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lecture cource on

Astroparticle physics

15.09.2009 – 15.12.2009

9 Background in underground experiments

Content

9 Background in underground experiments

General

- The radioactive isotopes found in the nature are generally divided into three groups
  - primordial isotopes
  - cosmogenic isotopes
  - artificial isotopes
- The natural radioactivity is common in rock and soil, oceans, lakes and rivers, and in construction materials
  ☞ it exist everywhere
  - Mostly harmless for humans, animals and plants, but can be extremely harmfull for sensitive physics experiments

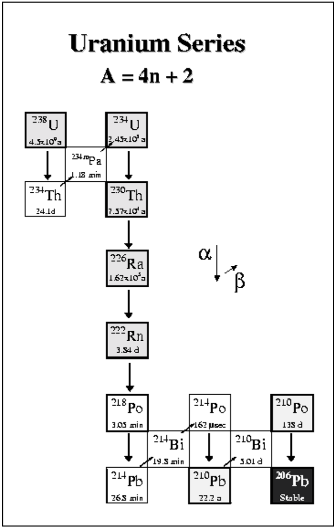
9.1 Primordial isotopes

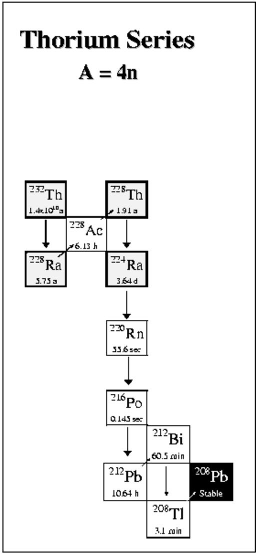
General

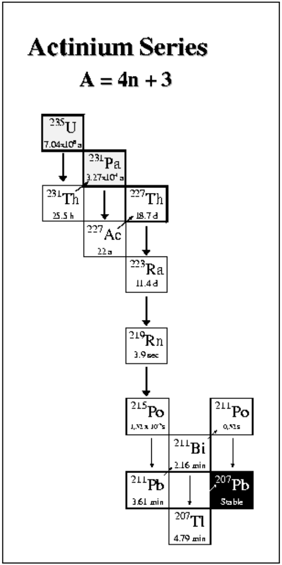
- Older than the Earth
- Typically very long lived, lifetime billions of years
- For example
  - ^{232}Th 1.41×10^{10} yr thorium series at the soil
  - ^{238}U 4.47×10^{9} yr uranium series δ=99.2745%, at the soil
  - ^{235}U 7.04×10^{8} yr actinium series δ=0.72%
  - ^{237}Np 2.2×10^{6} yr neptunium-sarja
  - ^{40}K 1.28×10^{9} yr δ=0.012%, 0.04–1.1 Bq/g at soil
  - Others: ^{50}V, ^{87}Rb, ^{113}Cd, ^{115}In, ..., ^{190}Pt, ^{209}Bi
  - ^{226}Ra 1.60×10^{3}yr member of uranium series
  - ^{222}Rn 3.82 d noble gas, member of uranium series
- As the final results of the four decay chains (thorium, uranium, actinium and neptunium) the heaviest stable isotopes are formed: ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{209}Bi

9.1 Primordial isotopes

Radioactive series







9.2 Cosmogenic isotopes

General

- Radioactive isotopes produced by cosmic-ray-induced interactions
- Cosmic-ray radiation can be divided into two classes: primary and secondary cosmic rays
  - at upper atmosphere interaction with primary (and high-energy) particles
  - closer to the surface interactions with secondary (and lower-energy) particles (electrons, muons, protons, neutrons, photons, ...)

    ➙ interactions between cosmic-ray particles and atoms in the atmosphere and the soil
- Typically lighter and much shorter-living that primordial isotopes
- For example
  - ^{14}C   5730 yr ^{14}N(n,p)^{14}C   0.22 Bq/g in organic materials
  - ^{3}H   12.3 yr   CR: N,O; spall: ^{6}Li(n,α)^{3}H
  - ^{7}Be   53.3 d   CR: N,O
  - Others: ^{10}Be, ^{26}Al, ^{36}Cl, ^{37,39}Ar, ..., ^{38}Mg, ^{80}Kr

9.2 Cosmogenic isotopes

in germanium – 1

- Radioactive isotopes created in a Ge crystall during 10 days by cosmic-ray induced reactions. Then taken underground (Gran Sasso) for one year and measured.
  ([H.V. Klapdor-Kleingrothaus *et al.*, NIM A481 (2002) 149])
  ☞

9.2 Cosmogenic isotopes

in germanium – 2

Isotope	Decay Mode	$T_{1/2}$	Energia kiteesen [keV]	Aktivity [μBq/kg]
^{3}H	β^-	12.33 yr	E_{β^-}=18.6	3.6
^{49}V	EC	330 d	E_K(Ti)=5, no γ	0.79
^{54}Mn	EC+β^+	312.3 d	E_γ=840.8, E_K(Cr)=5.5	10.3
^{55}Fe	EC	2.73 yr	E_K(Mn)=6, no γ	0.52
^{57}Co	EC	271.8 d	E_γ=20.81, E_K(Fe)=6.4	1.17
^{58}Co	EC+β^+	70.9 d	E_γ=817.2, E_K(Fe)=6.4	0.49
^{60}Co	β^-	5.27 yr	E_{β^-}=318, E_γ=1173,1133	0.24
^{63}Ni	β^-	100.1 yr	E_{β^-}=66.95, no γ	0.01
^{65}Zn	EC+β^+	244.3 d	E_γ=1124.4, E_K(Cu)=8-9	9.08
^{68}Ge	EC	270.8 d	E_K(Ga)=10.37	676
^{68}Ga	EC+β^+	67.6 m	Q-value=2921.1	676

9.3 Artificially produced isotopes

General

- Artificial production of radioactive isotopes started in 1930's and 1940's and is since then cumulated in the nature mainly by nuclear weapon test and operation of nuclear power plants
  - amounts of articifially produced isotopes are, however, quite small
  - their lifetimes are, usually, also small compared to those of primordial or cosmogenic isotopes
- Examples
  - ^{3}H 12.3 yr weapon tests and production, reactors
  - ^{131}I 8.04 d fission product of weapon test and reactors, medical applications
  - ^{129}I 1.57×10^{7} yr weapon tests and production, reactors
  - ^{137}Cs 30.17 yr weapon tests and production, reactors
  - ^{90}Sr 28.78 yr weapon tests and production, reactors
  - ^{99}Te 2.11×10^{5} yr decay product of ^{99}Mo used for medical applications
  - ^{239}Pu 2.41×10^{4} yr $^{238}\mathrm{U} + \mathrm{n} \longrightarrow {}^{239}\mathrm{Np}\ (\beta^{-}) \longrightarrow {}^{239}\mathrm{Pu}$

9.4 Natural radioactivity

The soil activity

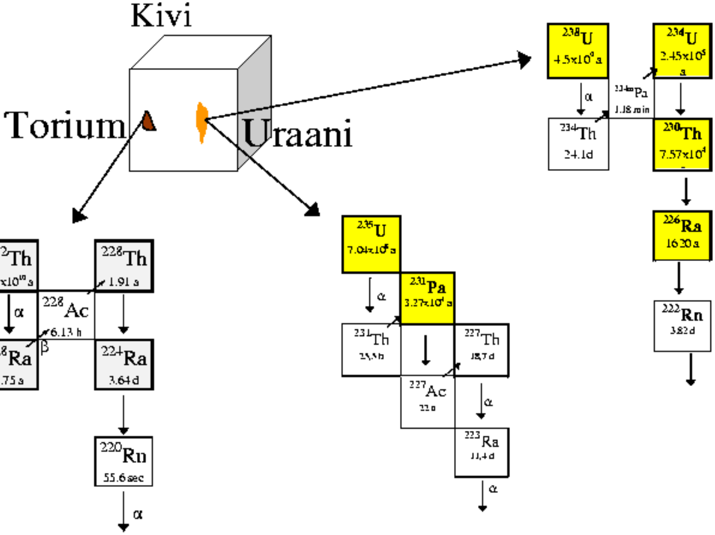
- Estimation
  A one square-mile area and one-foot thick piece of soil, having the total volume of approximately 8×10^5 m^3.

Element	Activity	Mass	Total activity
Uranium	25 Bq/kg	2200 kg	31 GBq
Thorium	40 Bq/kg	12000 kg	52 GBq
Potassium (^{40}K)	400 Bq/kg	2000 kg	500 GBq
Radium	48 Bq/kg	1.7 g	63 GBq
Radon	10 kBq/m^3	11 μg	7 GBq
TOTAL			$>$653 GBq

Typical values have been used, local variations exist

9.4 Natural radioactivity

Radioactivity in rock



9.4 Natural radioactivity

The oceanic activity

- Amounts of water (volumes) [Ref. 1990 World Almanac]
  - Pasific Ocean $= 6.6 \times 10^{17}$ m^3
  - Atlantic ocean $= 3.1 \times 10^{17}$ m^3
  - All oceans $= 1.3 \times 10^{18}$ m^3

Element/ Isotope	Activity	Oceanic activity Pasific	Atlantic	All
Uranium	33 mBq/l	22 EBq	11 EBq	41 EBq
^{40}K	11 Bq/l	7400 EBq	3300 EBq	14000 EBq
Tritium	0.6 mBq/l	370 PBq	190 PBq	740 PBq
^{14}C	5 mBq/l	3 EBq	1.5 EBq	6.7 EBq
^{87}Rb	1.1 Bq/l	700 EBq	330 EBq	1300 EBq

Ref. 1971 Radioactivity in the Marine Environment,
National Academy of Sciences

9.4 Natural radioactivity

In construction materials

Material		Uranium		Thorium		Potassium
	ppm	[mBq/g]	ppm	[mBq/g]	ppm	[mBq/g]
graniite	4.7	63	2	8	4	1184
sandstone	0.45	6	1.7	7	1.4	414
cement	3.4	46	5.1	21	0.8	237
limestone concrete	2.3	31	2.1	8.5	0.3	89
sandstone concrete	0.8	11	2.1	8.5	1.3	385
dry wallboard	1.0	14	3	12	0.3	89

Figures are typical values

9.5 Natural radioactivity as background

Radioactive series – 1

- Uranium ($Z = 92$) and thorium ($Z = 90$) isotopes and their daughter activities (like radon, Z=86) exist as impurities in all materials found in the nature
  - Th-series : ^{232}Th
  - U-series : ^{238}U
    ➙ the problem comes usually from ^{208}Tl and ^{214}Bi (γ-rays)
  - Ac-series : ^{235}U
- Protection, by liquid purification or clean method of material production
  - liquid scintillation detectors
    [J.B. Benzinger et al., NIM A417 (1998) 278]
  - electrolytically manufactured copper
    [R.L. Brodzinski et al., NIM A292 (1990) 337]
  - CVD (Chemical Vapor Deposited) nickel
    [J. Boger et al., NIM A449 (2000) 172]

9.5 Natural radioactivity as background

Radioactive series – 2

- For the (neutrinoless) double β-decay
  - lifetimes of the decay chains are proportional to the age of the universe, but they are small compared to the (neutrinoless) double β-decay activities
    - ➙ only a small amount of Uranium or Thorium isotopes may cause difficulties
    - ➙ ^{208}Tl and ^{214}Bi have high Q-values
- Isotopes ^{3}H, ^{14}C, and ^{40}K have low Q-value
  - do not generally disturb $\beta\beta$-experiments
  - do disturb those $\beta\beta$-experiments in which the sensitivity is low enough for dark matter searches
    - ➙ WIMPs elastic scattering ➙ low energy

9.5 Natural radioactivity as background

Radon

- Radon (^{220}Rn ja ^{222}Rn)
  - $T_{1/2}(^{220}\mathrm{Rn}) \approx 1$ min
  - $T_{1/2}(^{222}\mathrm{Rn}) \approx 4$ days ("nasty")
  - gaseous material
    - ➙ travels easily in all places
    - ➙ diffuses easily through materials
  - daughter activities stack easily on dust or electrostatic surfaces
  - protection
    - ➙ tight structure, overpressure
    - ➙ efficient air condition

9.6 Cosmic-ray induced activity as background

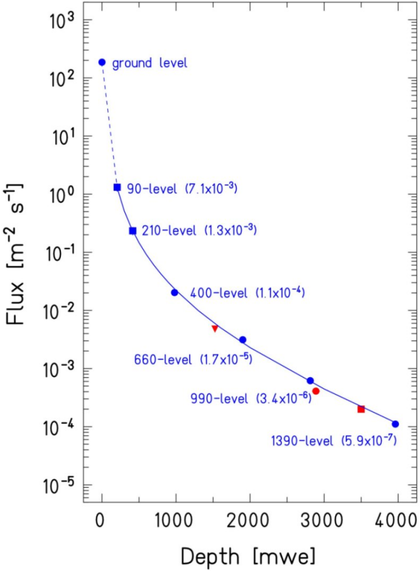
Cosmogenics – 1

- There are several various cosmic-ray induced reactions that may produce long-lived radioactive isotopes
  - muons, neutrons, protons, ...
  - decay energy (Q-value) varies from low to high energies
    - ➙ high-energy part may cause problems for double β-decay experiments (2–3 MeV)
    - ➙ low-energy part may cause problems for dark matter searches (– 100 keV)
- Cosmogenics can be produced in the detector material or in the detector schielding material
  - for example, ^{68}Ge ($T_{1/2} = 271$ d) is created in interactions of fast neutrons ($E > 100$ MeV) and ^{76}Ge (stable)
  - fast neutrons (and other particles, as electrons) are produced by high-energy muons
    - ➙ anti-coindicence with arriving muon helps to reduce fast-neutron induced events but it does not help to reduce cosmogenics of being created in the detector

9.6 Cosmic-ray induced activity as background

Cosmogenics – 2

- Cosmic-ray induced muons
  - the muon flux at the Earth surface $\Phi_\mu \sim$100–150 m^{-2}s^{-1}
- Protection
  - underground laboratories
  - cosmic-ray induced muon flux attenuates at the rock (or in any material)
  - $\sim$1400 metres of rock is equivalent with $\sim$4000 metres of water



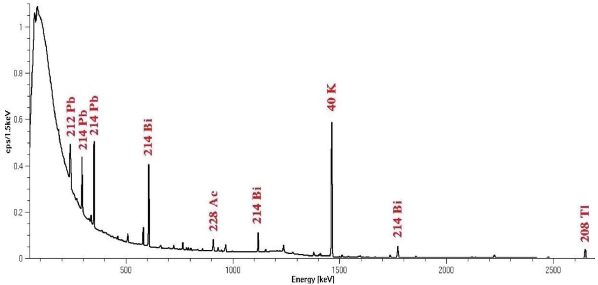
9.7 Artificial radioactivity as background

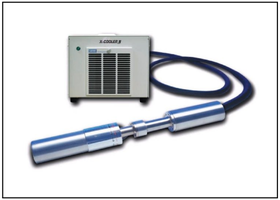
Man made

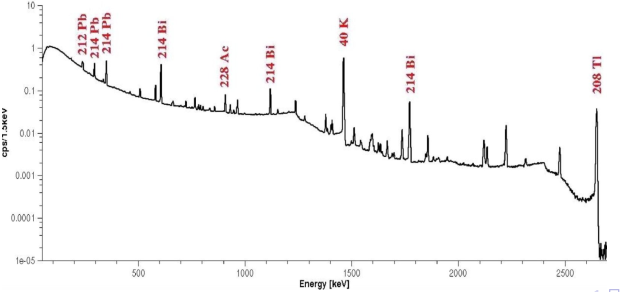
- Nuclear bomb test at the atmosphere
  ➙ 10^5 Bq ^{239,240}Pu spread at the Earth surface
- Accidents in nuclear power plants
  ➙ long-lived isotopes ^{90}Sr, ^{137}Cs, Pu spread in the environment
  ➙ radioactive noble-gas isotopes ^{42}Ar and ^{85}Kr
- Artificial radioactivity is not usually a problem for sensitive physics experiments

9.8 Example: Gamma-ray background

Measured at Pyhäsalmi mine at the depth 75 m



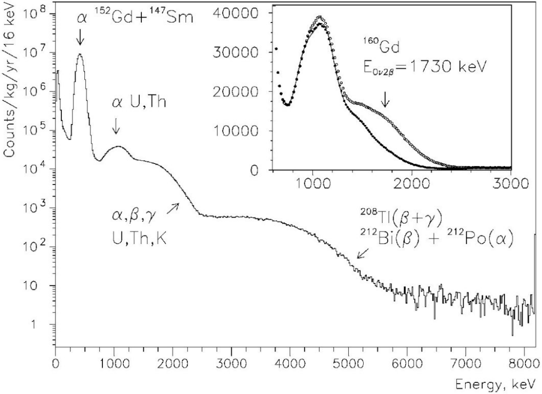




9.8 Example of background spectrum

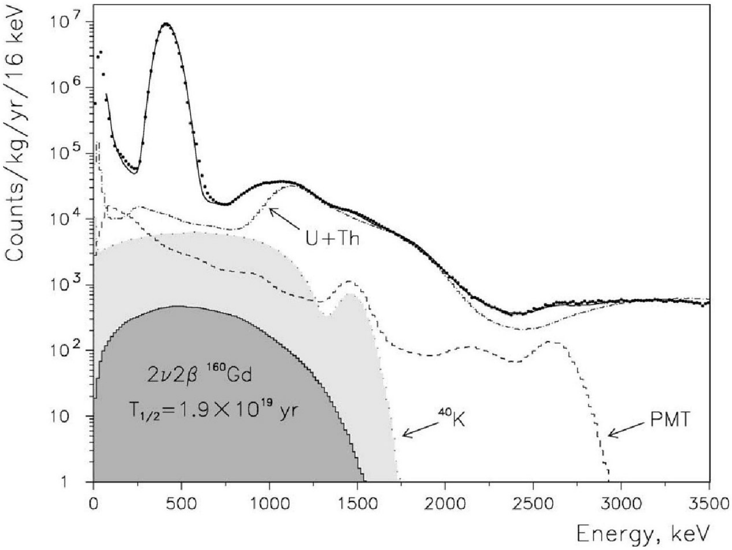
in double β-decay – 1

- Detector: Gd_2SiO_5:Ce (GSO)
  (Cerium-doped gadolinium silicate scintillation detector)
- Solotvina Underground Laboratory, salt mine 430 metres underground (1000 mwe)
- Measurement time: 13950 h
- The size of GSO crystal: 95 cm^3
- Muons: 1.7×10^{-6} $cm^{-2} \cdot s^{-1}$
- Neutrons: 2.7×10^{-6} $cm^{-2} \cdot s^{-1}$
- Radon in air: < 30 Bq/m^3



9.8 Example of background spectrum

in double β-decay – 2



9.8 Example: Borexino

General

- Currently the most sensitive detector in neutrino physics
  - 278 tons of liquid scintillator and 889 tons of buffer shielding
- Main aim to measure the 862-keV ^{7}Be neutrino flux from the Sun
  - the flux, according to the standard solar model, at the Earth surface is $\sim 4.3\times10^9$ cm$^{-2}\cdot$s^{-1}
- That flux produces 0.5 event/day/ton of scintillation material from $\nu - e$ scattering
- The liquid scintillator is a solution of 1.5 g/l of PPO (2,5-diphenyloxazole) in pseudocumene (1,2,4-trimethylbenzene, PC)
  - chosen due to relatively simple purification process and appropriate scintillation properties
- In order to detect the flux of this order requires radiopurity levels shown in the table next page

9.8 Example: Borexino

Radiopurity requirements

Radioisotope	Source	Typical level in scintillator without purification	Removal strategy	Design level (<1 cpd/100 ton)
^{14}C	Cosmic ray activation of ^{14}N	$^{14}C/^{12}C \sim 10^{-12}$. Corresponds to equilibrium from cosmic radiation at earth's surface	Petroleum derivative (old carbon)	$^{14}C/^{12}C \sim 10^{18}$
^{7}Be	Cosmic ray activation of ^{12}C	2.7×10^{3} cpd/ton. Corresponds to equilibrium for cosmic ray activation of ^{12}C to ^{7}Be at earth's surface	Distillation and underground storage of scintillator	<0.01 cpd/ton
^{222}Rn	Air and emanation from materials	1.3×10^{7} cpd/ton. Corresponds to equilibrium Rn absorption into PC for air with $^{222}Rn = 10$–$100\ Bq/m^3$ air	Nitrogen stripping	<0.01 cpd/ton
^{210}Bi	^{210}Pb decay	2×10^{4} cpd/ton. Corresponds to ^{210}Pb decay after exposing surface of the containment vessel to air with $10\ Bq/m^3$ ^{222}Rn for 1 year.	Surface cleaning	
^{210}Po	^{210}Pb decay	2×10^{4} cpd/ton. Corresponds to ^{210}Pb decay after exposing surface of the containment vessel to air with $10\ Bq/m^3$ ^{222}Rn for 1 year	Surface cleaning	
^{238}U	Suspended dust, organometallics	10^{4} cpd/ton (includes the $^{238}U \rightarrow {}^{206}Pb$ decay chain) $<10^{-12}$ g-U/g-scintillator Corresponds to 1 g-dust suspended in 1 ton of scintillator. Dust has U content equal to average of earth's crust, 10^{-6} g-U/g-dust	Distillation, filtration	$<10^{-17}$ g-U/g-scintillator
^{232}Th	Suspended dust, organometallics	10^{4} cpd/ton $<10^{-12}$ g-Th/g-scintillator. Corresponds to 1 g-dust suspended in 1 ton of scintillator. Dust has Th content equal to average of earth's crust, 10^{-5} g-Th/g-dust	Distillation, filtration	$<10^{-17}$ g-Th/g-scintillator
^{40}K	Contaminant found in fluor	2700 cpd/ton $\sim 10^{-9}$ g-K/g-scintillator Corresponds to scintillator with 1.5 g-PPO/L and PPO has 10^{-6} g-K/g-PPO.	Water extraction, filtration and distillation of fluor solution	$<10^{-14}$ g-K/g-scintillator
^{39}Ar	Air	200 cpd/ton. Corresponds to equilibrium Ar absorption into PC for air with $^{39}Ar = 13\ mBq/m^3$ air	Nitrogen stripping, leak-tight system	<500 nBq/ m−−N_2
^{85}Kr	Air	4.3×10^{4} cpd/ton. Corresponds to equilibrium Kr absorption into PC for air with $^{85}Kr =$ Bq/m^3 air	Nitrogen stripping, leak-tight system	$<100\ nBq/m^3$-N_2

9.8 Example: Borexino

Purification

- Distillation
  - the most effective process to improve the optical clarity of the scintillator
  - highly effective of reducing several of the radioactive impurities in the scintillator – does not remove noble-gas impurities Ar, Kr and Rn
- Nitrogen stripping
  - Ar, Kr and Rn could also be removed using a second line of distillation column
  - in Borexino noble-gases are removed using a separate gas-stripping operation (nitrogen)
- PPO
  - commercial product, with too high contamination level of K (level of ppm)
  - purified by modified distillation process

9.8 Example: Borexino

The detector and purification system