Università degli Studi di Milano-Bicocca
Dipartimento di Fisica “G.Occhialini”

Spettroscopia gamma ad alta sensibilità

Laboratorio di Radioattività Milano-Bicocca

Spettroscopia gamma

La **spettroscopia gamma** è una tecnica radiometrica utilizzata per la determinazione della concentrazione dei radionuclidi

Analisi di tipo **qualitativo e quantitativo** del campione in esame

- Industria nucleare (Produzione di energia, Medicina…)
- Monitoraggio ambientale
- Non proliferazione
- Studio di elementi in tracce
- Neutron Activation Analisys
- Ambito scientifico (doppio beta, studio di eventi rari, astrofisica…)

Le attività del gruppo di radioattività di Milano-Bicocca

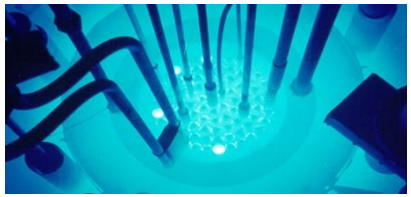
Fisica delle Particelle

- Sviluppo di rivelatori a basso fondo ad alta sensibilità per misure di radioattività
- Selezione dei materiali per esperimenti di fisica degli eventi rari

Fisica Ambientale

- Analisi del contenuto radioattivo di campioni ambientali
- Studio di elementi in tracce

Fisica Applicata

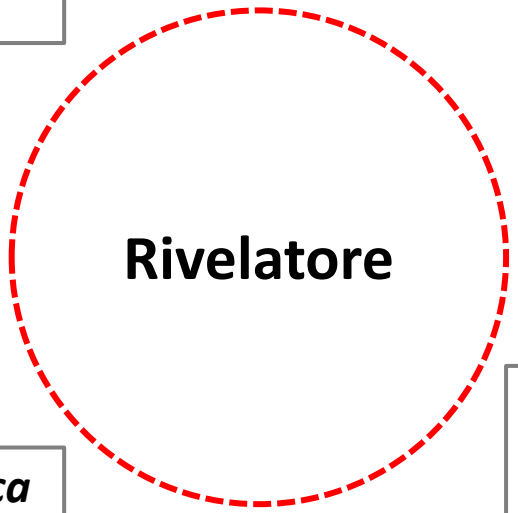


- Caratterizzazione sorgenti di neutroni
- Test danno da radiazione su componenti elettronici

Sorgenti del fondo radioattivo

Radioattività intrinseca
Eventi generati dalla radioattività U/Th/K contenuta nei materiali del rivelatore

Radioattività ambientale
Radioattività primordiale contenuta nelle strutture circostanti il rivelatore



Radon (^{222}Rn;^{224}Rn)

Raggi cosmici

Nuclei di origine antropogenica
Prodotti di fissione, Fallout radioattivo

Nuclei di origine cosmogenica
Prodotta dall'interazione dei raggi cosmici con i materiali del laboratorio

E' necessario applicare tecniche di riduzione del fondo: **PASSIVE** e **ATTIVE**

Tecniche passive di riduzione del fondo

Raggi cosmici

↓

Muoni

↙ *Neutroni*

↘ *Sciami elettromagnetici*

Radioattività intrinseca

Radioattività ambientale

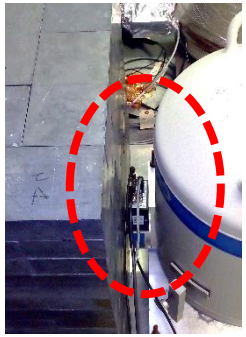
Radon

Laboratorio sotterraneo

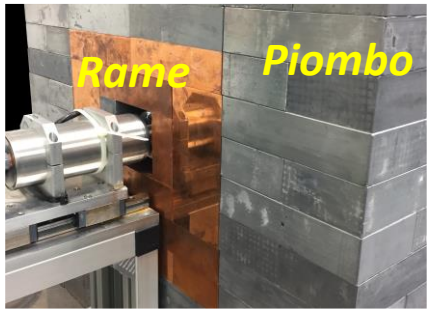
La copertura dell'edifico permette di ridurre la componente adronica, ma **non i muoni**

Selezione dei materiali

Elettronica separata



Schermatura



Radon-Box

Sensibilità: $<10^{-2}$Bq/kg

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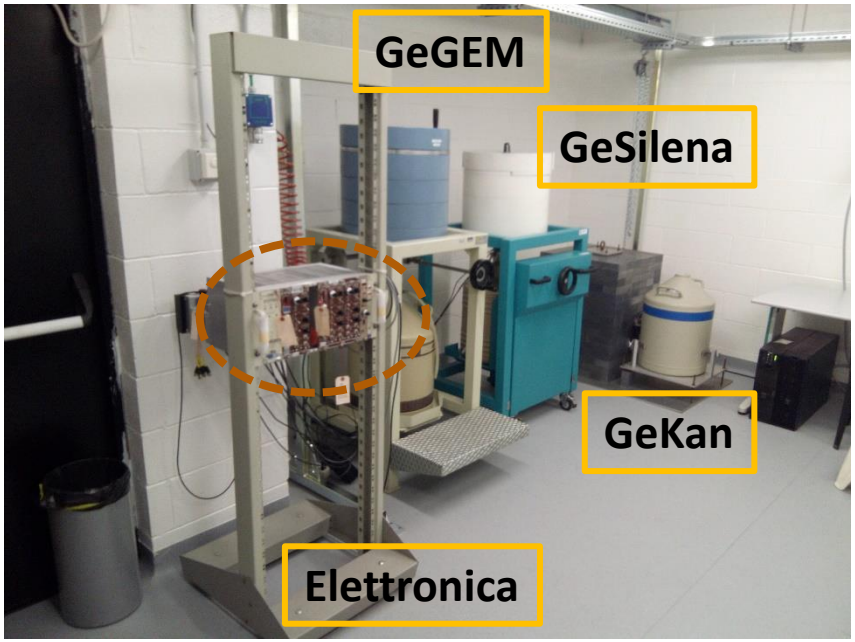


Radiazione gamma → Parte attiva del rivelatore → Catena di lettura → Spettro

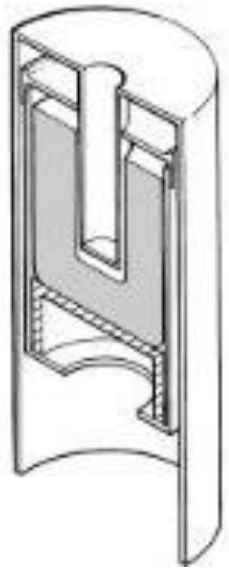
Tipologia di rivelatori HPGe

I rivelatori al germanio iperpuro sono particolarmente adatti a misure di spettroscopia gamma

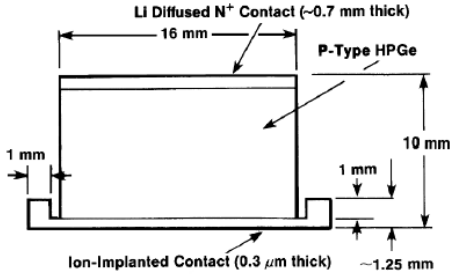
Germanio
Semiconduttore
Z= 32
ρ= 5,3g/cm^3
Band gap a 300K: 0,66eV
En coppia e-h a 77K: 2,96eV

Differenti geometrie e dimensioni

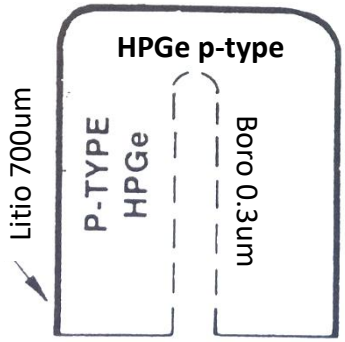
Well detector



Planare



Coassiale



Rivelatori HPGe

Range: ~keV ÷ 3600keV
Cristalli ad alta purezza
Volumi sensibili
Risoluzione Energetica <2keV

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GeSilena: ε_{rel} 30%

GeGEM: ε_{rel} 30%

GePozzetto: ε_{rel} 60%

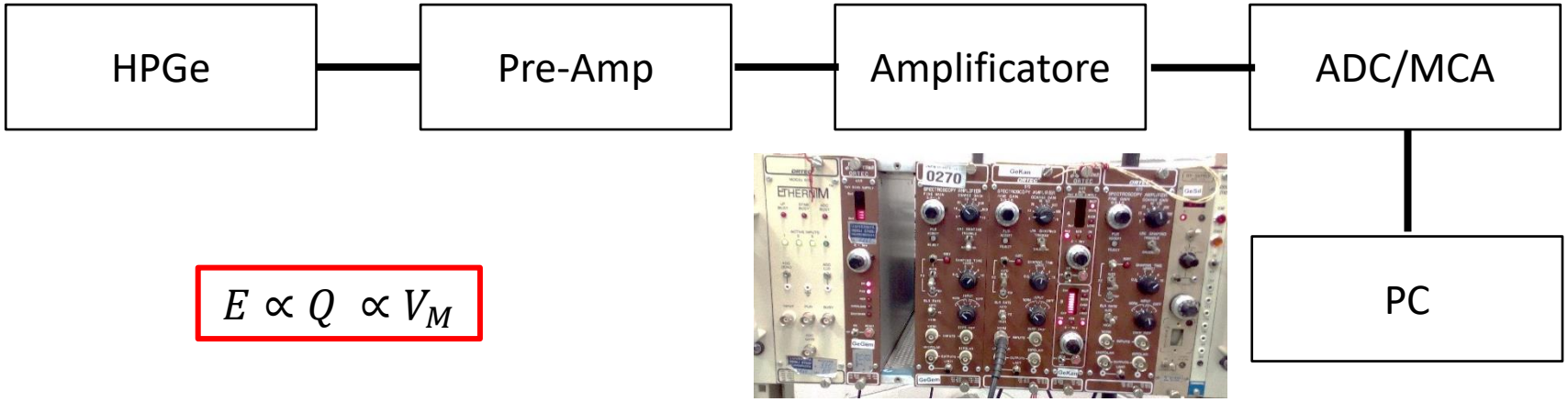
GeKan: ε_{rel} 70%

HPGe – Componenti principali

Cristallo di Germanio

Holder in rame

Catena di lettura per il trattamento del segnale



$$E \propto Q \propto V_M$$

Ottimizzazione del sistema di misura

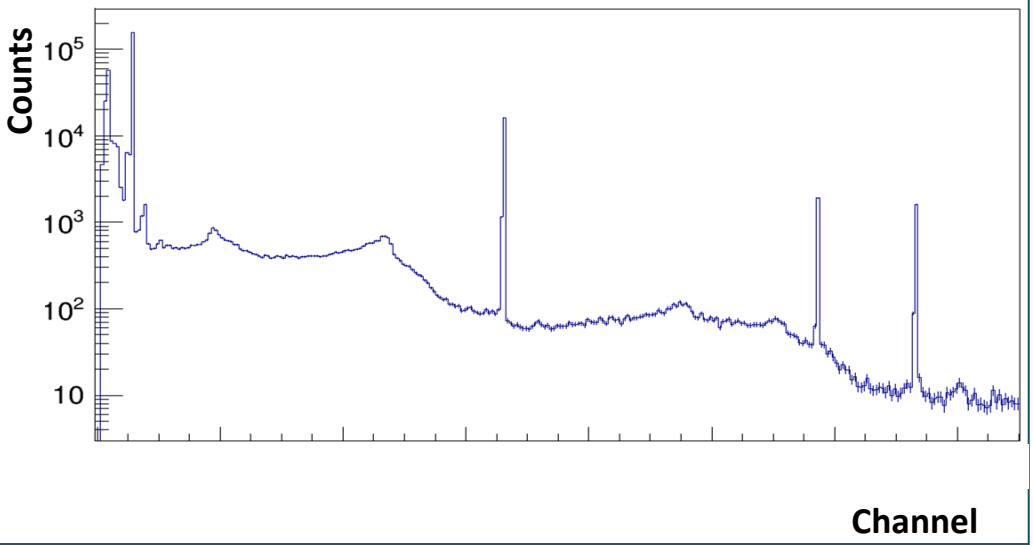
Tensione di Polarizzazione

Ottimizzazione del S/N

Calibrazione in Energia

Calibrazione in Efficienza

Spettro Differenziale



Tensione di polarizzazione

Scelta della corretta differenza di potenziale applicata ai capi del rivelatore

1 ÷5kV

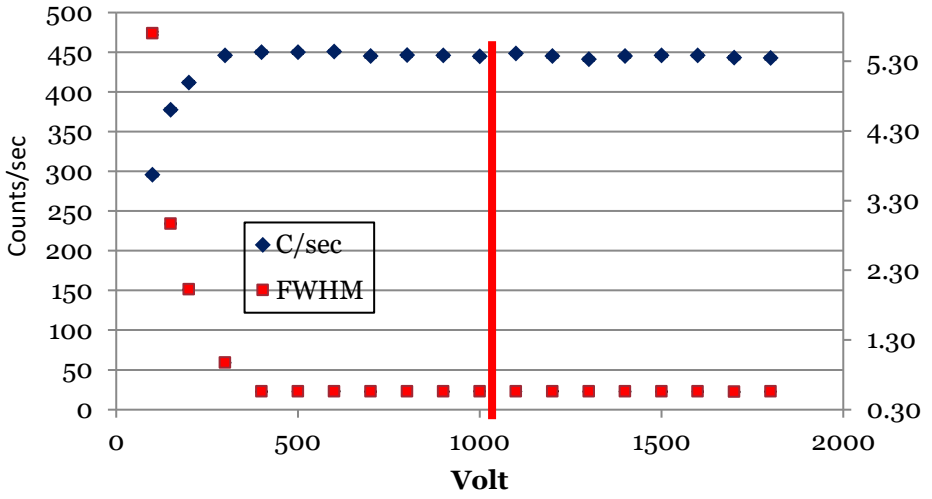
Volume attivo

$$d = \left(\frac{2\epsilon V}{eN}\right)^{1/2}$$

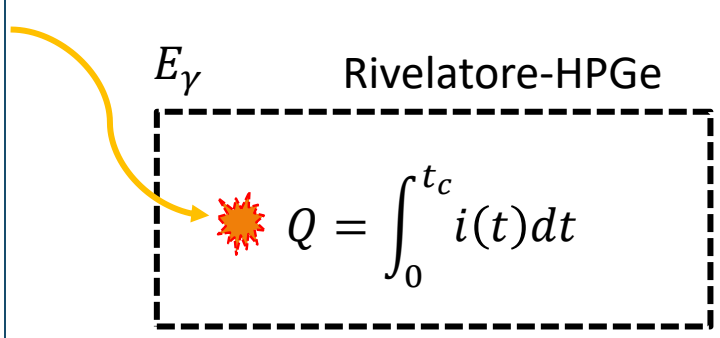
Campo Elettrico

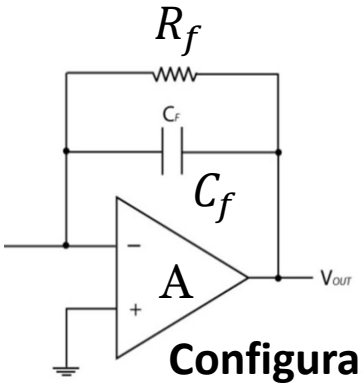
Evita ricombinazione

Raccolta completa



Pre-Amplificatore di carica





$$V_{out} \cong -\frac{Q}{C_f}$$

La carica prodotta viene raccolta attraverso il campo elettrico agli elettrodi e inviata al pre-amplificatore

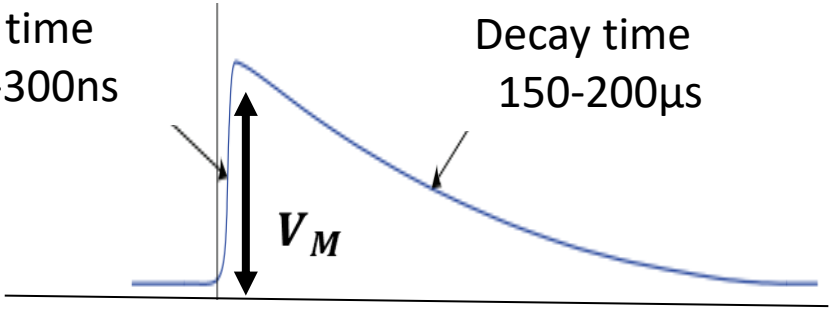
Configurazione PopTop

HPGe

Elettronica

Configurazione Low Background

Segnale preamplificato



In uscita ho un segnale a coda lunga

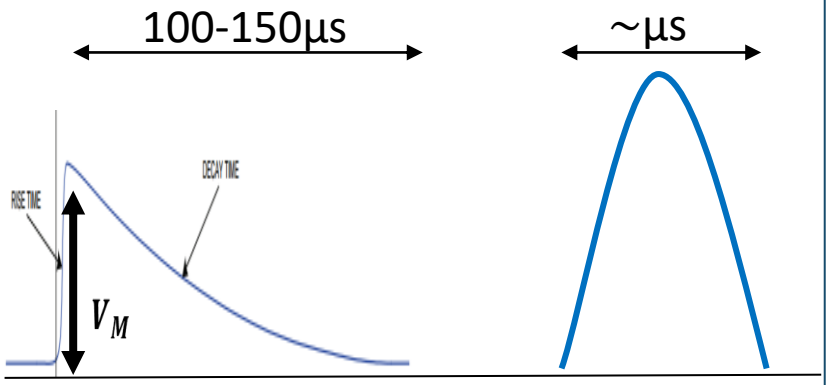
Amplificatore

Guadagno

Pre-Amp [mV] ➡ Volt

Dinamica ADC/MCA 0÷10V

Formatura del segnale



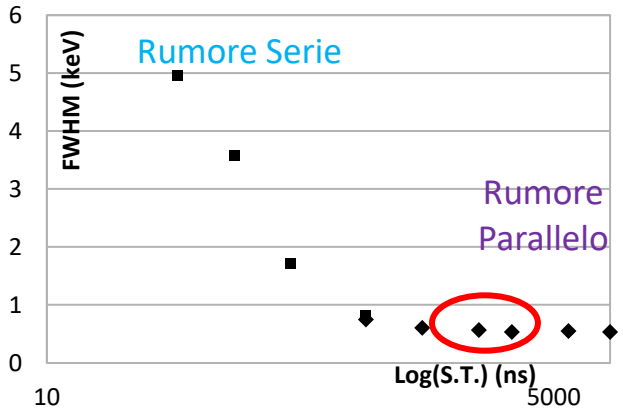
Gaussiana- CR-$(RC)^n$

Ottimizzazione rapporto S/N

$$R=\frac{FWHM}{E}$$

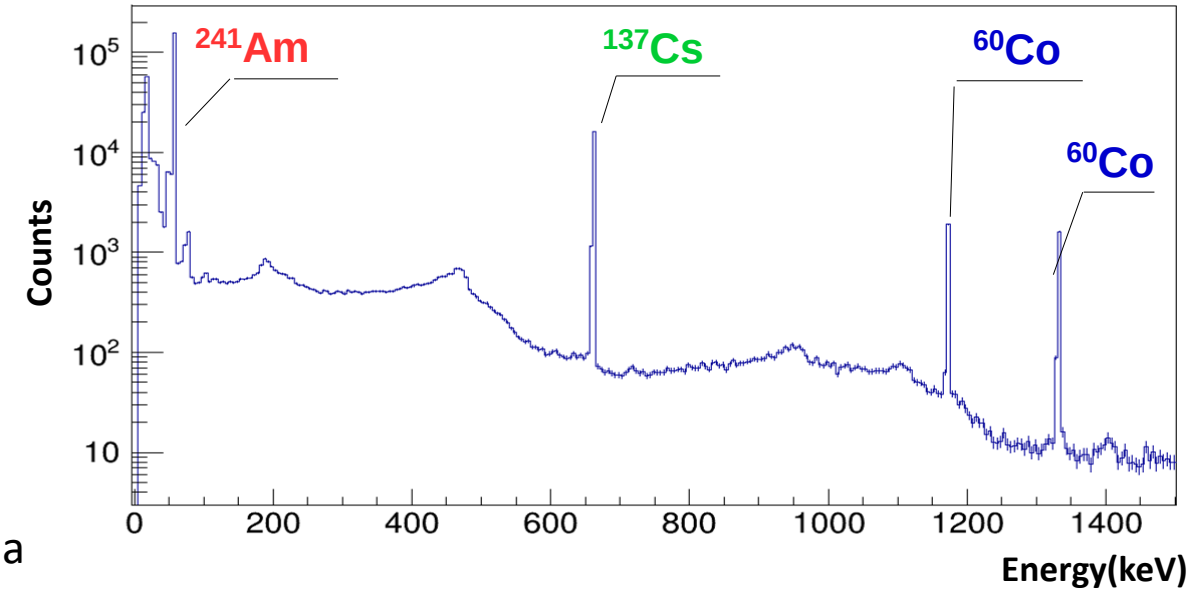
$$FWHM_{Tot}^2 = FWHM_{Stat}^2 + FWHM_{Elett}^2 + FWHM_{Drift}^2$$

$$FWHM_{Elettr}^2 = 2.35 \cdot \varepsilon \cdot \mathrm{ENC} \Rightarrow ENC \propto \left(\alpha \frac{C_{tot}^2}{\tau_{sh}} + \beta \tau_{sh} I_d\right)^{\frac{1}{2}}$$



Calibrazione in energia

Determinazione di una relazione tra la posizione del picco nello spettro e la corrispondente energia gamma

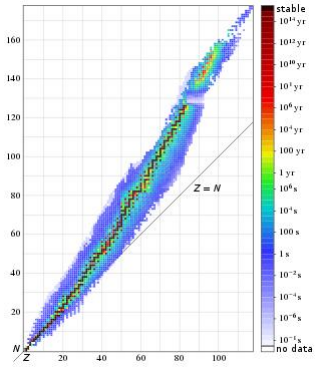


Multi-Gamma certificata

Nuclide	E_γ[keV]	BR[%]
^{241}Am	59.5	39.9
^{137}Cs	661.7	85.1
^{60}Co	1173.2	99.9
^{60}Co	1332.5	99.9

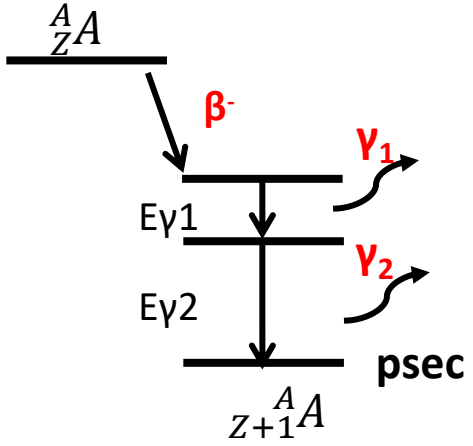
http://nucleardata.nuclear.lu.se/toi/

https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

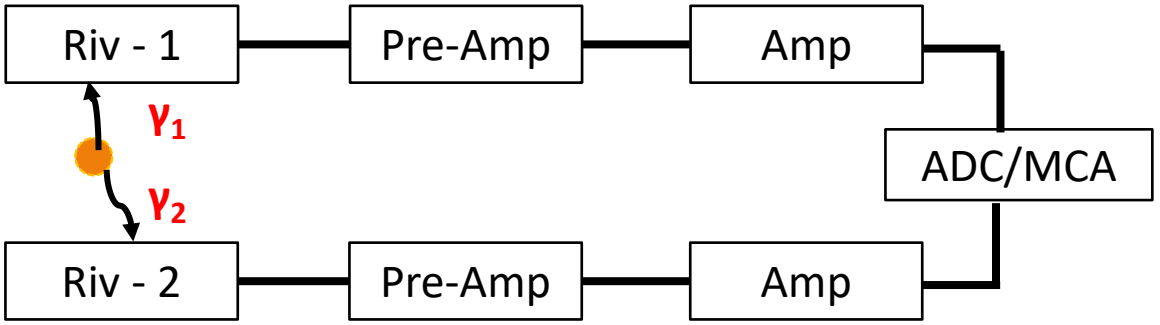


Tecniche attive di riduzione del fondo

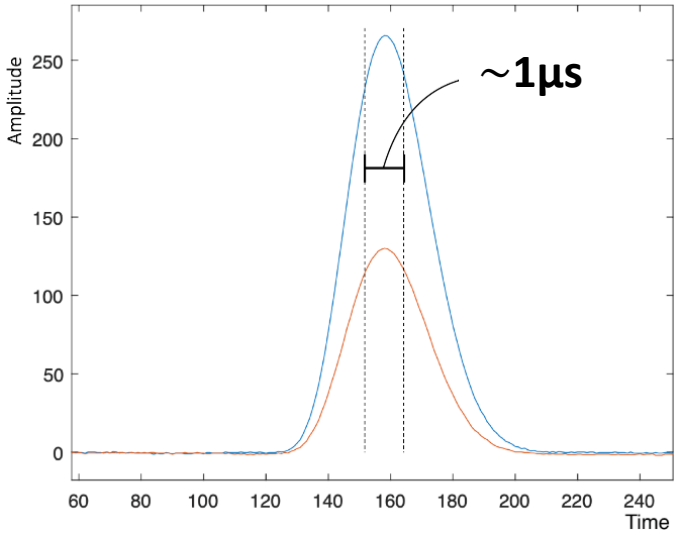
Rivelatori operanti in coincidenza



Tempi di elaborazione del segnale **µsec**



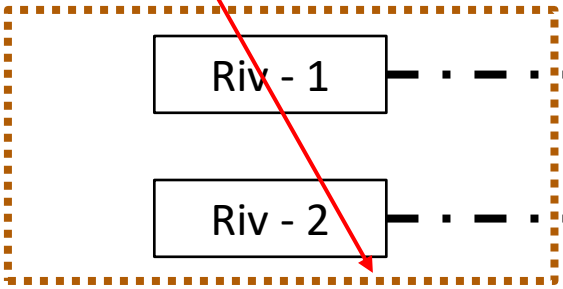
Segnali in coincidenza



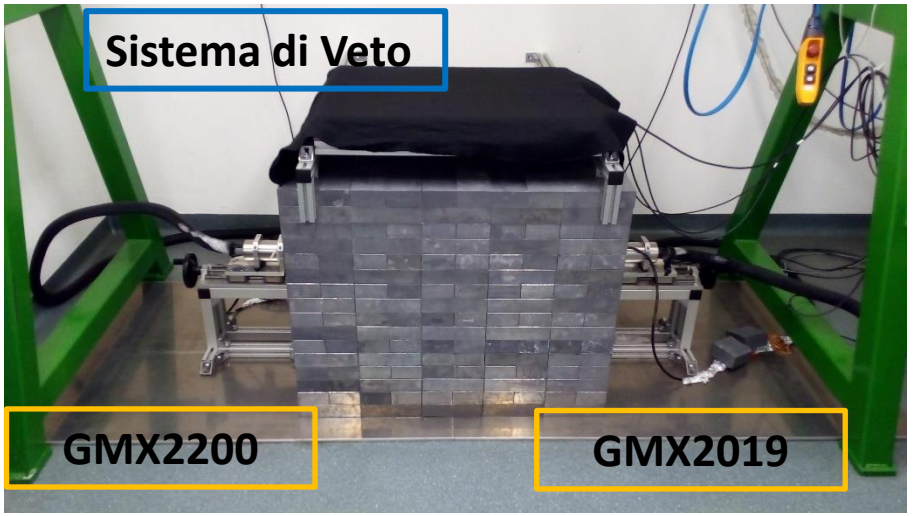
Sistema di veto operante in anti-coincidenza

Muoni - Sciami elettromagnetici

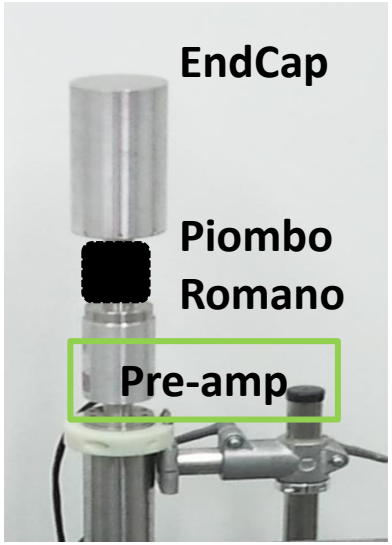
Schermatura



GMX – Rivelatore γ-γ



2x GMX detectors

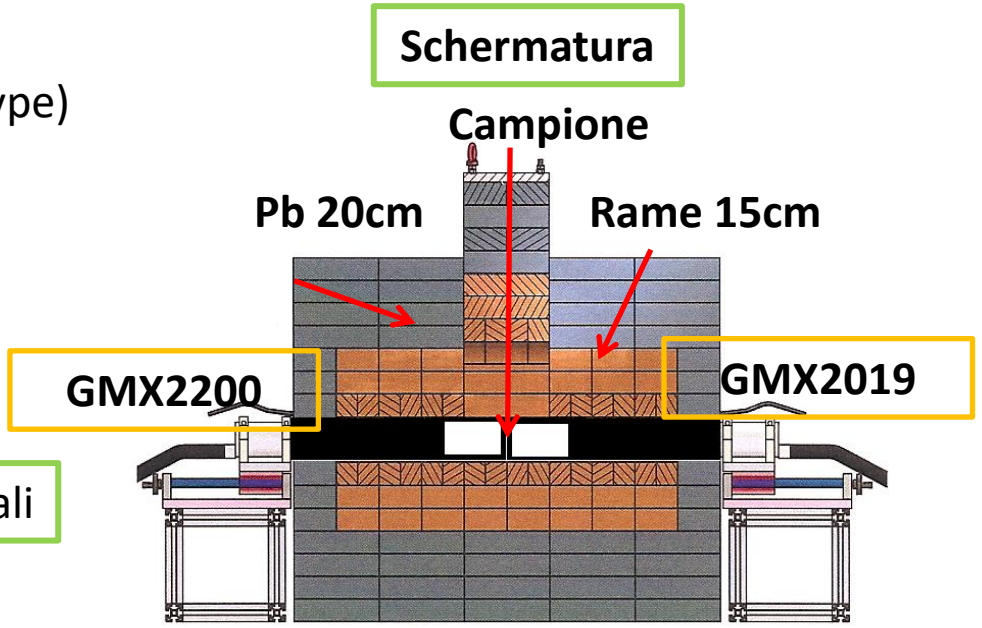


Coaxial detector (n-type)

$\varepsilon_{rel} = \sim 100\%$

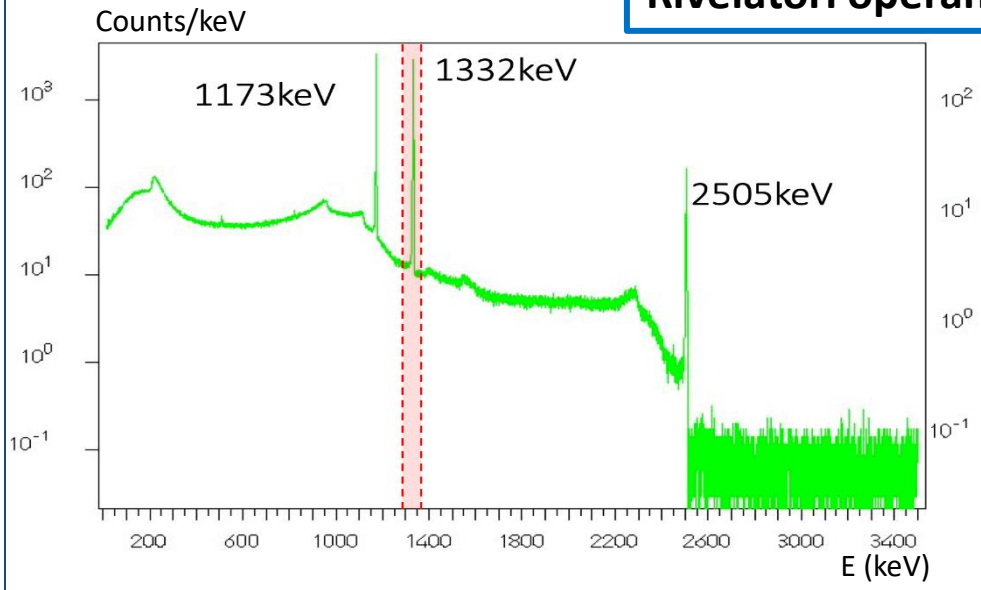
Range 17-3200keV

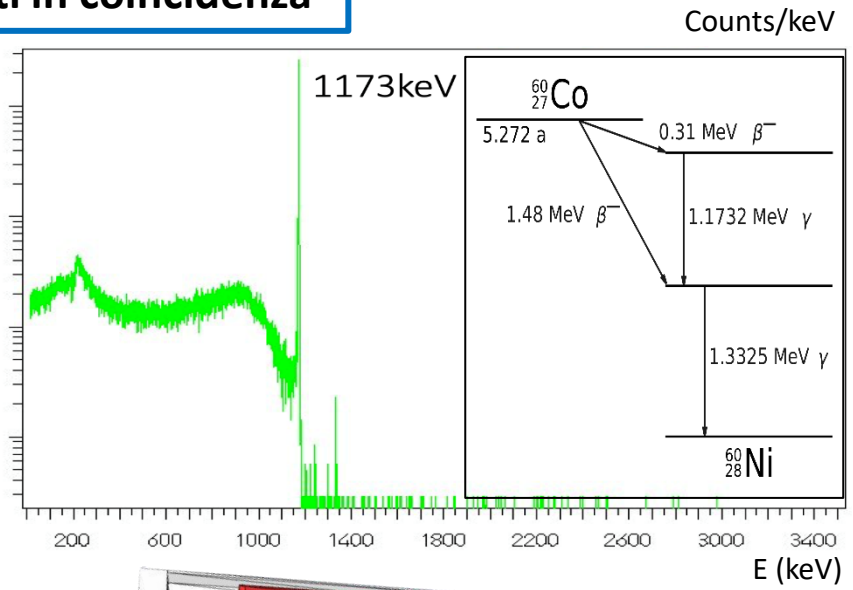
Selezione dei materiali

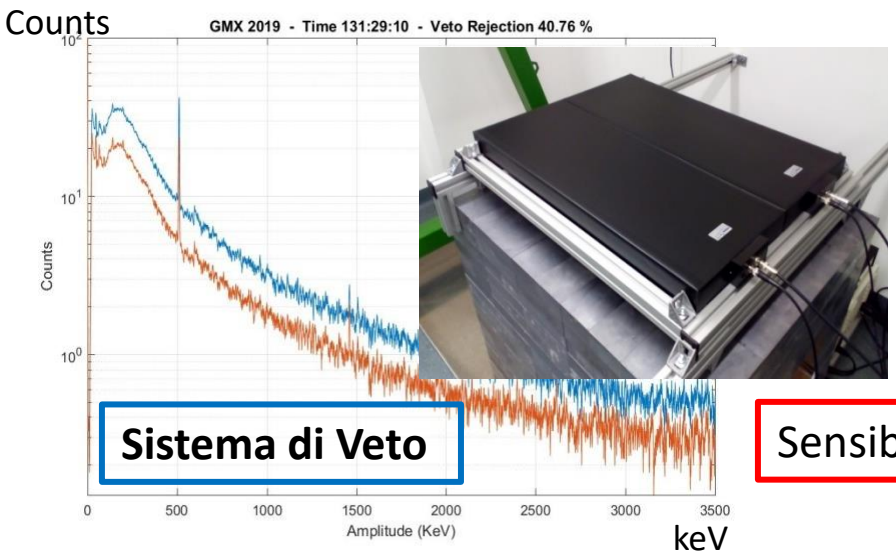


GMX – Rivelatore γ-γ

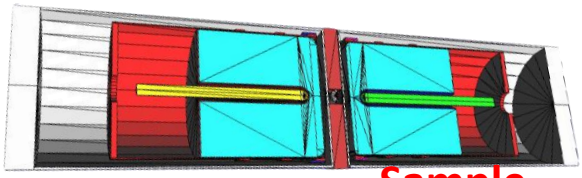
Rivelatori operanti in coincidenza



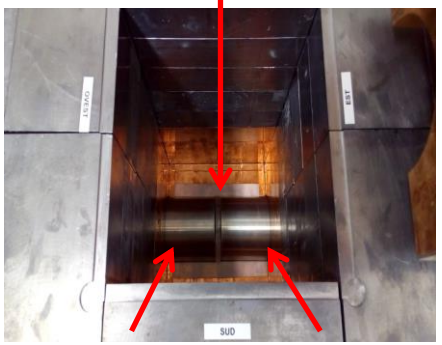




Sistema di Veto



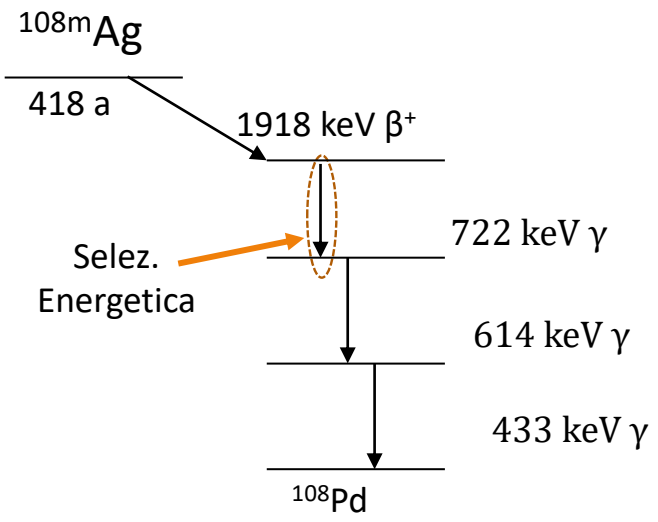
Sample

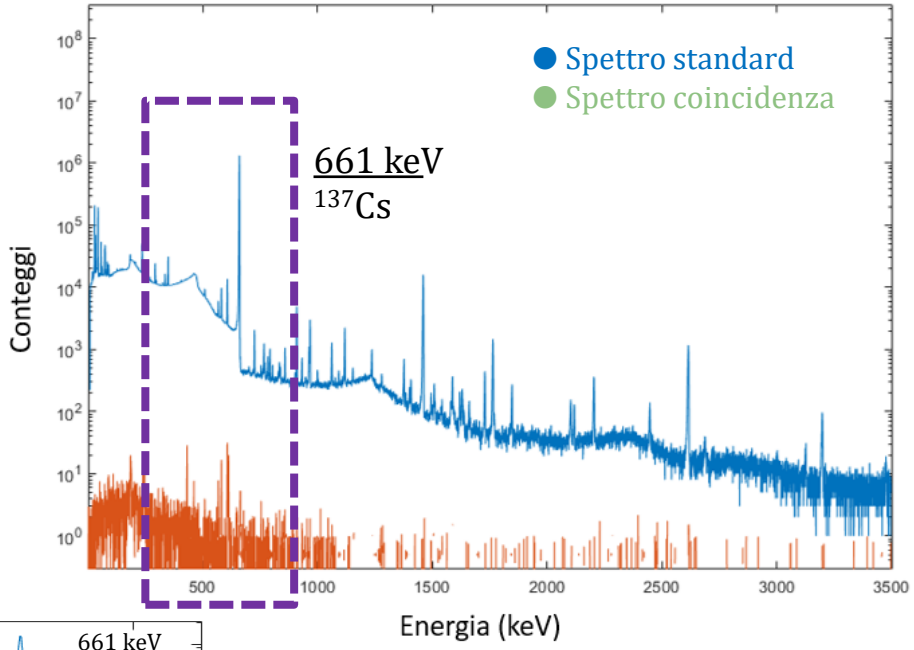


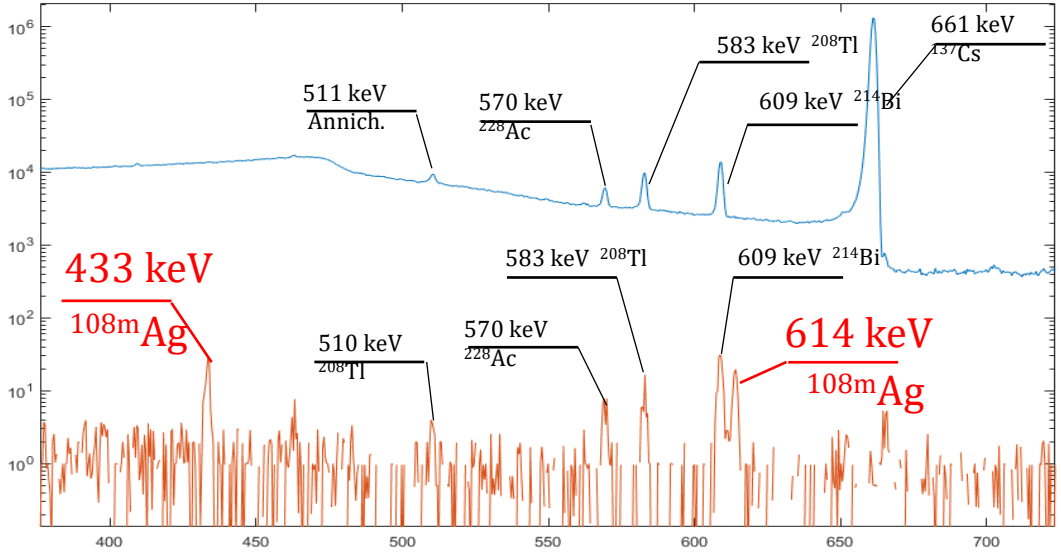
Sensibilità: $<10^{-4}$Bq/kg

GMX2019 **GMX2200**

GMX – ^{108m}Ag in campioni di origine glaciologica

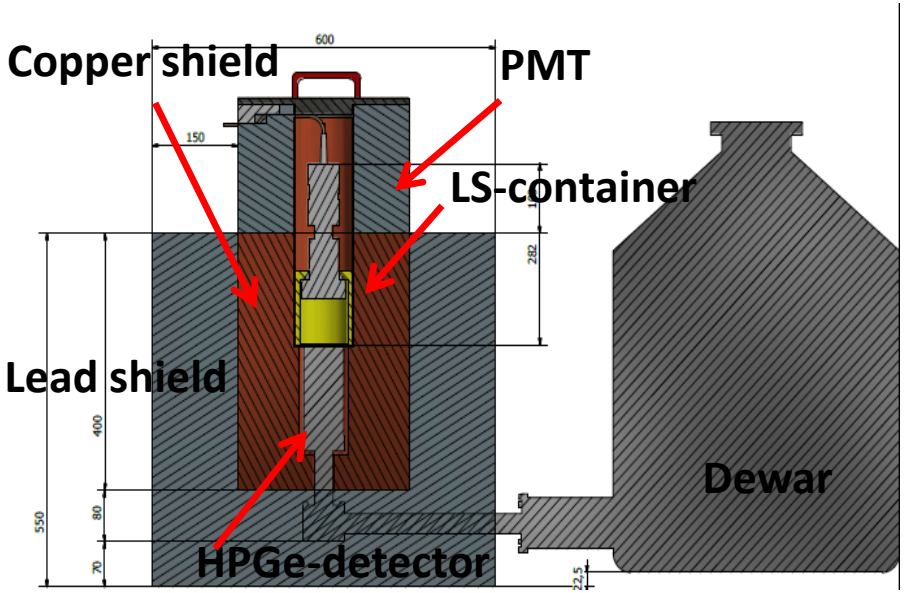


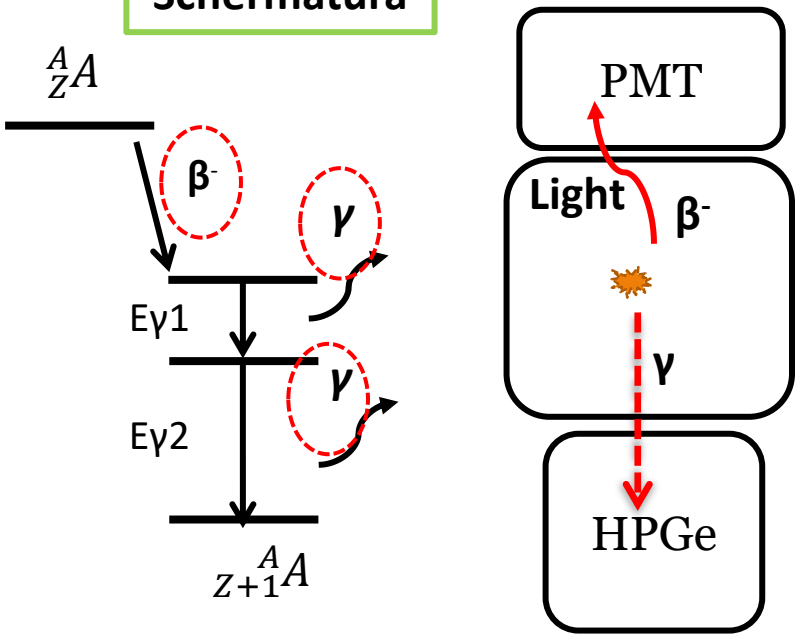




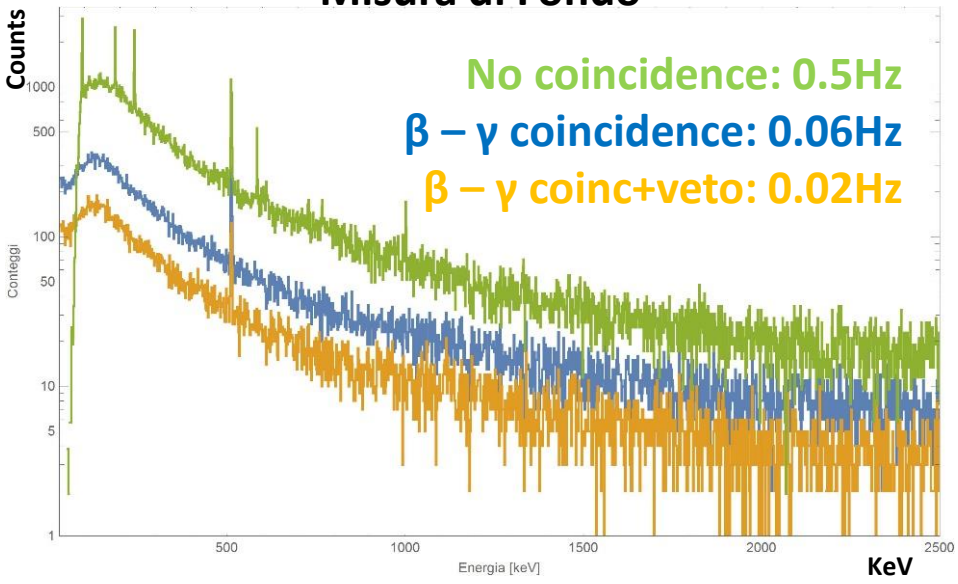
keV	BR[%]
433	90
614	89.9
722	90.9

GeSparK – Rivelatore β-γ



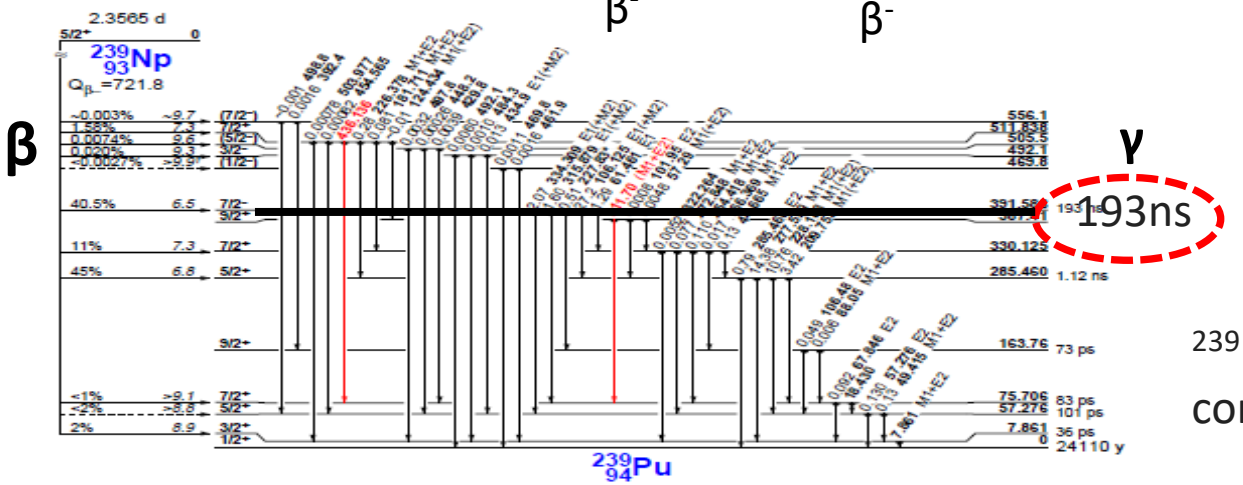


Misura di Fondo



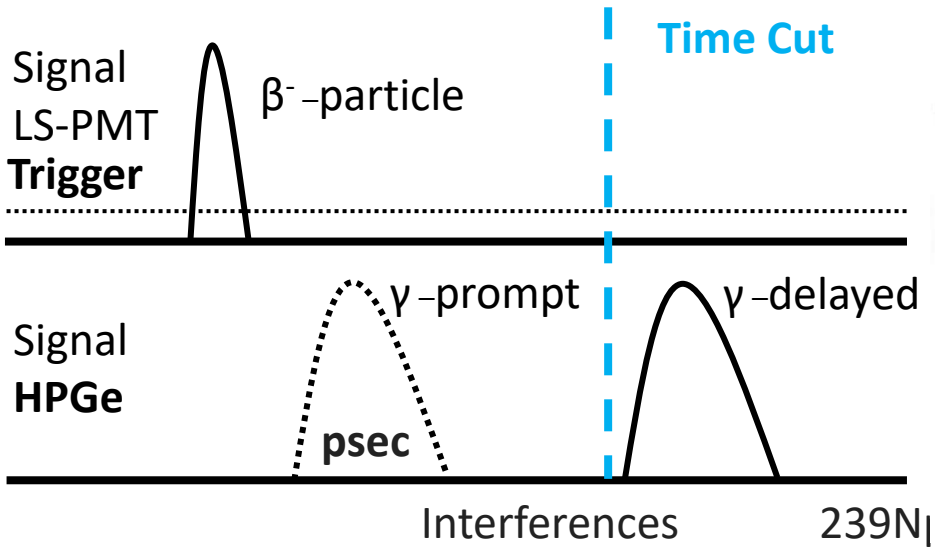
^{239}Np – Coincidenza ritardata

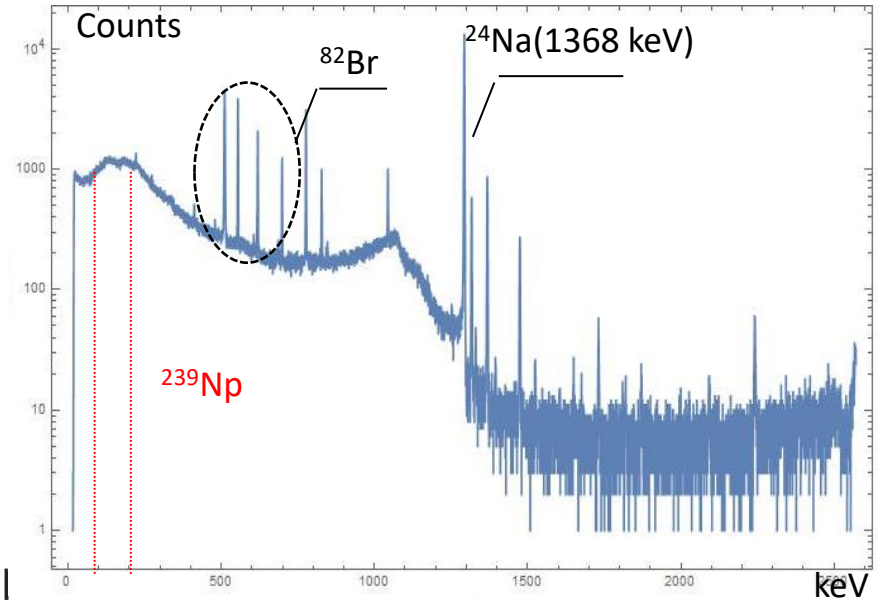
$n + {}^{238}U \xrightarrow{23.5m} {}^{239}U \xrightarrow[\beta^-]{} {}^{239}Np \xrightarrow[\beta^-]{2.36d} {}^{239}Pu$



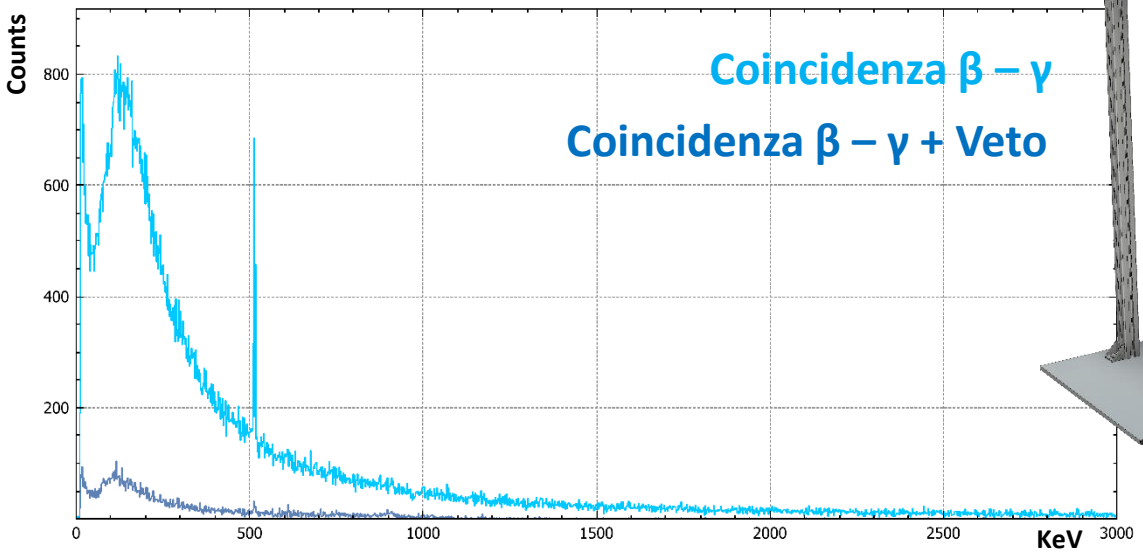
^{239}Np ϒ-ray(keV)	BR(%)
106.12	26.3
228.18	11.14
277.60	14.44

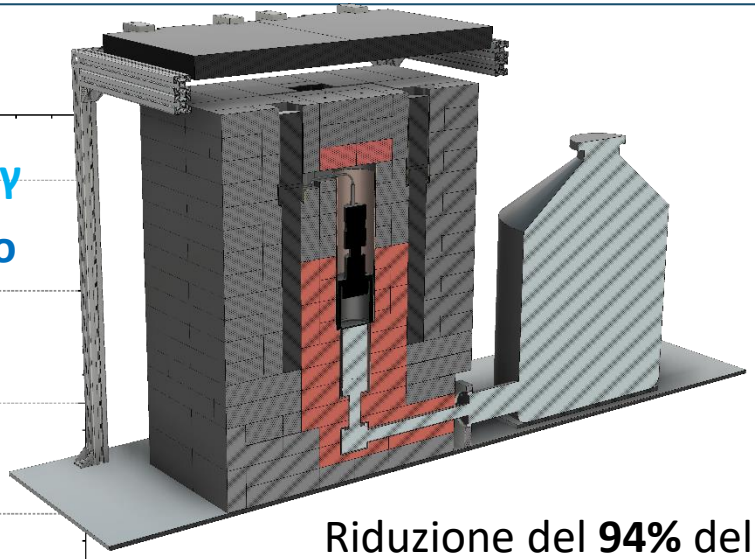
^{239}Np ha un livello metastabile con vita media di **193ns**



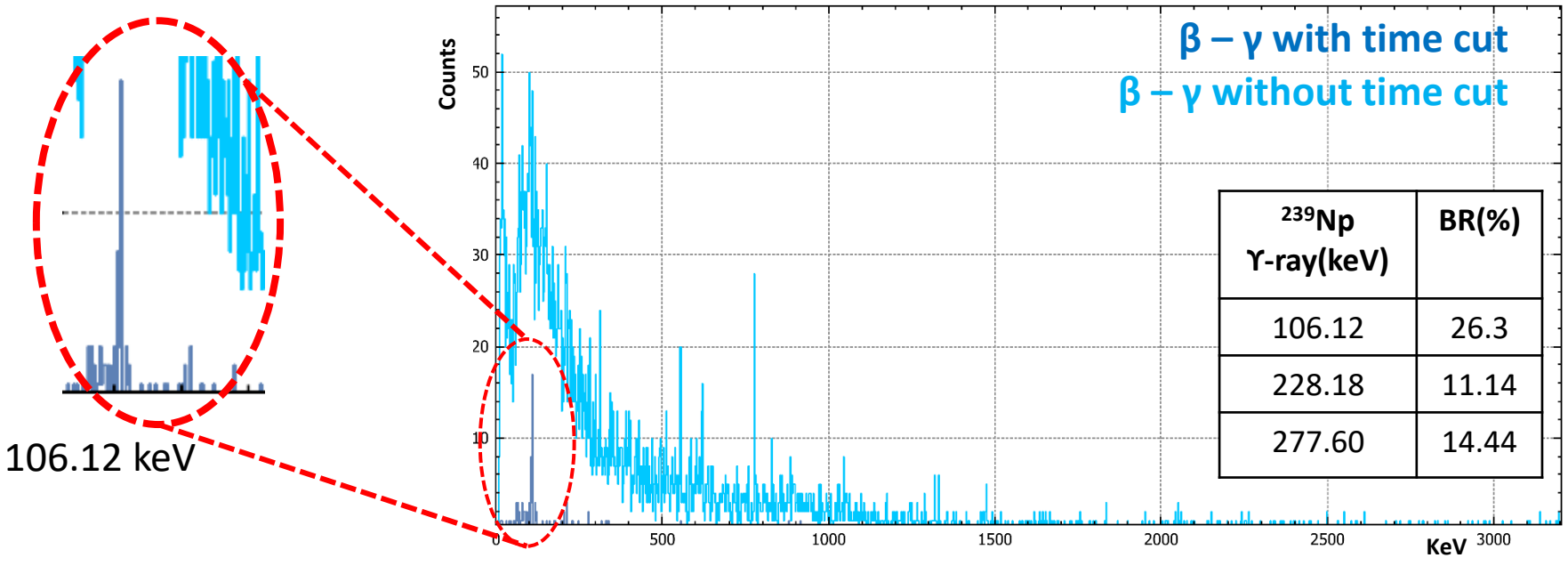


^{239}Np – Campione Attivato





Riduzione del **94%** della radiazione cosmica



^{239}Np Υ-ray(keV)	BR(%)
106.12	26.3
228.18	11.14
277.60	14.44

Efficienza

Efficienza di rivelazione

Parametro fondamentale per la determinazione quantitativa dell'attività di una sorgente incognita

$$A[Bq] = \frac{Conteggi/s}{\boldsymbol{\epsilon_{abs}} \cdot BR}$$

Efficienza assoluta

$$\epsilon_{abs} = \frac{Numero\ di\ eventi\ registrati}{Numero\ di\ eventi\ emessi\ dalla\ sorgente}$$

- Geometria del sistema rivelatore-sorgente
- Autoassorbimento della sorgente
- Materiale interposto fra sorgente e rivelatore
- Volume morto del rivelatore

Efficienza - Metodo standard

Misura sorgenti calibrate

↓

Curva efficienza sperimentale

↓

Estensioni analitiche delle misure effettuate

Limitato range energetico

Limitato numero di geometrie

Autoassorbimento

Decadimenti complessi

Rate della sorgente

Introduzione sistematiche

Costo e gestione delle sorgenti

Soluzione: Simulazioni numeriche mediante Metodo Monte Carlo

Metodo Monte Carlo

Input

Il sistema viene descritto con la maggiore precisione possibile

Simulazione numerica

Generazione di una grande quantità di numeri casuali che seguano la distribuzione di probabilità imposta dalla descrizione del problema

Output

I risultati descrivono il comportamento medio del sistema

Software di simulazioni MonteCarlo: ARBY

Nel corso degli anni il Gruppo di ricercatori di Milano-Bicocca ha sviluppato un tool di simulazioni MC chiamato ARBY.

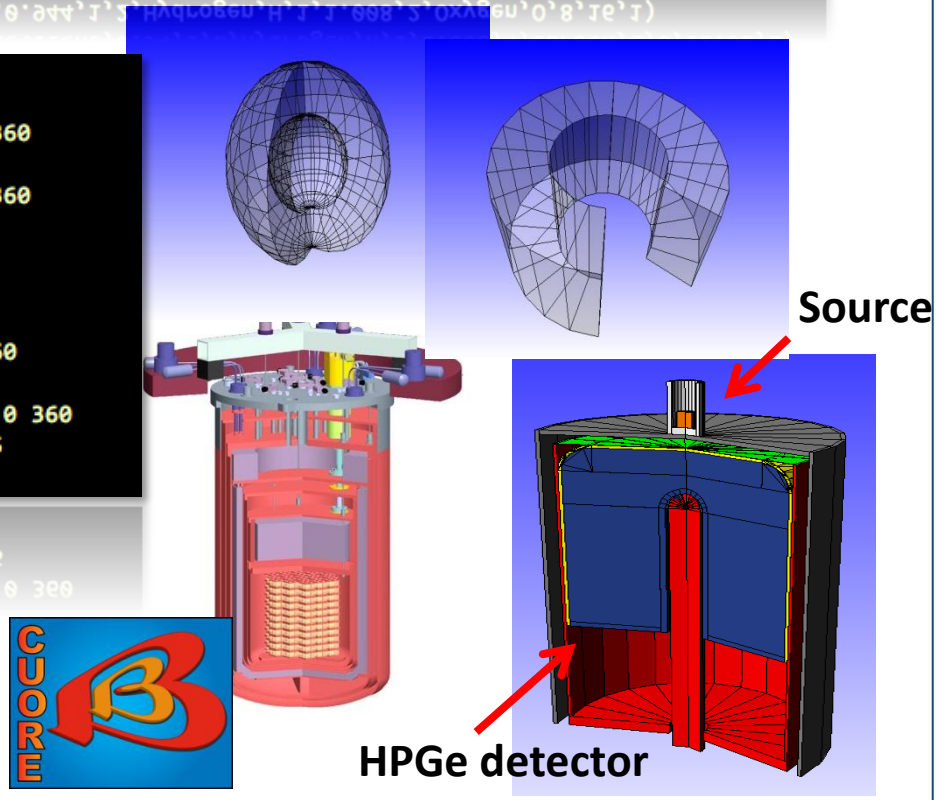
Allo scopo di generare le simulazio l'utilizzatore deve creare un **file di configurazione** con una **semplice sintassi**

```
NewMaterial = (Ge,5.323,0,1,Germanium,Ge,32,72.59,1)
NewMaterial = (Li,5.32,0,1,Germanium,Ge,32,72.59,1)
NewMaterial = (Polietilene,0.94,1,2,Hydrogen,H,1,1.008,4,Carbon,C,6,12.01,2)
NewMaterial = (H2O,0.944,1,2,Hydrogen,H,1,1.008,2,Oxygen,O,8,16,1)
```

```
#Detector
SOLID Tubs
0.6 3.825 6.0 0 360
SOLID Tubs Union
0.0 3.825 0.9 0 360
0 0 0.0 0.0 3.45
SAVE GeDet
#Litio
SOLID Tubs
0 3.825 0.16 0 360
SOLID Tubs Union
3.825 3.985 7.06 0 360
0 0 0.0 0.0 -3.45
SAVE LiGe
```

Solidi elementary come ***Tubs***, ***Cylinder***, ***Sphere*** *permettono di creare attraverso operazioni* booleane (***Union***, ***Intersection***, ***Subtraction***) solidi complessi

I volume assumono un ruolo indicato da specifiche keyword ***Absorber***, ***Source e Detector*** definite all'interno del file di configurazione.



Arby – Diagramma di flusso

- **Descrizione geometrica** rivelatore-sorgente
- **Numero di eventi** da generare
- **Distribuzione del radioisotopo** (uniforme, puntuale, esponenziale,…)
- **Radionuclide emettitore**
  - Singolo isotopo (137Cs, 60Co, 152Eu,…)
  - Catene radioattive (238U, 235U, 232Th)
  - Singolo particelle (Alfa, Beta, Gamma)

Descrizione del processo fisico
(schemi di decadimento; Br; tempi di decadimento)

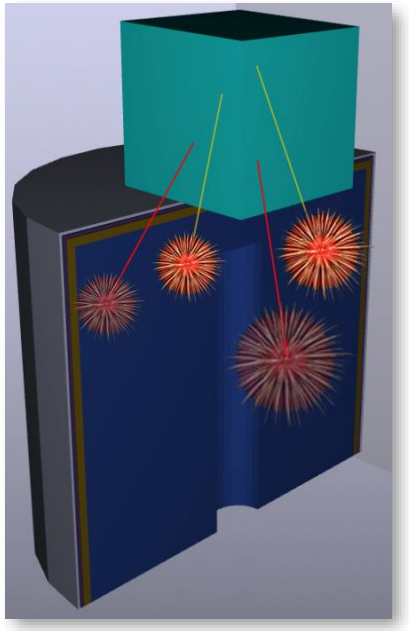
Meccanismi di **interazione radiazione-materia**

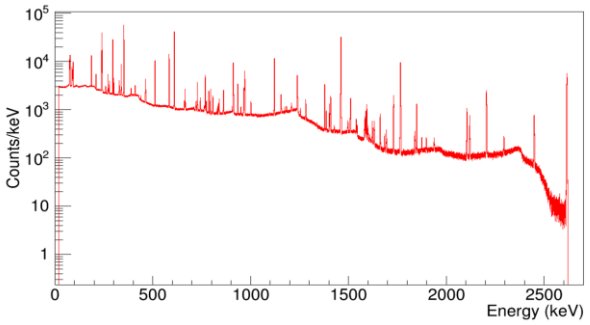
Rate di decadimento

Risoluzione del rivelatore

Tempo di integrazione del segnale

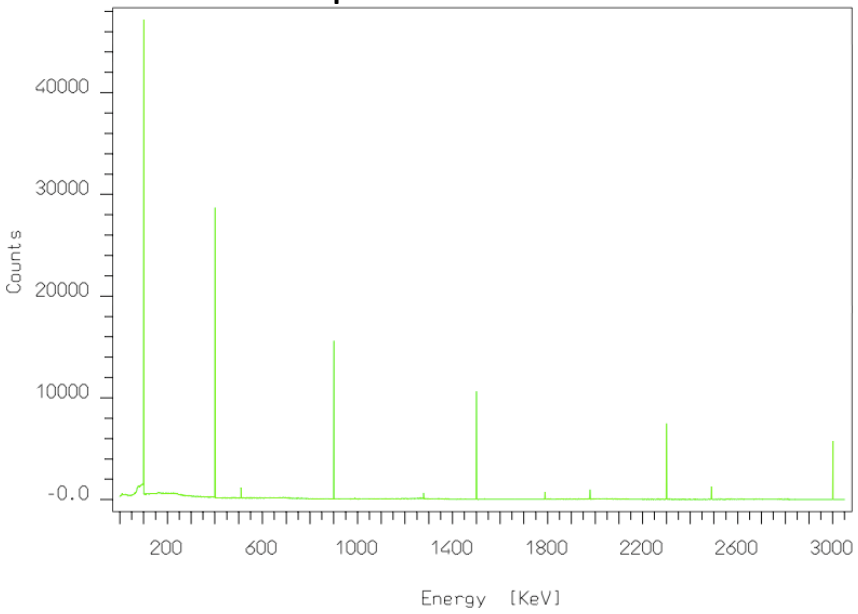
Esperimento virtuale

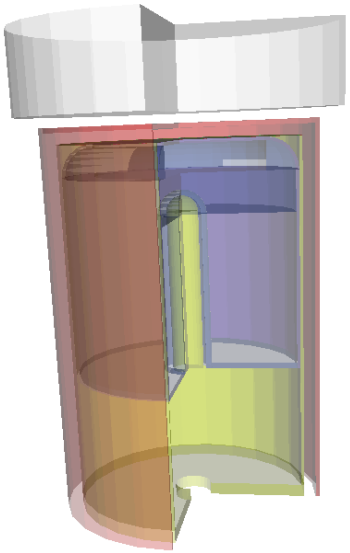




Arby: Ricostruzione Curva di Efficienza

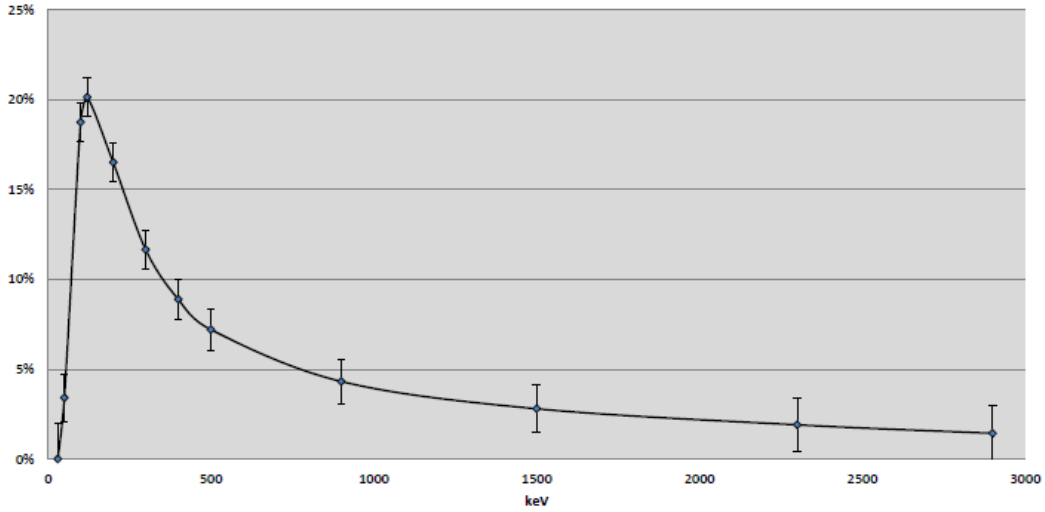
Spettro simulato





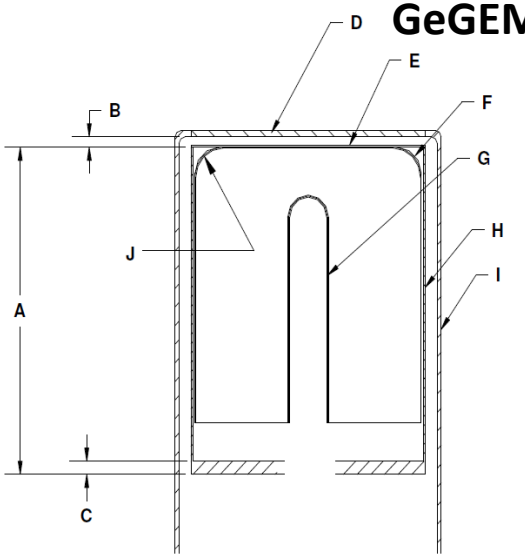
$$E_{abs} = \frac{Conteggi\ al\ picco}{Nr\ eventi\ generati}$$

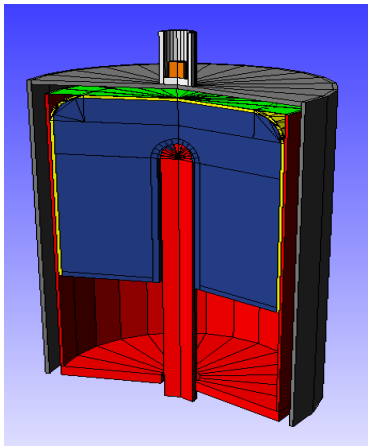
Curva di Efficienza



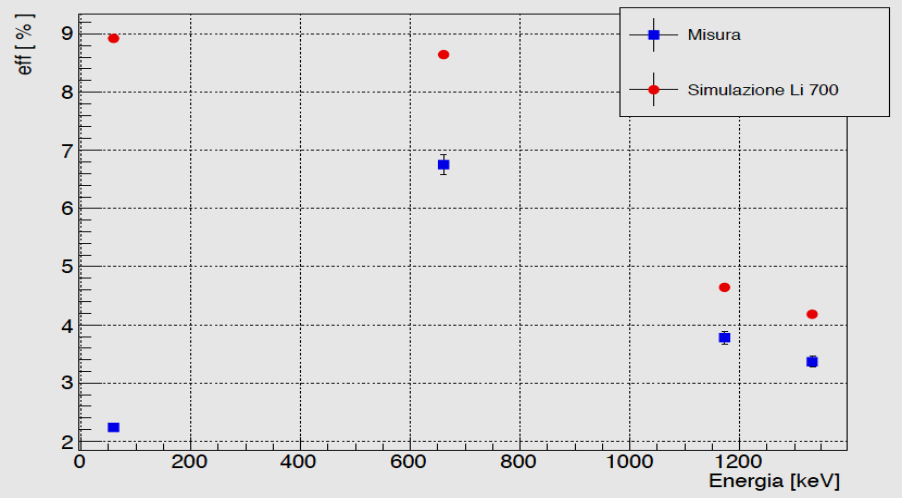
Calibrazione in efficienza

GeGEM

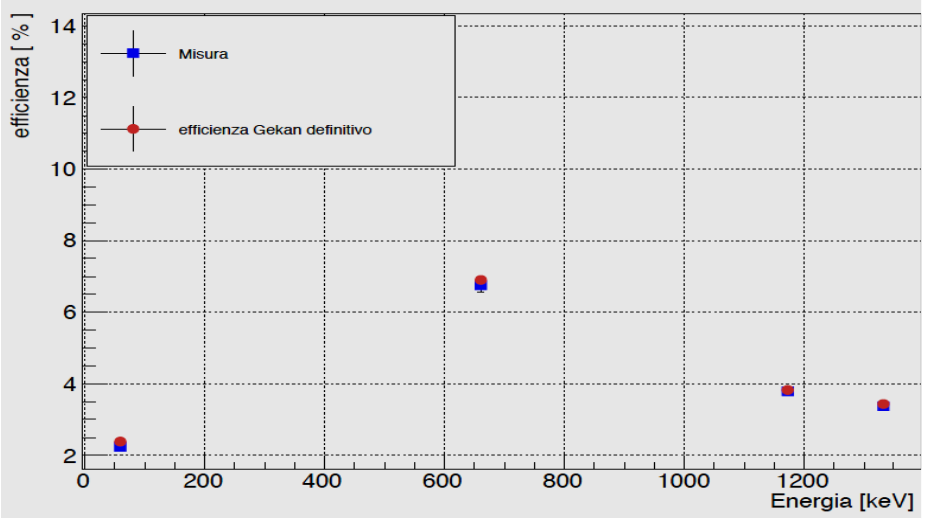


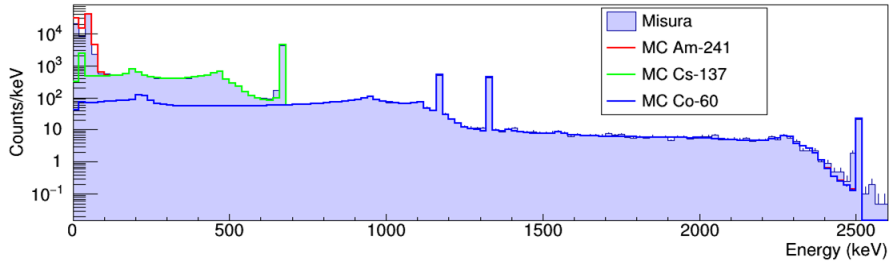


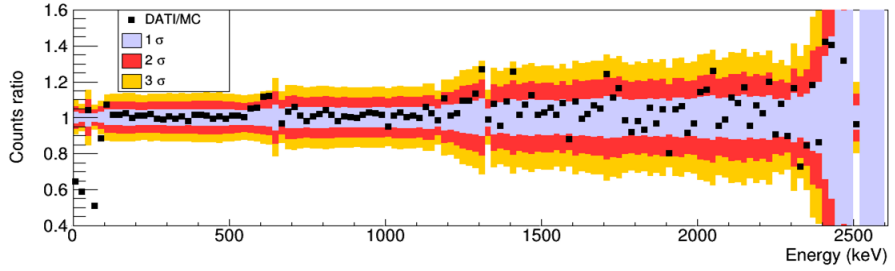
Parametri Nominali



Modello ottimizzato

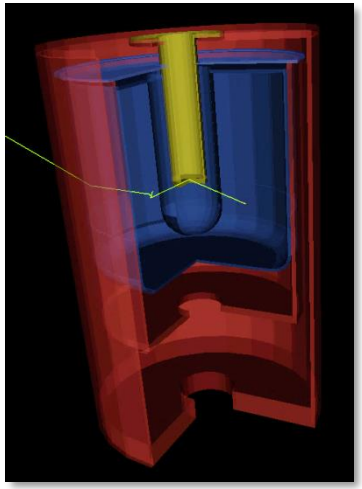




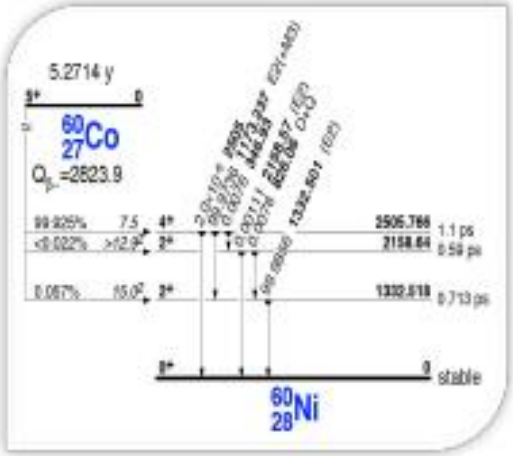


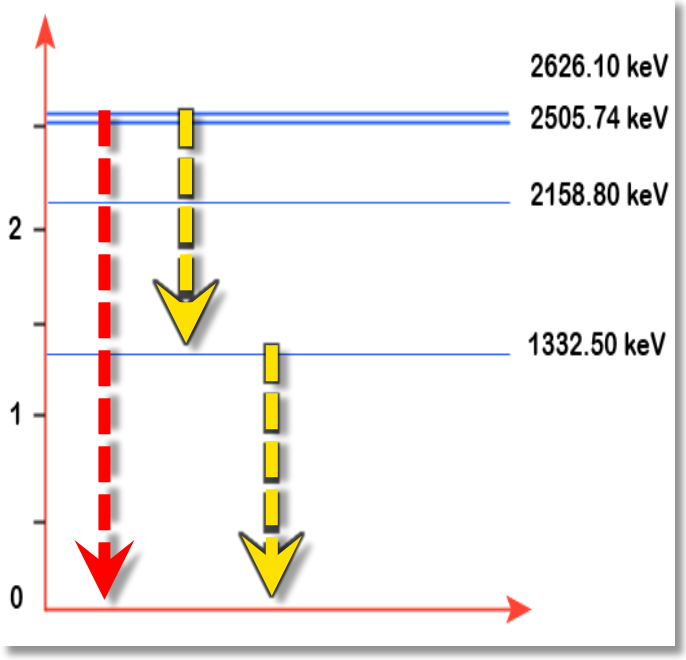
Cascate nucleari

GePozzetto

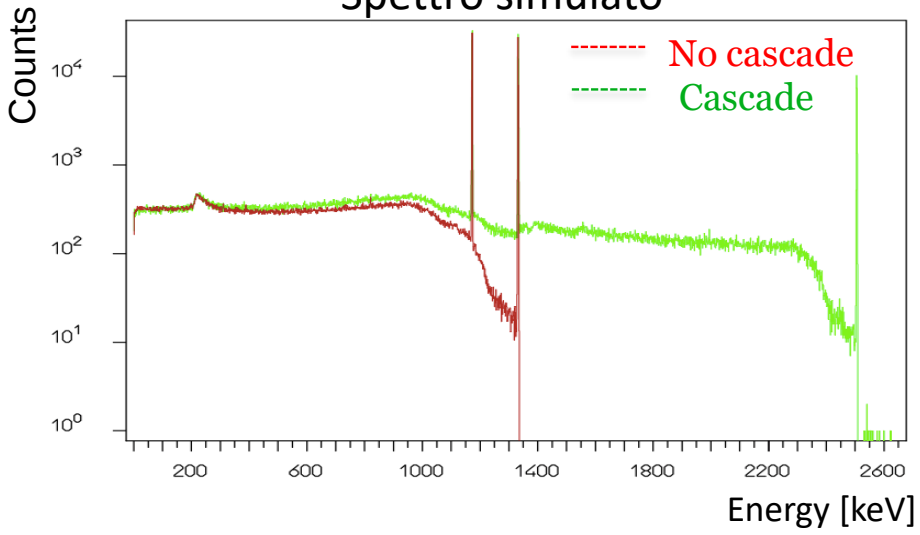


Schema di decadimento ^{60}Co

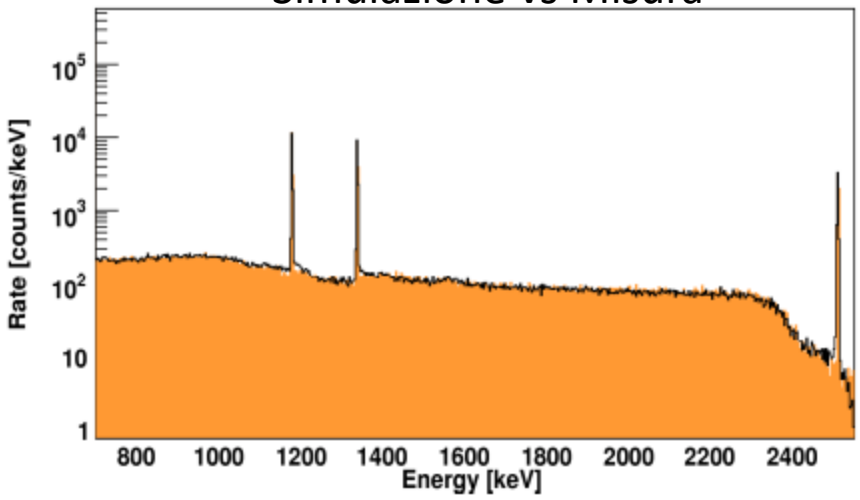




Spettro simulato

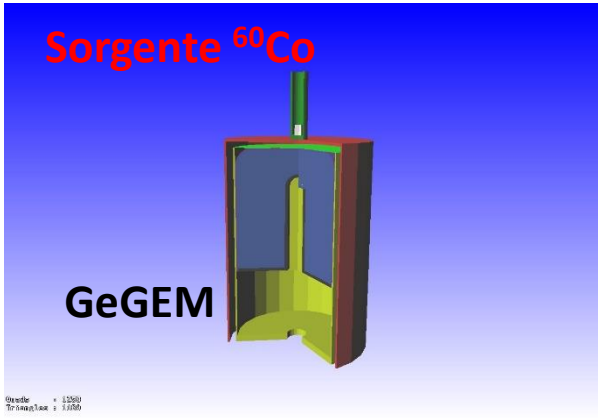


Simulazione vs Misura

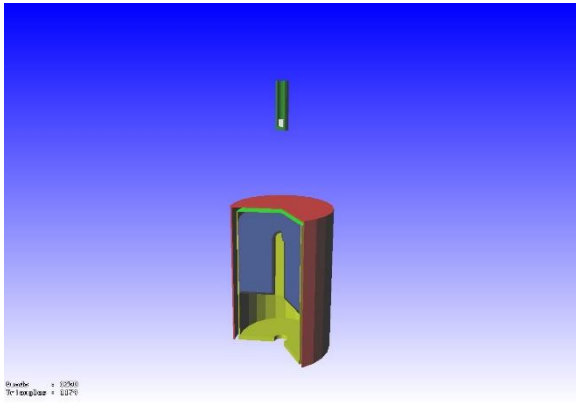


Pile-up

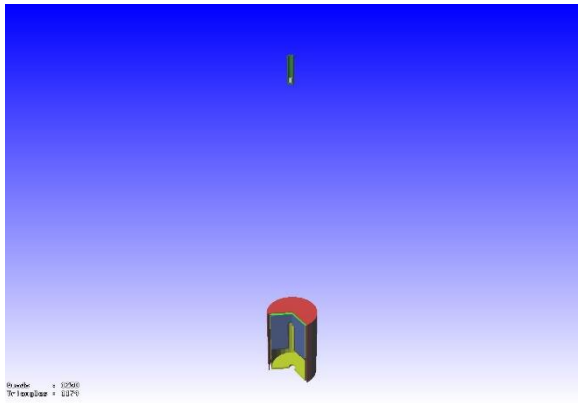
Distanza: 0cm



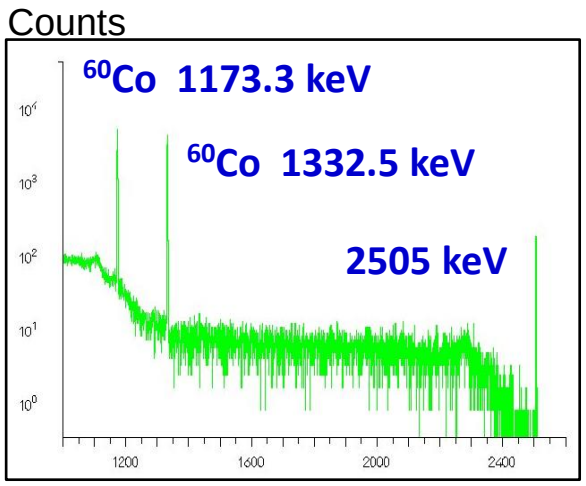
5cm



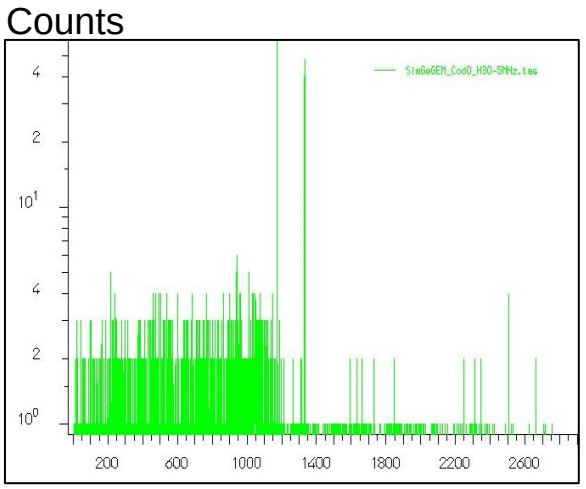
30cm



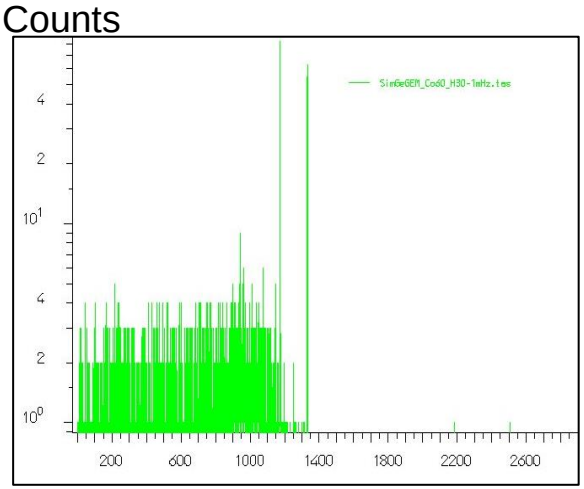
Distanza: 0cm



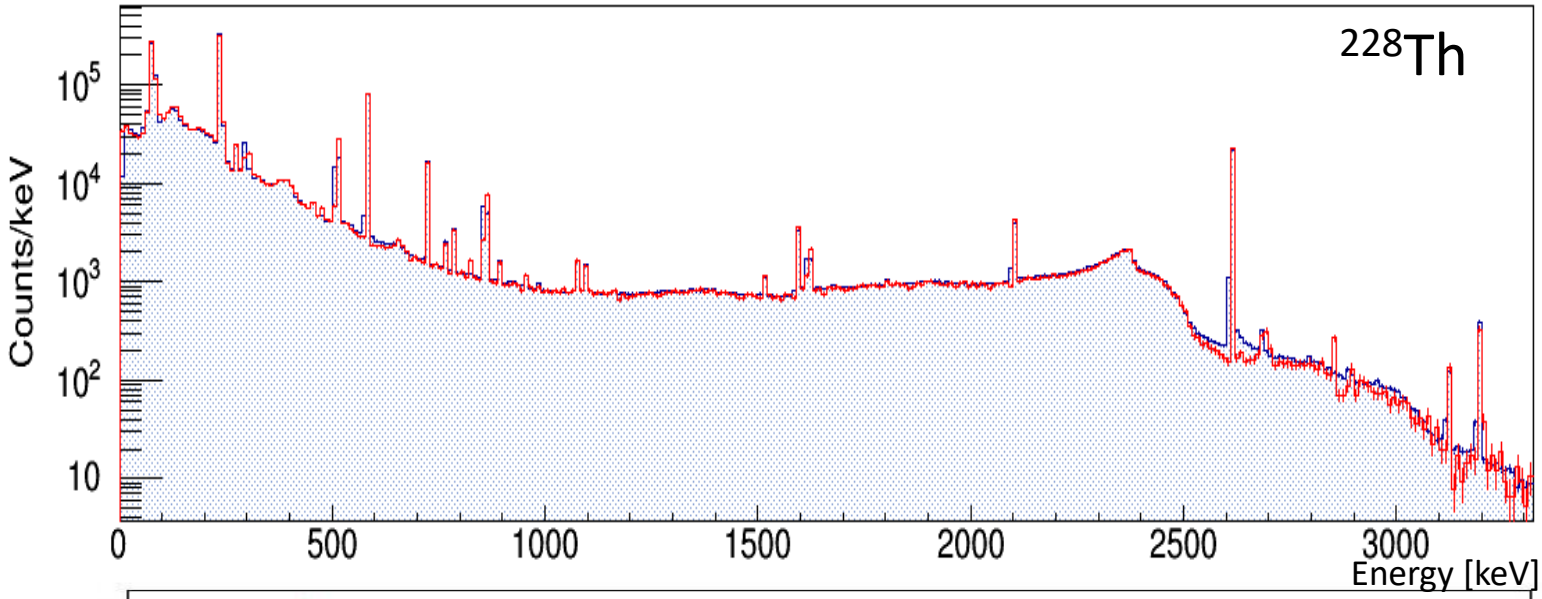
5cm

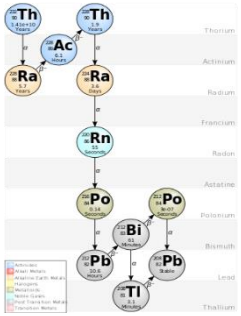


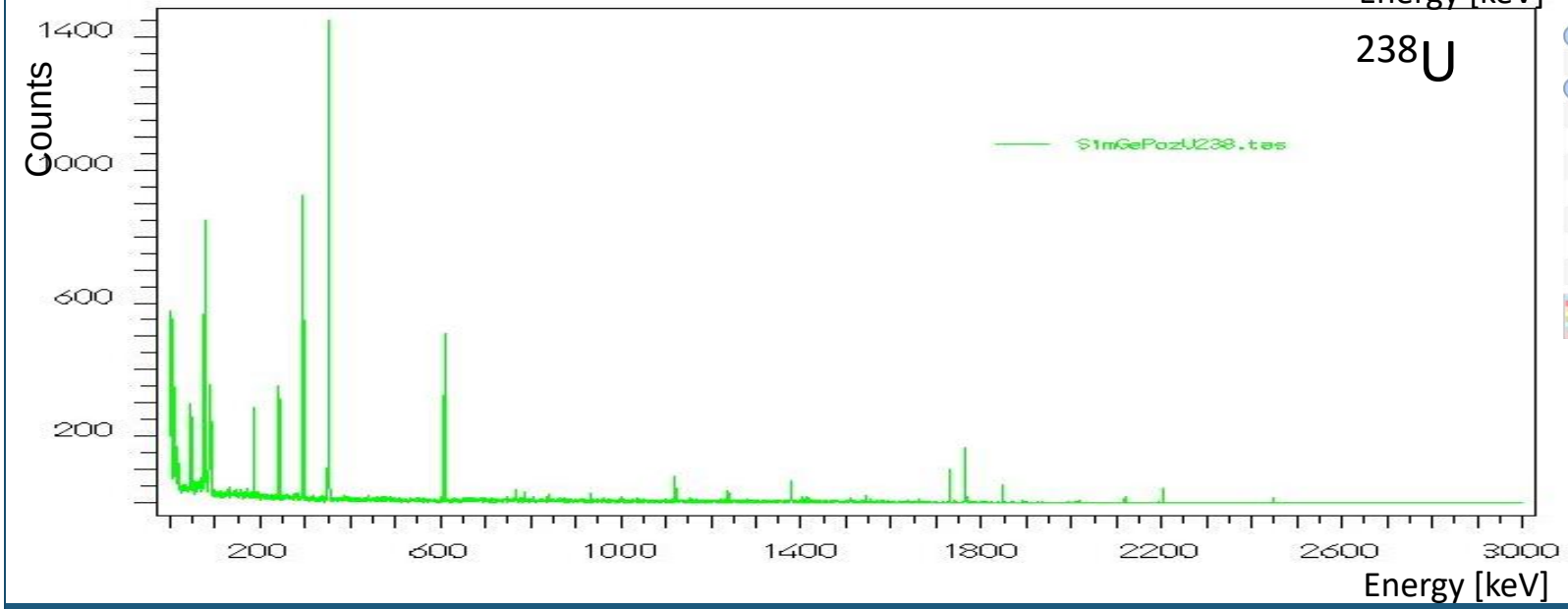
30cm

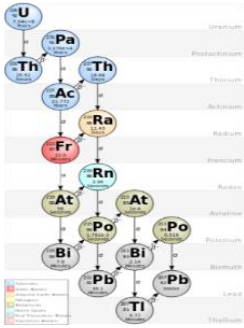


Generazione di catene radioattive

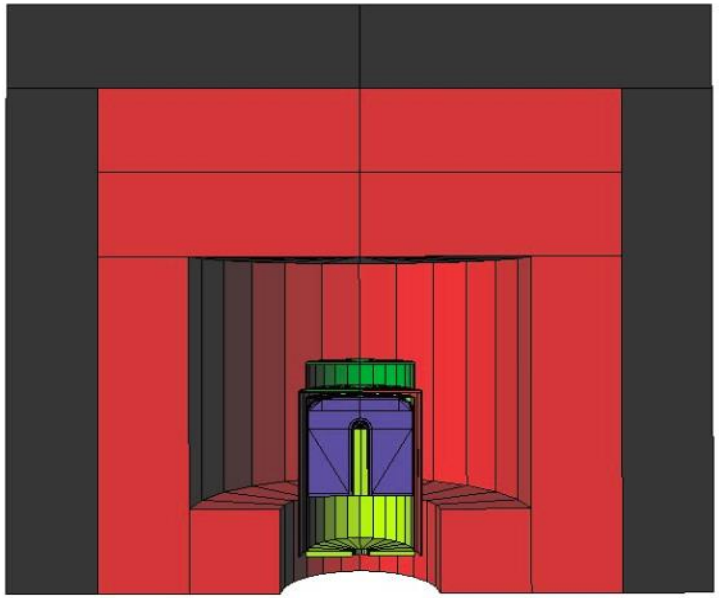


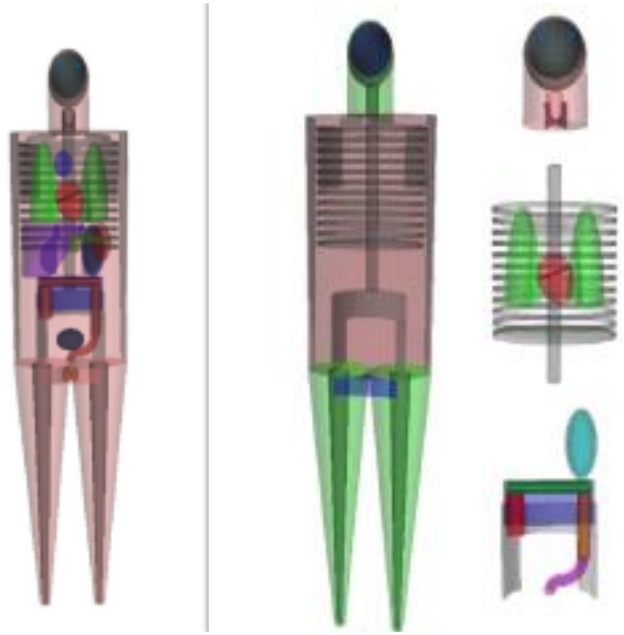


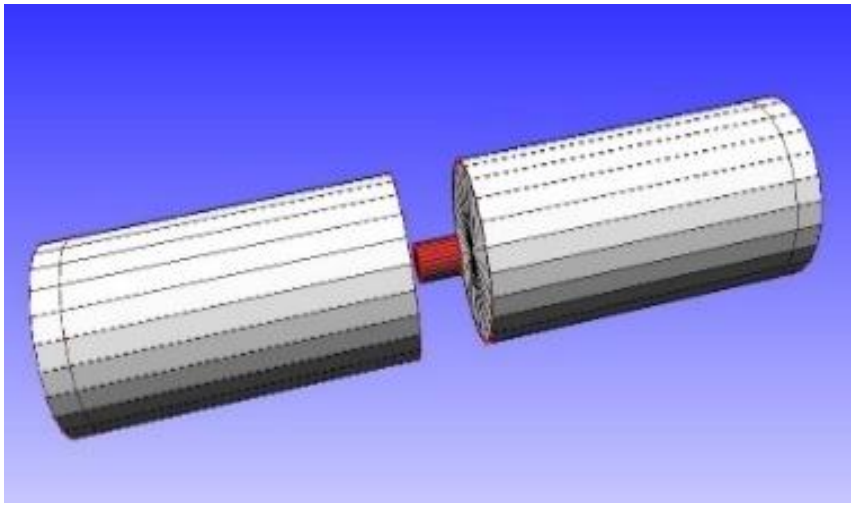


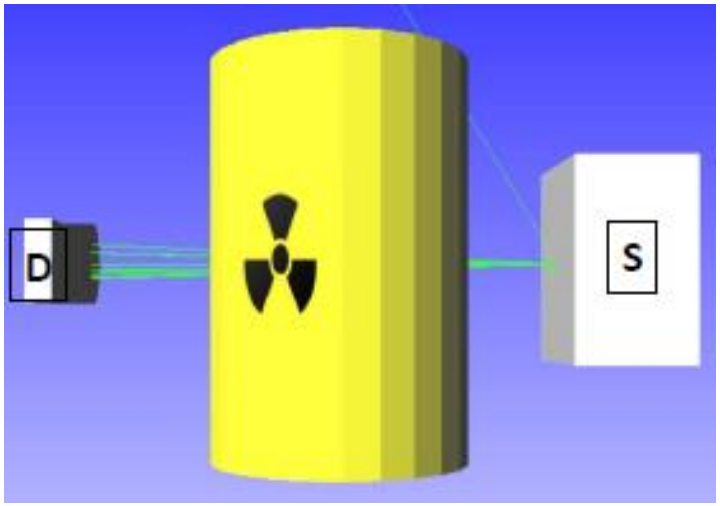


Applicazioni specifiche

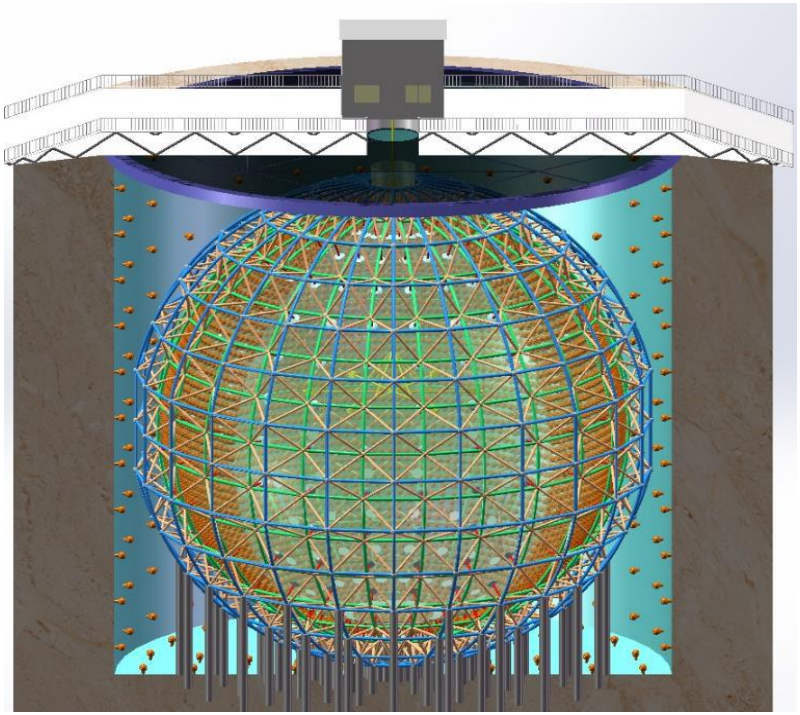


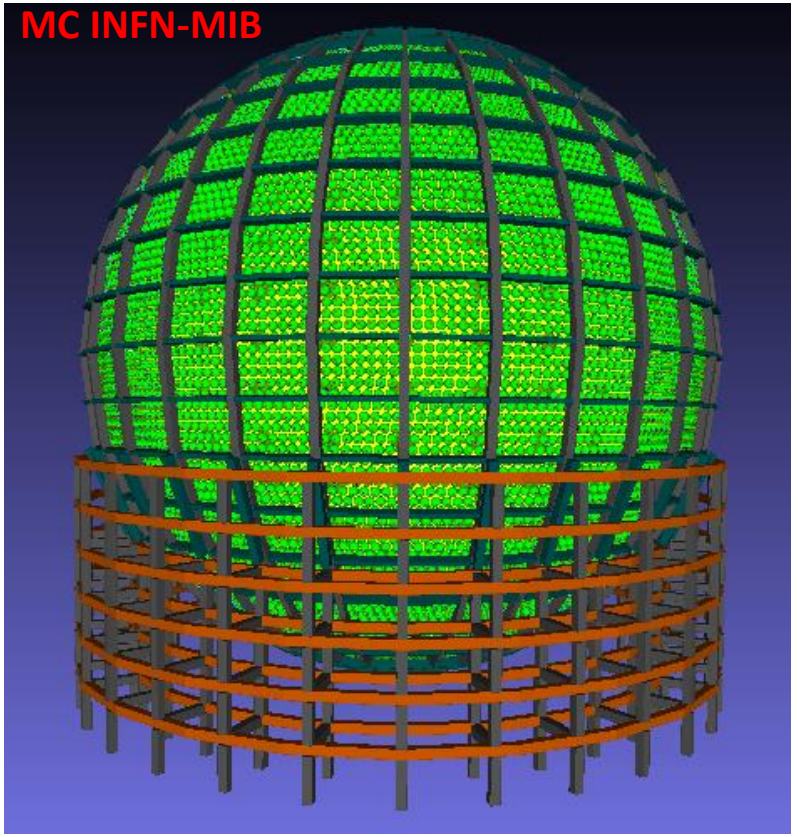


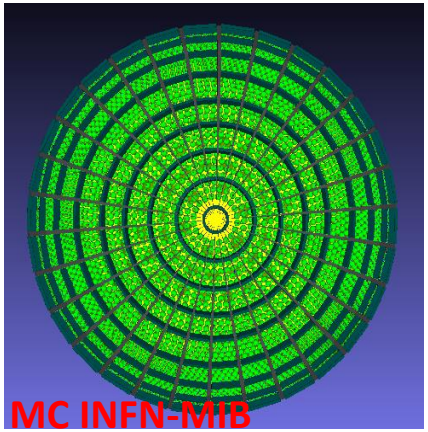


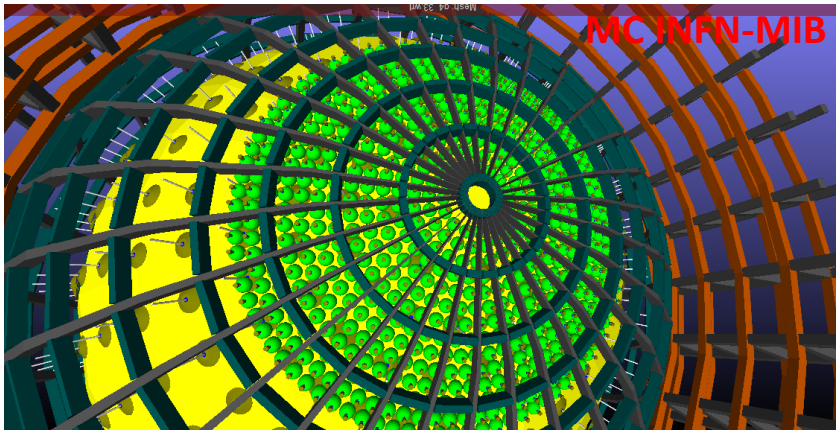


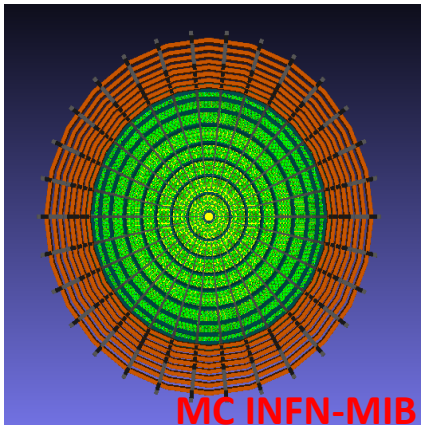
MC- Esperimento JUNO











Misura sperimentale di un campione

1. Preparazione del campione

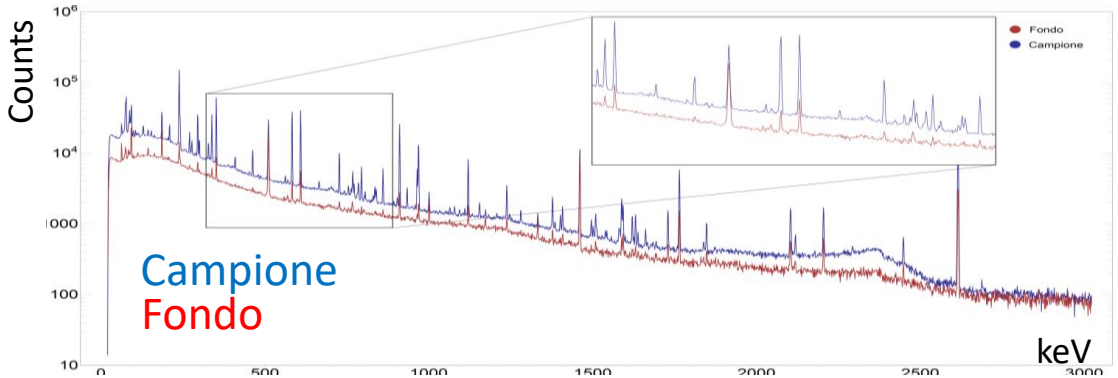
2. Scelta del rivelatore

GePozzetto

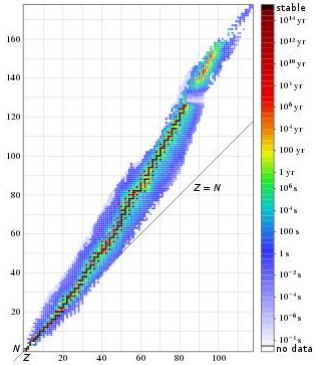
GeKan

GeGEM

3. Misura sperimentale



Analisi dei dati



4. Riconoscimento dei radionuclidi http://nucleardata.nuclear.lu.se/toi/

https://nds.iaea.org/relnsd/vcharthtml/VChartHTML.html

5. Ricostruzione al simulatore della configurazione di misura ϵ_{abs}

6. Quantificazione dei contaminanti

$$A[^{Bq}/_{kg}] = \frac{Counts_{Camp} - Counts_{Fondo}}{\epsilon_{abs} \cdot BR \cdot M \cdot T_{mis}}$$