cf source	NIST, NRC and LNMRI
CCRI(III)-K12	neutron fluence measurements in monoenergetic neutron fields	NIST and LNMRI
CCRI(III).S1	ambient dose equivalent meters	NIST(2019), NRC(2024) LNMRI(2023)
CCRI(III)-S2.Hp(10)	personal dose equivalent meters in ISO neutron fields	NIST, NRC, IRD, ININ

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SIM **METROLOGY SCHOOL**

Thanks!

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