Radioxenon Detection via Beta-Gamma Coincidence Technique

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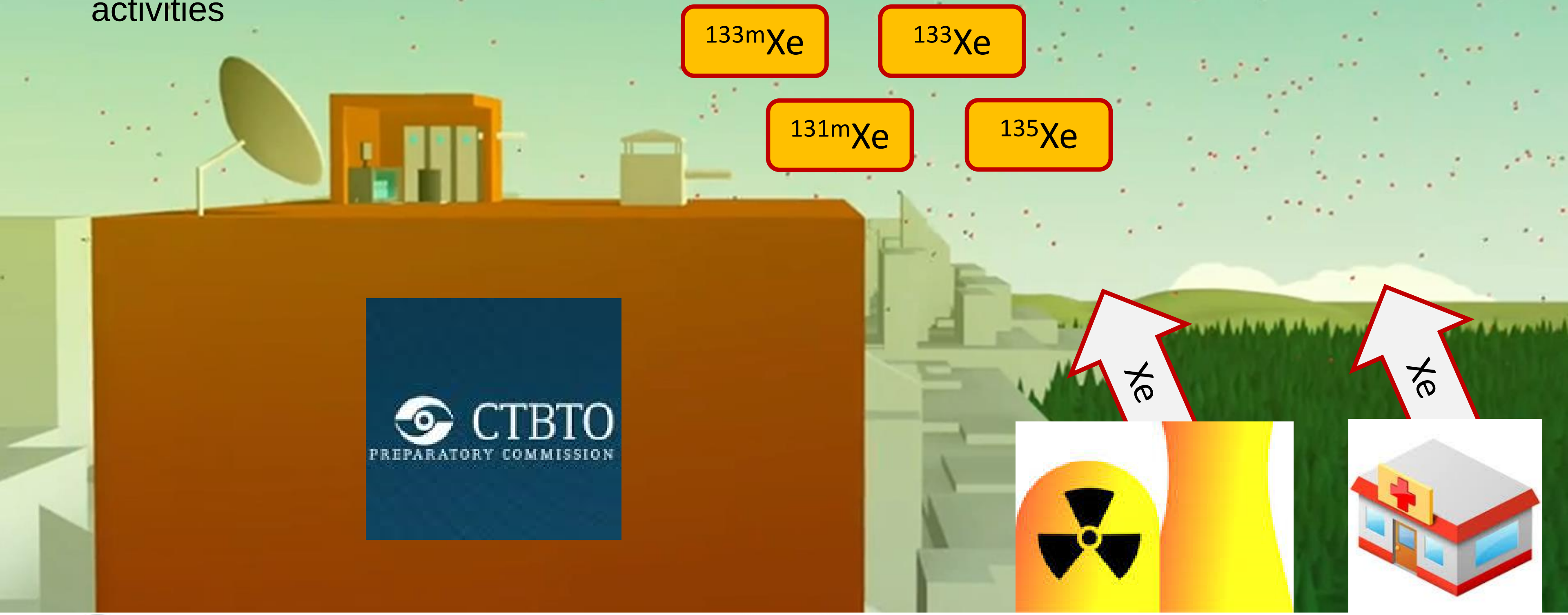
Radioxenon release in a nuclear weapon test

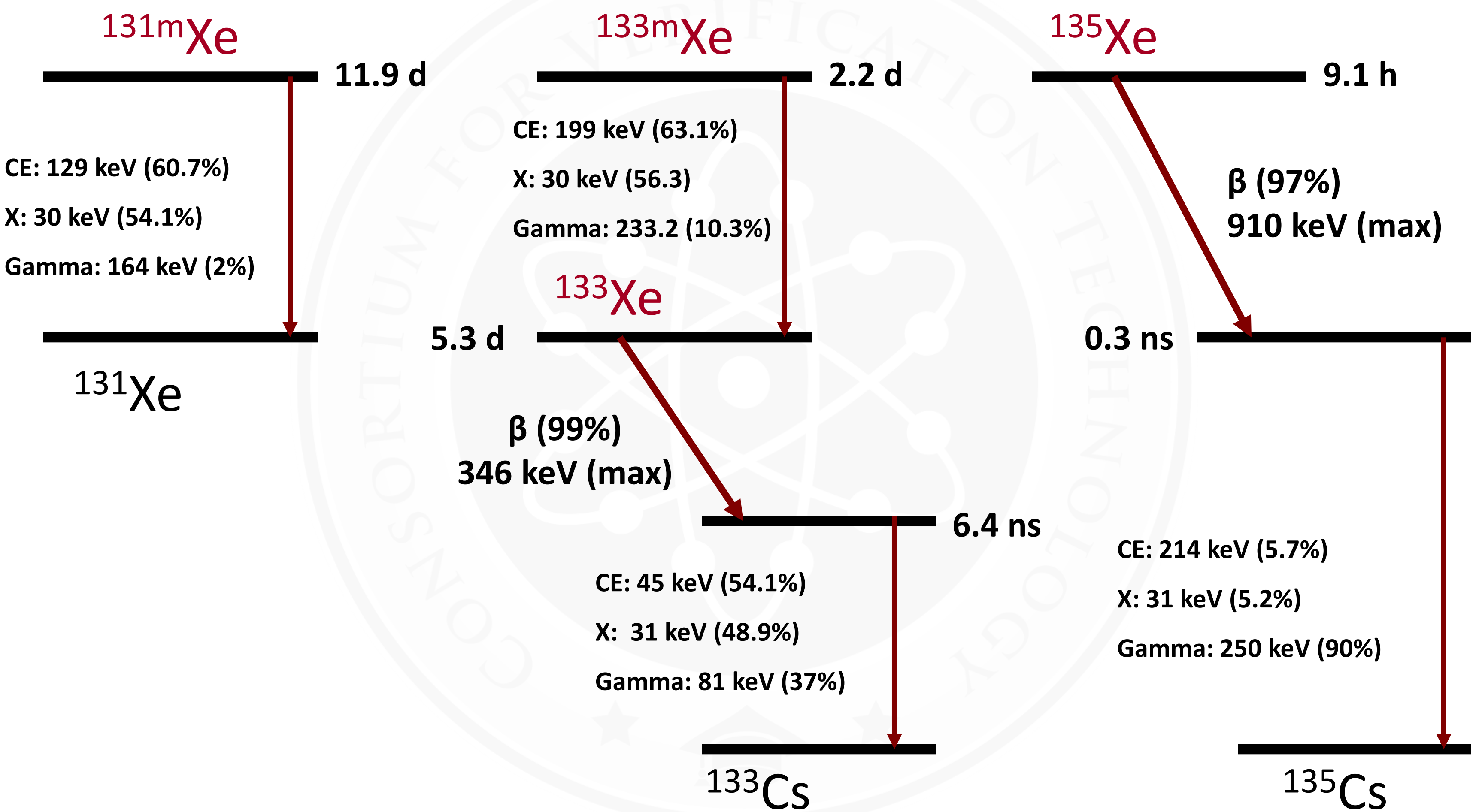
- In fission of uranium and plutonium, several isotopes of the noble gas xenon are produced in large amounts.
- Most of the isotopes are short-lived, and will decay shortly after production into other elements.
- Four isotopes are long-lived enough to be relevant for **verification purposes**:

- ^{133}Xe ($t_{1/2}$ = 5.25 d),
- ^{131m}Xe ($t_{1/2}$ = 11.9 d),
- ^{133m}Xe ($t_{1/2}$ = 2.19 d), and
- ^{135}Xe ($t_{1/2}$ = 9.14 h).

- Measurement of a single xenon-isotope is not sufficient to identify a nuclear test
- Xenon isotopes are also produced during reactor operations and in hospitals
- The dominant source of ^{133}Xe is reactor operation
- Typical mean values in areas with a high density of nuclear reactors, like Europe and North America are between 3 and 10 mBq/m^3
- The activity ratios of $^{133m}Xe/^{133}Xe$ and $^{135}Xe/^{133}Xe$ from nuclear tests are larger by a factor 100 and 10,000, respectively, than for reactor activities



Simplified Decay Schemes of ^{131m}Xe, ^{133m}Xe, ^{133}Xe and ^{135}Xe



Characteristic energies for the decay of ^{131m}Xe, ^{133m}Xe, ^{133}Xe, and ^{135}Xe

Nuclide	^{131m}Xe	^{133m}Xe	^{133}Xe	^{135}Xe
Half-life	11.93 d	2.19 d	5.25 d	9.14 h
Gamma-rays (keV)	163.9	233.2	**81.0**	**250.0**
Gamma-ray abundance (%)	1.96	10.3	37.0	90.0
X-ray, K-shell (keV)	**30.**	**30.**	**31.**	31.
X-ray abundance (%)	54.1	56.3	48.9	5.2
Beta, Max Energy (keV)	-	-	**346.**	**905.**
Beta abundance (%)	-	-	99.	97.
CE, K-shell (keV)	**129.**	**199.**	**45.**	214.
CE abundance (%)	60.7	63.1	54.1	5.7

Beta (CE) and gamma (X-ray) coincidence events

^{131m}Xe → **X-ray** (30 keV) + **CE** (129 keV)

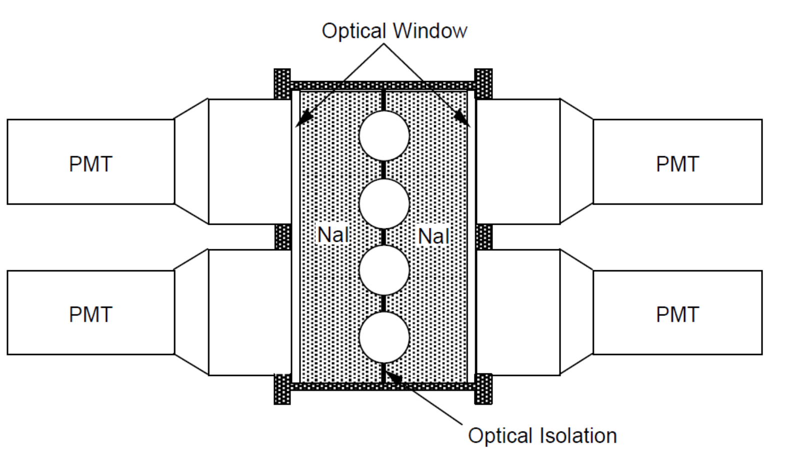
^{133m}Xe → **X-ray** (30 keV) + **CE** (199 keV)

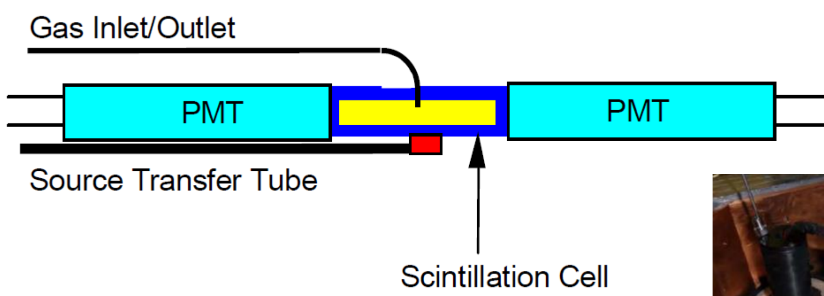
^{133}Xe → **X-ray** (30 keV) + **β+CE** (0-391 keV)
^{133}Xe → **gamma** (81 keV) + **β** (0-346 keV)

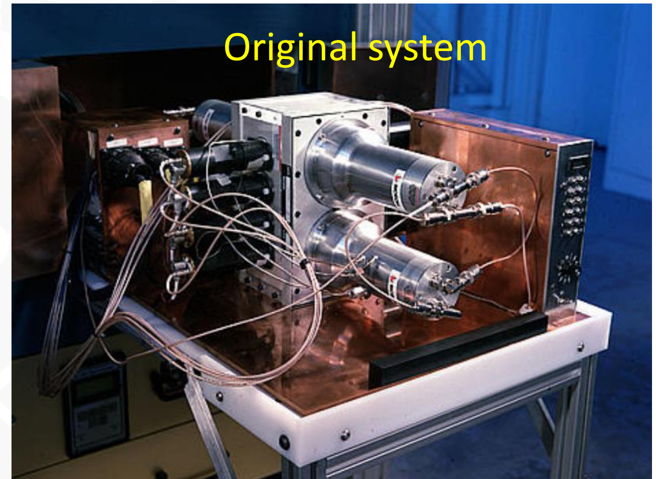
^{135}Xe → **gamma** (250 keV) + **β** (0-910 keV)

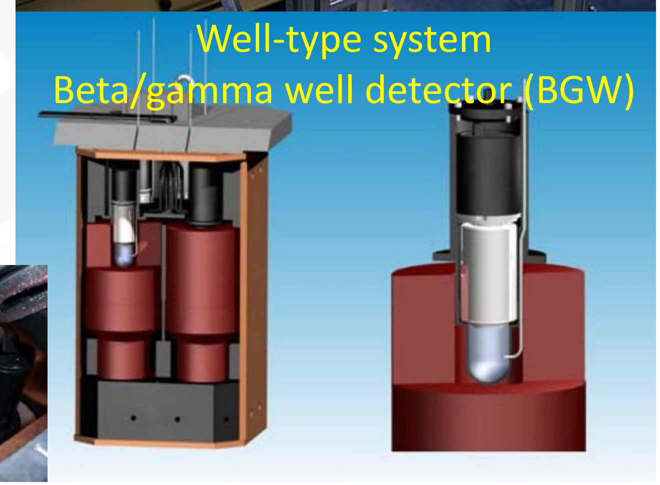
Radioxenon detectors based on β-γ coincidence

- Radionuclide Aerosol Sampler/Analyzer (ARSA) developed at PNNL
- Original and well-type (improved) versions



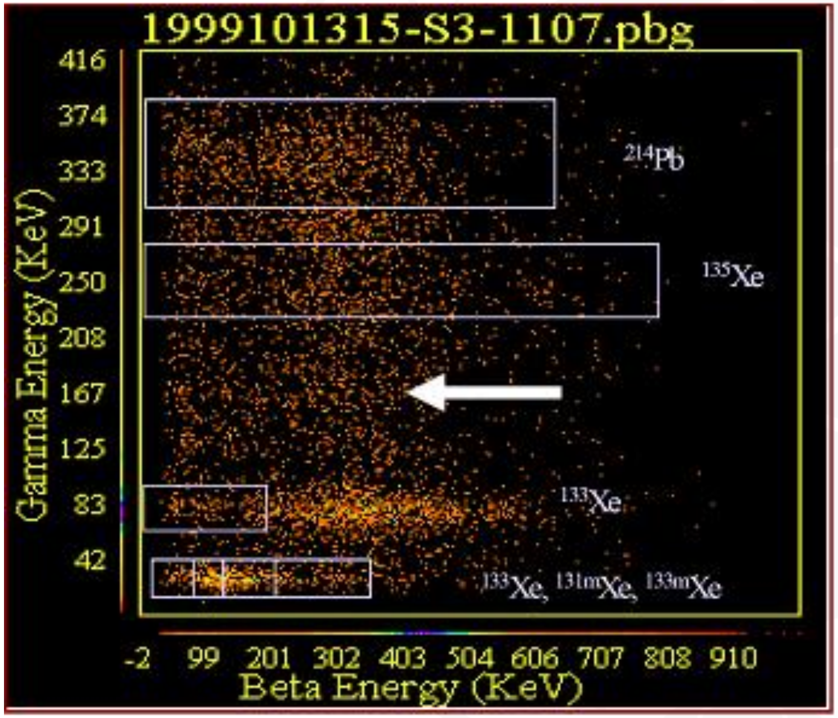


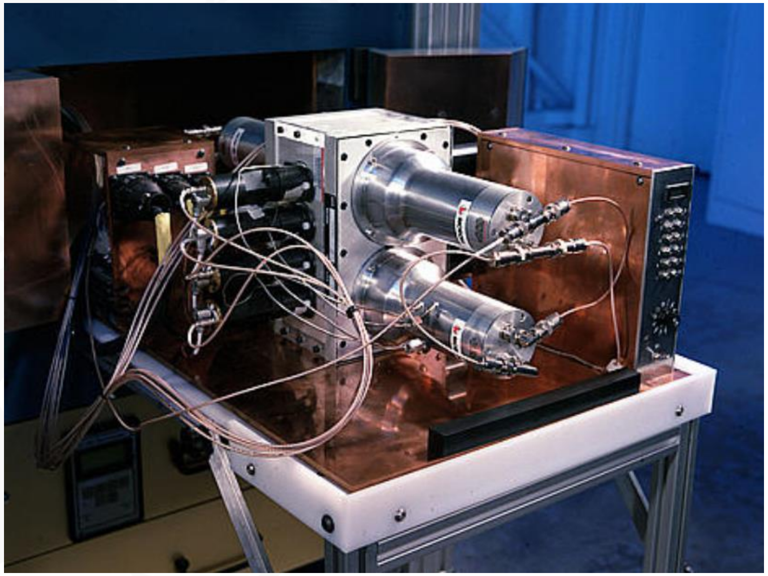




Radioxenon detectors based on β-γ coincidence

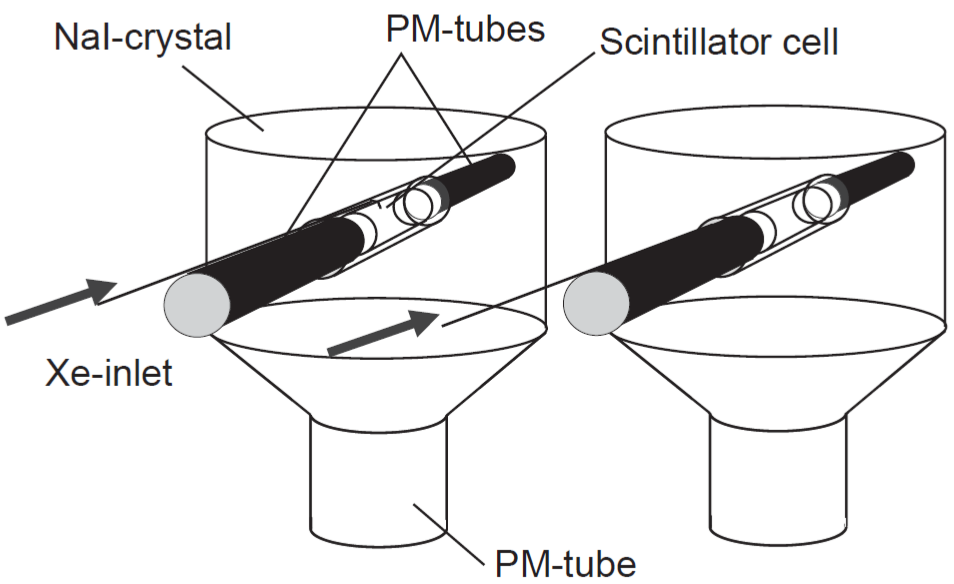
- Beta/gamma coincidence energy spectrum (ARSA)





Radioxenon detectors based on β-γ coincidence

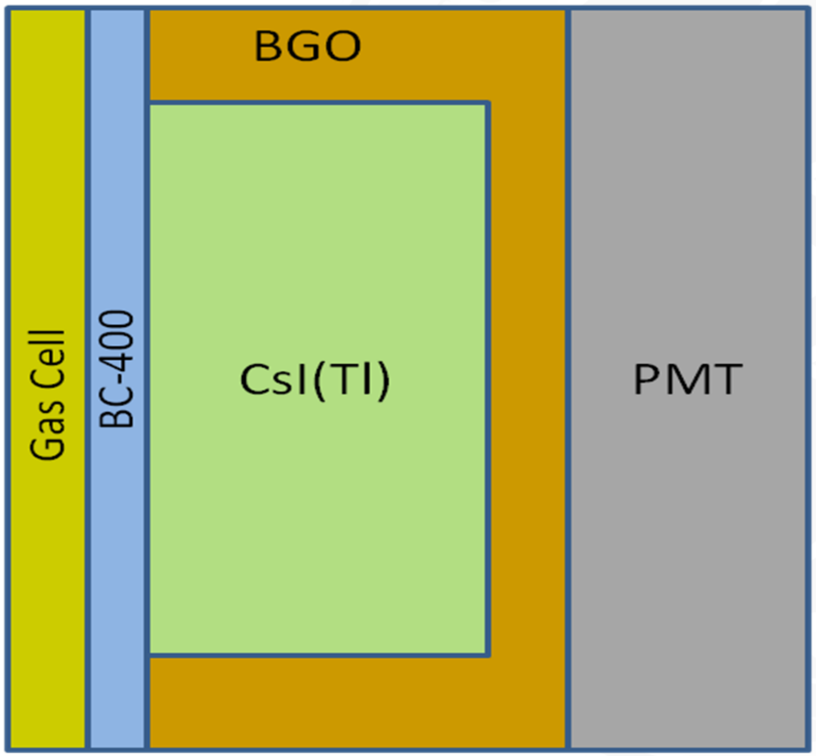
- Swedish Automatic Unit for Noble Gas Acquisition (SAUNA) developed at the Swedish Defense Research Agency

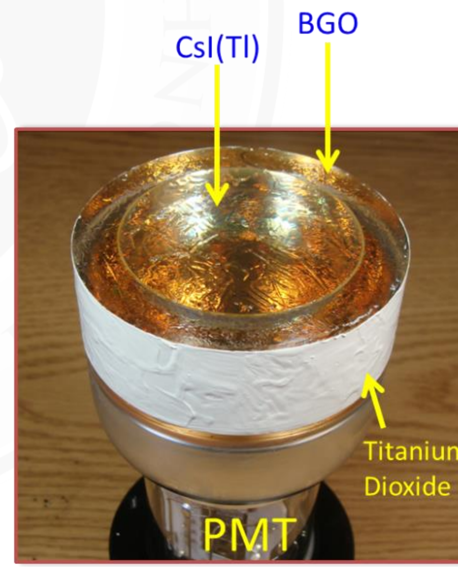


Radioxenon detectors based on β-γ coincidence

- Actively Shielded Phoswich Detector (ASPD) developed at OSU
- A triple-layer phoswich detector with Compton suppression capability
- Planer and well-type ASPD

Scintillator	BC-400	CsI(Tl)	BGO
Decay time (ns)	2.4	~1000	300
Light output (photon/MeV)	13,000	65,000	8200
Peak emission (nm)	423	540	480
Refractive Index	1.58	1.8	2.15
Density (g/cm^3)	1.032	4.51	7.13





Well-type Actively Shielded Phoswich Detector (WASPD)

Scintillator	BC-400	CsI(Tl)	BGO
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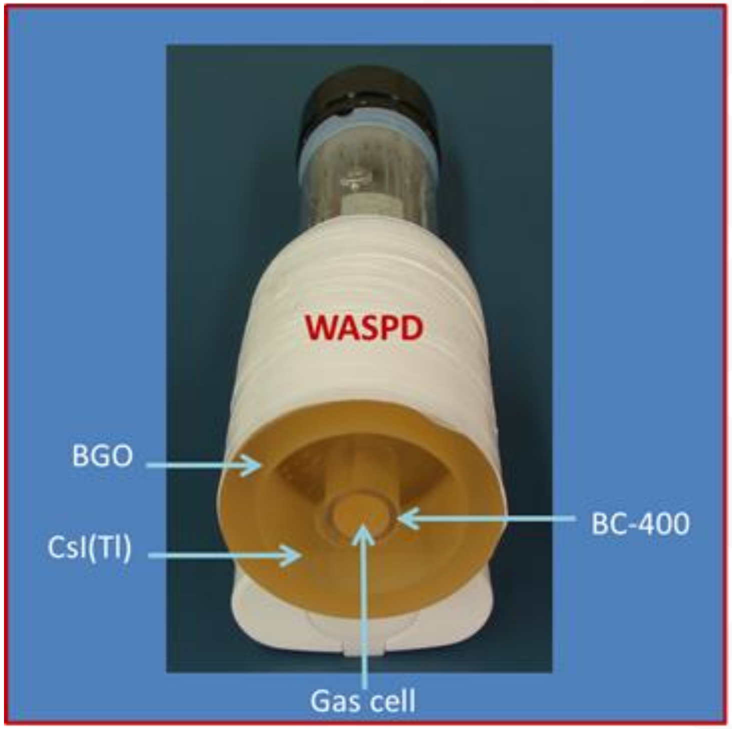
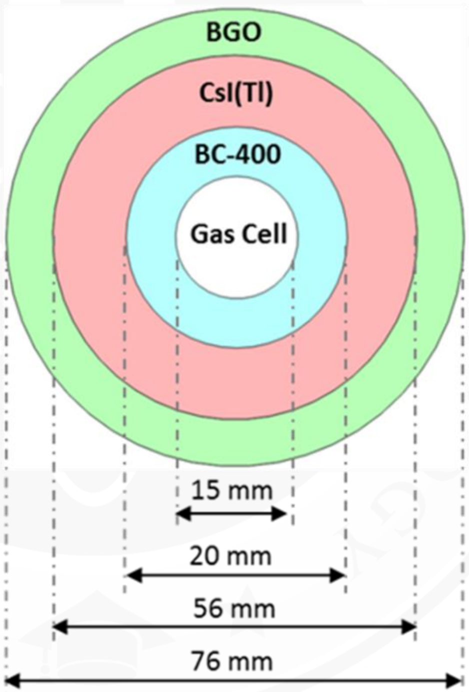
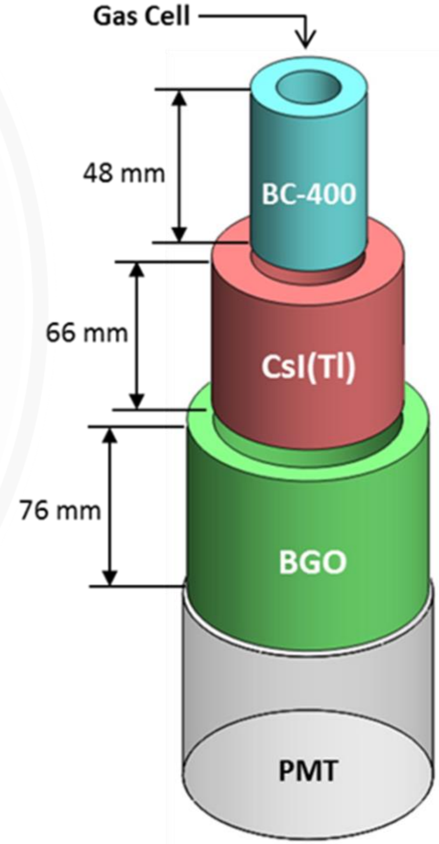
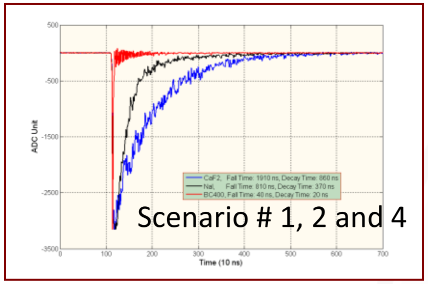


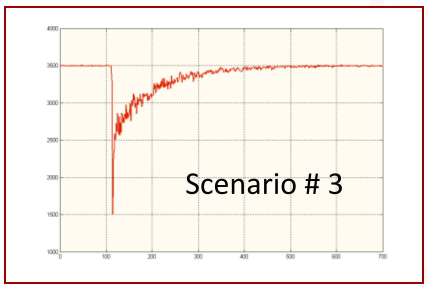


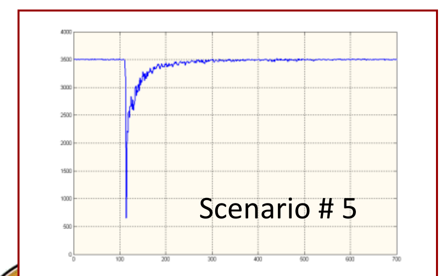


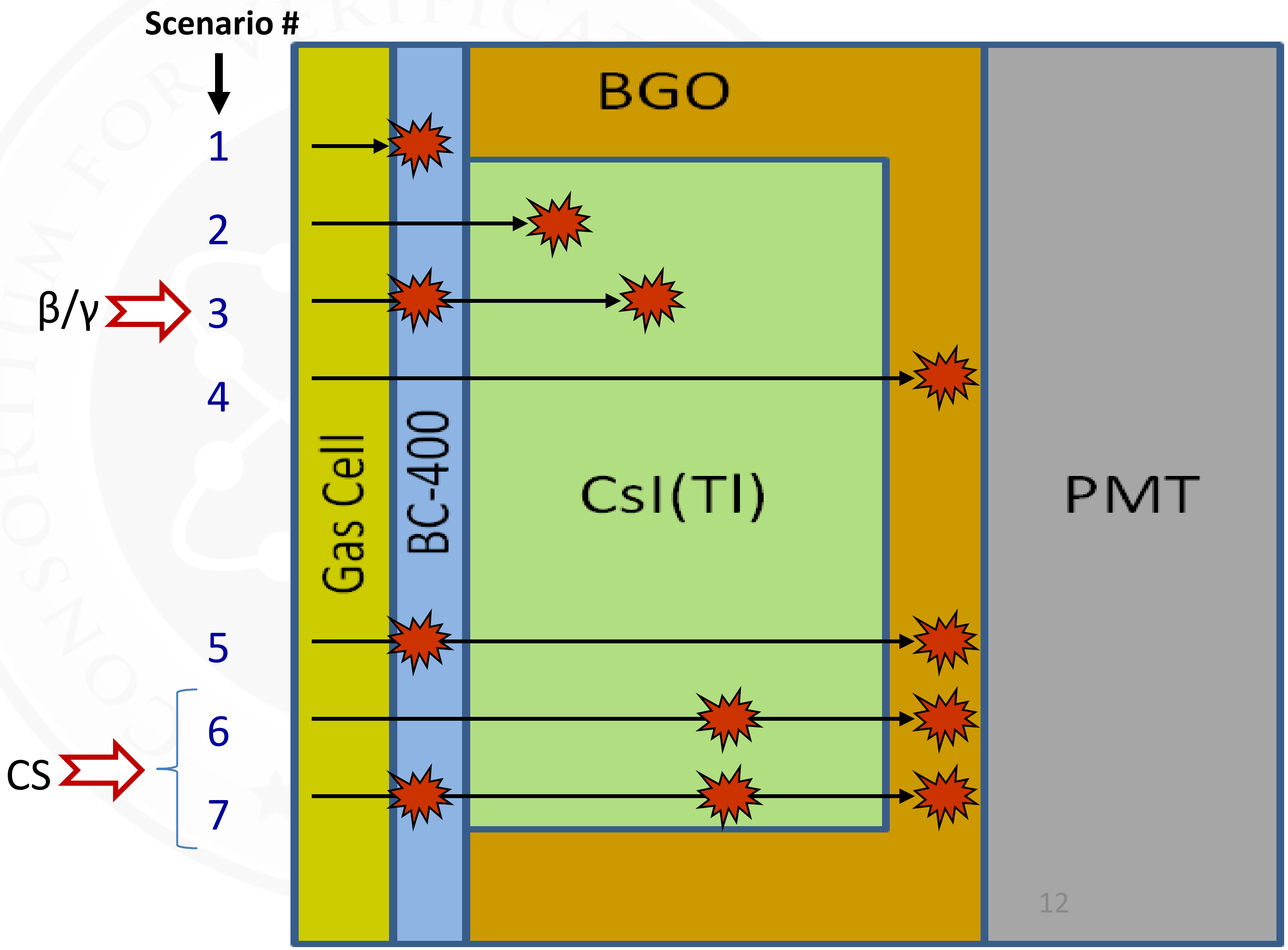
Digital pulse-shape discrimination (concept)

- From three scintillators, seven possible pulse shapes or types could be generated.



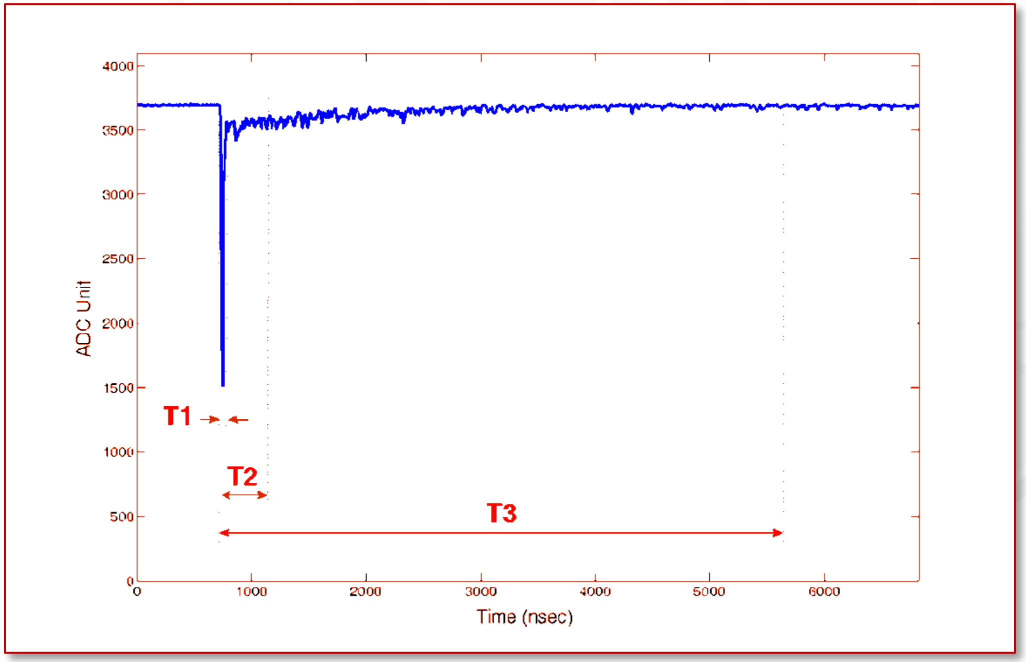






Digital pulse-shape discrimination (method)

- To discriminate between different pulse shapes, each anode pulse is integrated over three time intervals (T1, T2 and T3).
- S1, S2 and S3 represent the integration of each pulse over T1, T2 and T3 time intervals, respectively.
- Fast and Slow Component Ratios (FCR and SCR)

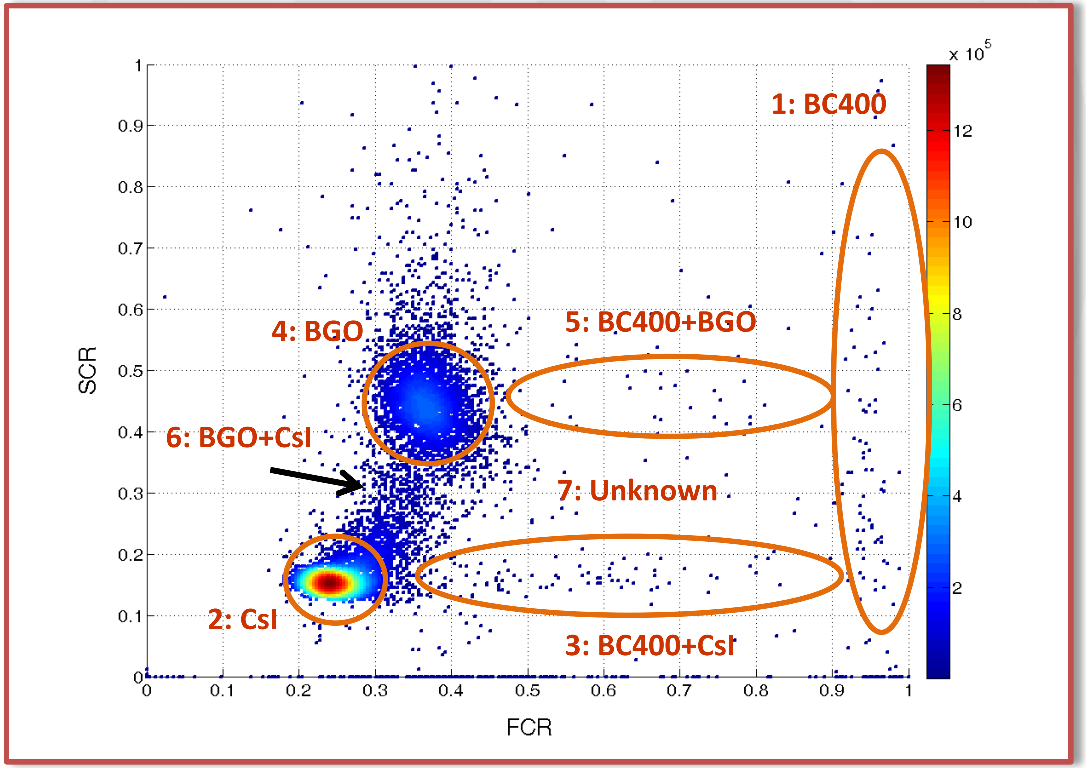


$$FCR = \frac{S1}{S2}$$

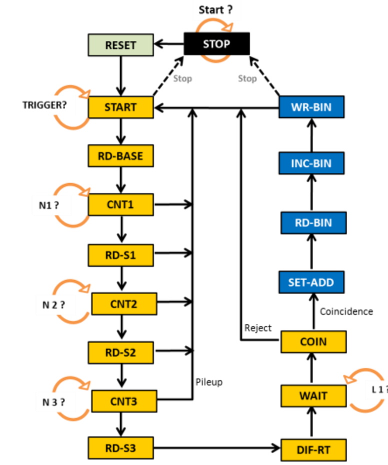
$$SCR = \frac{S2 - S1}{S3 - S1}$$

Digital pulse-shape discrimination (method)

- Scatter of Fast and Slow Component Ratios from ^{137}Cs (shielded against beta)
- Seven marked regions correspond to seven pulse shapes, indicating how gamma-rays interact with the three layers of phoswich detector

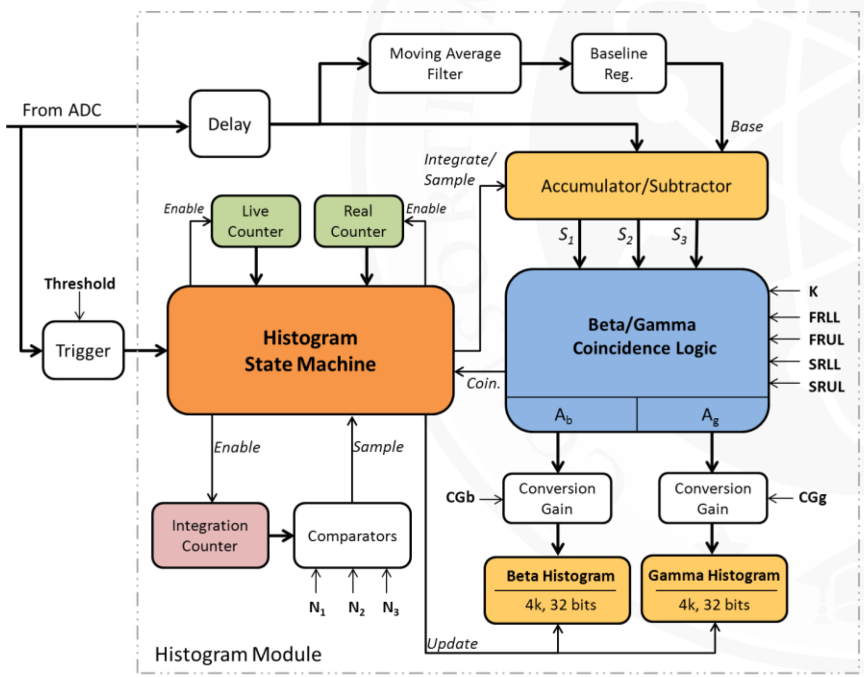


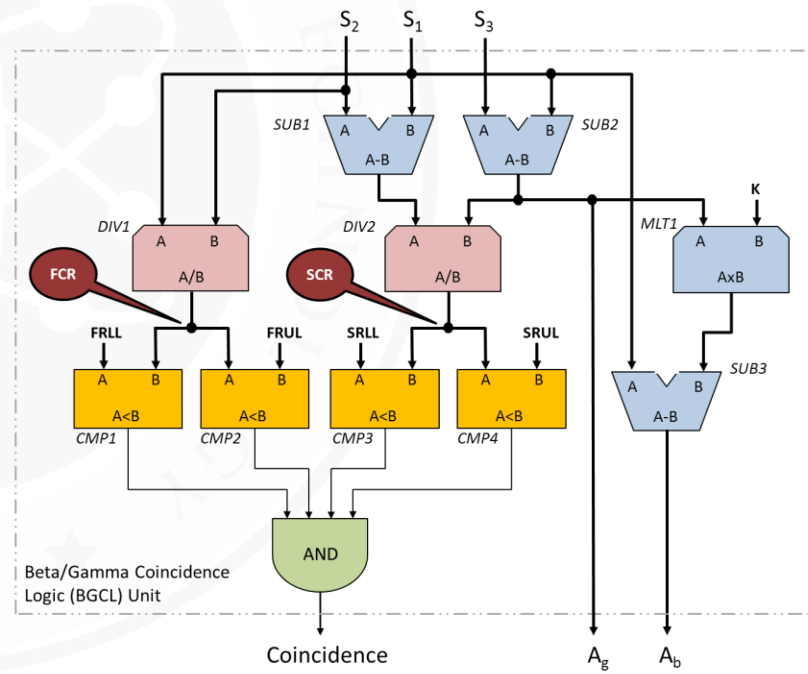
Real-time Digital Measurements in a FPGA Device



Histogram State Machine

- Real-time digital pulse-shape discrimination
- Real-time beta/gamma coincidence energy measurement





Background count rates in WASPD and in other radioxenon detectors

Detector	Background count rate (cps)	
	All events	Coincidence events
WASPD*	1.26	0.02
ASPD (a planar version of WASPD)	3.29	0.06
SAUNA (Sweden)	7.5-12	0.03
ARSA (PNNL)	30	0.1
BGW (PNNL)	5.5	0.025
PW5 (XIA LLC)	3-8	0.02-0.08

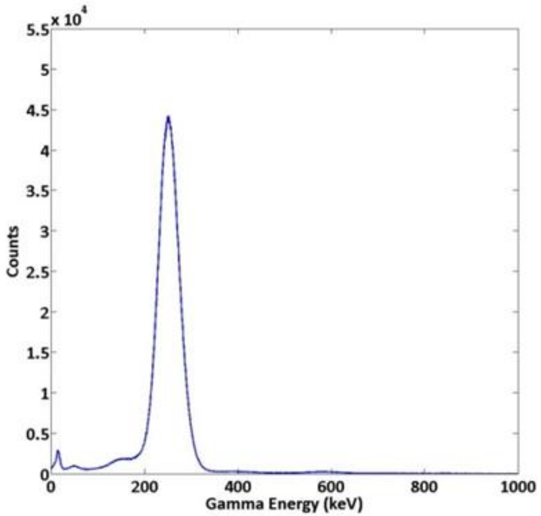
* The background count rates for all and coincidence events were measured for 24 hours while the detector was in a lead enclosure with a wall thickness of 5.0 cm.

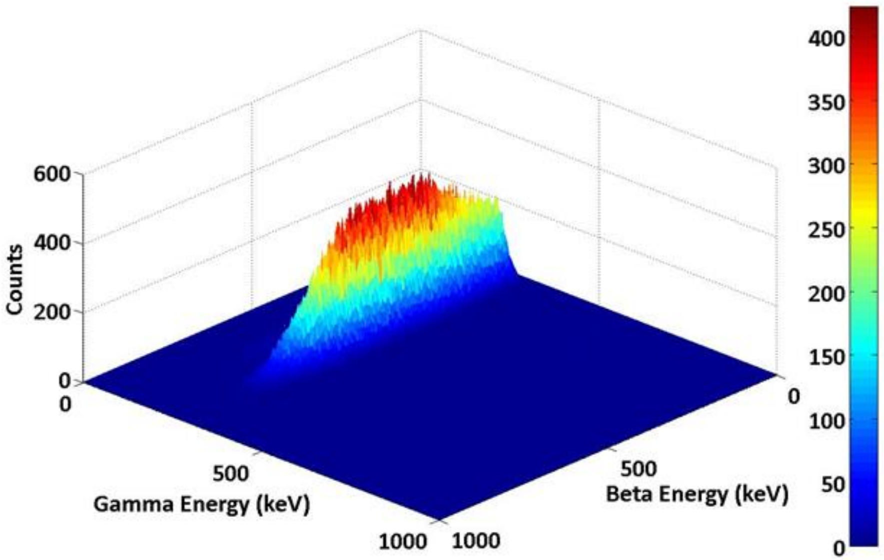
Radioxenon measurements with WASPD

To test the detector, 3 ml of stable and highly enriched (>99%) isotopes of ^{130}Xe, ^{132}Xe and ^{134}Xe were irradiated in thermal column of the OSU TRIGA reactor with a thermal neutron flux of ~7×10^{10} $n.cm^{-2}.sec^{-1}$.

^{135}Xe measurements

- ^{135}Xe emits 250 keV gamma-rays in coincidence with beta particles (E_{max} = 905 keV).

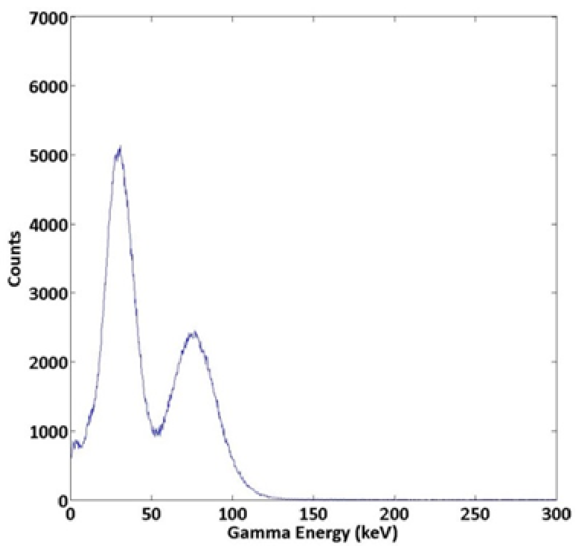


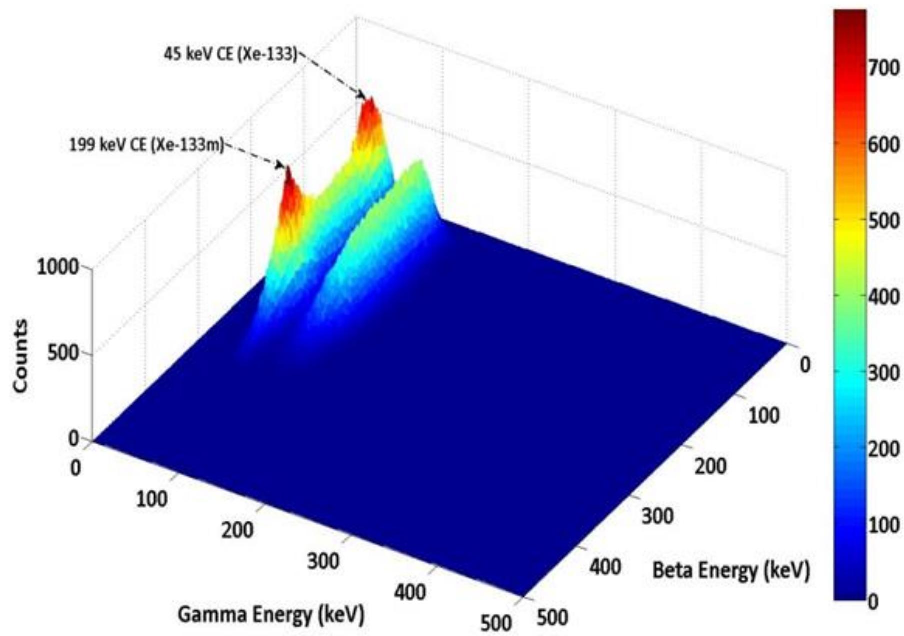


Radioxenon measurements with WASPD

^{133}Xe / ^{133m}Xe measurements

- ^{133}Xe emits 31 keV X-rays in coincidence with beta particles (E_{max} = 346 keV) and conversion electrons (45 keV) and 81 keV gamma-rays in coincidence with beta particles (E_{max} = 346 keV).
- ^{133m}Xe emits 31 keV X-rays in coincidence with conversion electrons (199 keV).

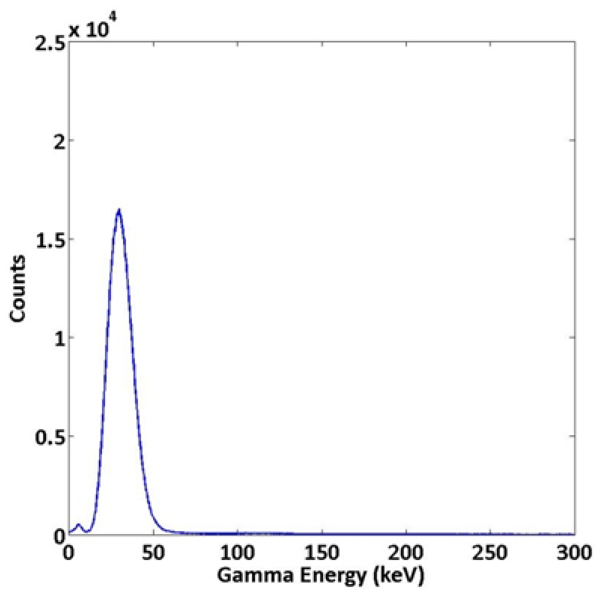


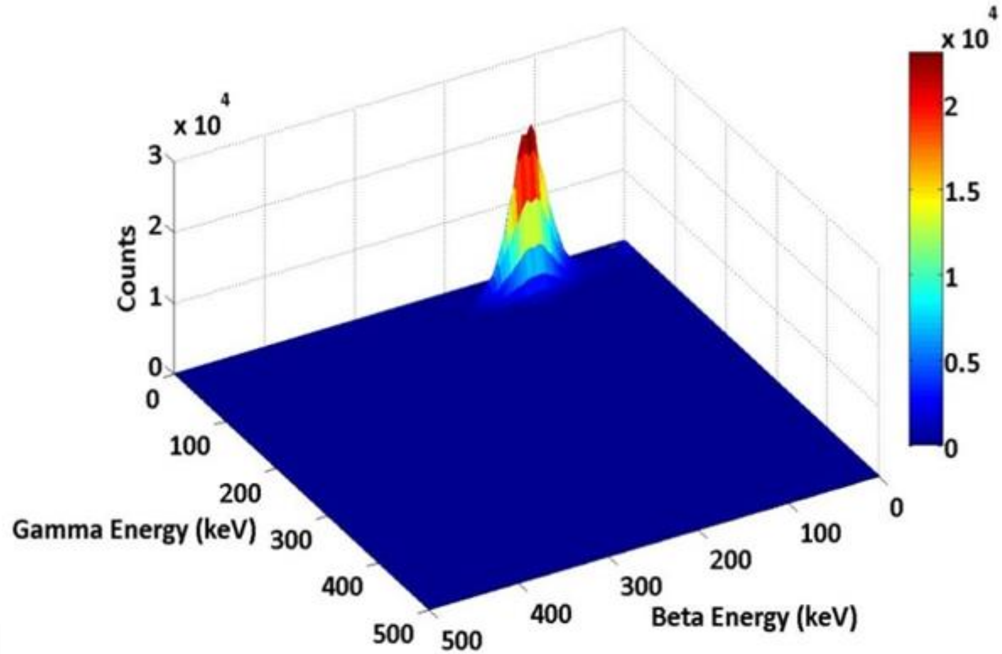


Radioxenon measurements with WASPD

^{131m}Xe measurements

- ^{131m}Xe emits 31 keV X-rays in coincidence with conversion electrons (129 keV).





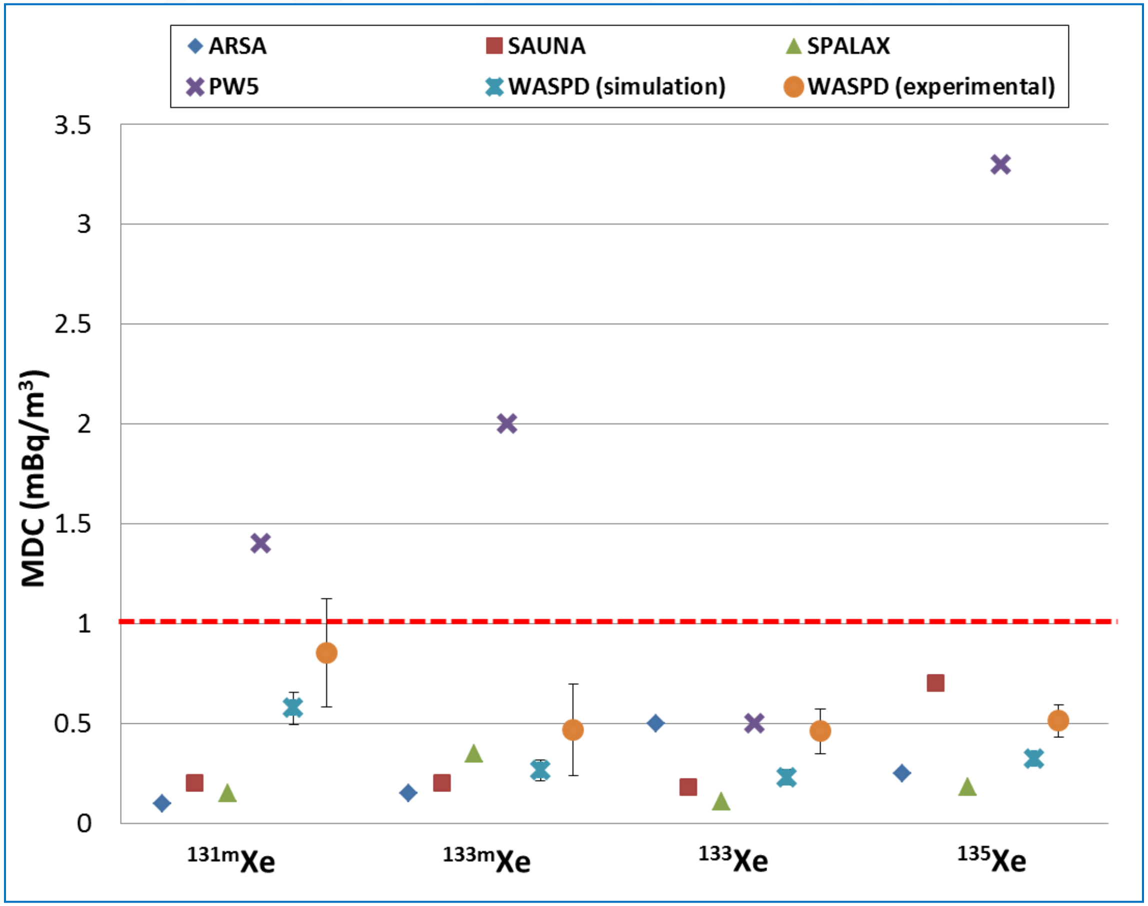
Minimum Detectable Concentration (MDC)

One important parameter in evaluating the sensitivity of the systems for atmospheric radioxenon measurement is the Minimum Detectable Concentration (MDC) for each radioxenon isotope.

The design criterion (CTBTO) for all of these radioxenon detectors is that the MDC of ^{133}Xe should be 1 mBq/m^3 or less for a 24-hour sampling period.

Minimum Detectable Concentration (MDC)

Both the simulated and experimental (preliminary) measurement results with the phoswich detector show MDC's below 1.0 mBq/m^3 for all xenon radioisotopes.



Questions?