Estimate of the ^{42}Ar content in the Earth's atmosphere

Kornoukhov Vasily

Institute of Theoretical and Experimental Physics/
Institute of Nuclear Research RAS

Moscow

Decay scheme of $^{42}\mathrm{Ar}$

$^{42}\mathrm{Ar}$ (33 yr, $Q_{\beta} = 600$ keV)

$^{42}\mathrm{K}$ (12.36 h, $Q_{\beta} = 3.52$ MeV)

$E_{\gamma} = 1.524$ MeV

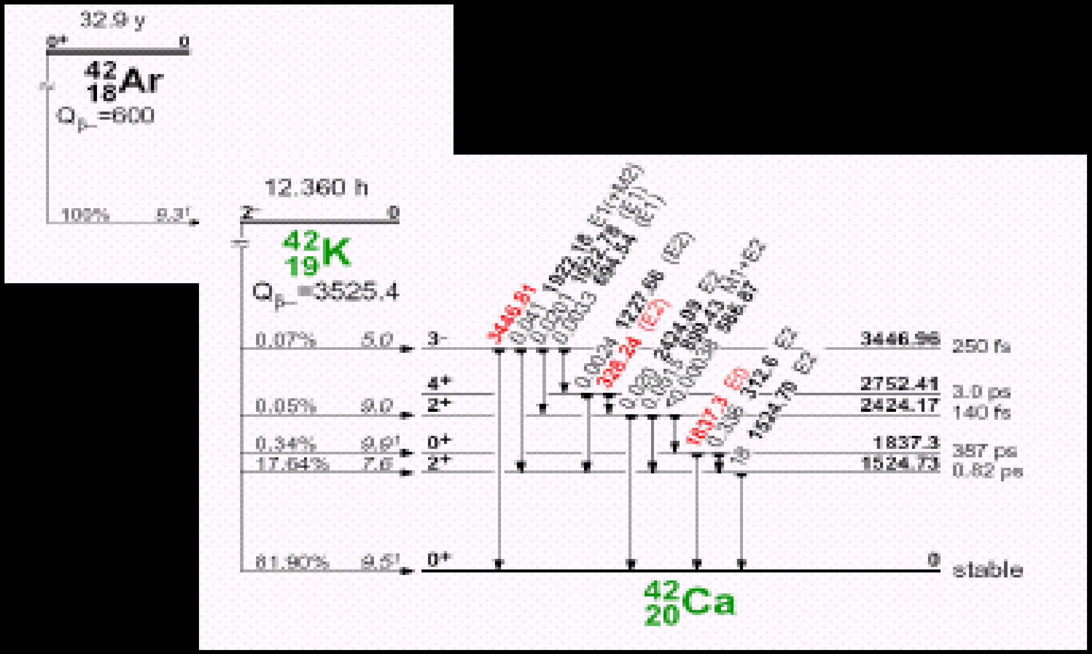
1.922 MeV,

2.423 MeV..

Decay scheme of ^{42}Ar

Bgd. in LAr: example ^{42}Ar

^{42}Ar / ^{nat}Ar = $3 \cdot 10^{-21}$ (30 μBq/kg) [Barabash et al., LAr-TPC @ LNGS]



References to the theme

- A.S.Barabash, V.N.Kornoukhov, V.E.Jants

  NIM A385 (1997) 530-534

- A.J.Peurrung, T.W.Bowyer, R.A.Craig, P.L.Reeder

  NIM A396 (1997) 425-426

^{42}Ar production modes

- A two-fold neutron capture process starting with the ^{40}Ar isotope:

$$^{40}Ar(n,\gamma)^{41}Ar,$$

$$^{41}Ar(n,\gamma)^{42}Ar$$

- Spallation reactions from the cosmic ray nucleon component on ^{40}Ar:

$$^{40}Ar(\alpha,2p)^{42}Ar$$

- Interactions of cosmic ray muons with the nuclei of the atmosphere and rocks near the surface of the Earth → negligible.

Two-fold neutron capture

$$^{40}Ar(n,\gamma)^{41}Ar$$

$$^{41}Ar(n,\gamma)^{42}Ar$$

The sources of neutrons in the atmosphere:

- ***from cosmic rays (**$< 10^{-42}$ of ^{42}Ar / ^{nat}Ar**);***
- ***from nuclear bomb tests (!)***

$t_{1/2}(41) = 1.83\ h$ → ***high flux of neutrons***

Bomb testing

- 1st stage: 1945-1957
- 2d stage: 1961-1962

Total energy release ~ 400 Mtn

- 1 explosion → 60 (90?) Mtn (30.10.1961)
- 3 explosions → 30 Mtn
- 1 explosion → 25 Mtn

^{42}Ar yield in bomb testing

$$N(42) = (1/8\pi) \times \sigma(40) \times \sigma(41) \times n(40) \times (\varphi \cdot t) \times dV$$

$$N(42) = (1/8\pi) \times \sigma(40) \times \sigma(41) \times n(40) \times N^2 \times P^2 \times \int_{r_{min}}^{\text{few km}} \exp(-2\, r/L)/(1/r^2)\, dr$$

- L - fast neutron attenuation length, $L = 2 \cdot 10^4$ cm
- $\sigma(40) = 0.65 \cdot 10^{-24}$ cm^2
- $\sigma(41) = 0.5 \cdot 10^{-24}$ cm^2
- $n(40) = 2.5 \cdot 10^{17}$ cm^{-3}

Neutrons production

Types of weapons:

1. nuclear bomb (U/Pu fission);

$N_n \sim 2.25 \cdot 10^{26}$ neutrons/Mtn

2. thermonuclear bomb:

- based on liquid deuterium;
- based on chemical compound of D and ^6L

$N_n \sim 2.25 \cdot 10^{26}$ neutrons/Mtn

^{42}Ar yield calculation

$$N(42)=1.64 \cdot 10^{20} \cdot P^2 \cdot m \cdot \int_{r_{min}}^{\text{few km}} \exp(-2\, r/L)/(1/r^2)\, dr$$

Where r_{min} – radius of scattering debris

$$r_{min} = f(P, Mtn)$$

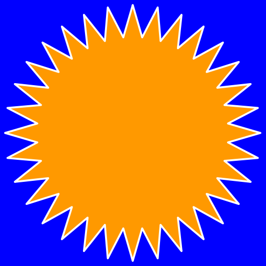
1st stage of the explosion, $t < 10^{-7}$ sec

- Energy release ~ $4.2 \cdot 10^{22}$ erg/Mtn:
  - → radiation;
  - → shock vawe.
- $t \sim (n*10) \cdot 10^{6}$ °C
- moderation of fast neutrons (on the light elements of TNT + the unspent nuclear charge + the matter of bomb shell)

2d stage of the explosion, $t \leq 10^{-5}$ sec;

- Expansion of the scattering debris ≡ ≡ the speed of shock vawe

$r = (E/\rho)^{0.2} \cdot t^{0.4}$



$r = 13$ m for $E \approx 1$ Mtn

3d stage of the explosion

- Partly moderated neutrons start to escape from the scattering bomb shell and interact with the nuclei of the air

- 60% of neutron flux $30\ \text{eV} \leq E \leq 1\ \text{MeV}$
- 40% of neutron flux $1\ \text{MeV} < E \leq 14\ \text{MeV}$

Estimation of ^{42}Ar production

$N \sim 3 \cdot 10^{20}$ atoms

($3 \cdot 10^{-22}$ atoms of ^{42}Ar / ^{nat}Ar atoms)

Overestimation due to the assumptions:

1. All neutrons are thermal ones → $k \geq 10$;
2. An air density is 2 times lower at heights of a few kilometers → $k \sim 2$

$N \sim 1.5 \cdot 10^{19}$ atoms

^{42}Ar after bomb testing

$\leq 1.5 \cdot 10^{-23}$ atoms of ^{42}Ar / ^{nat}Ar atoms

taking into account that nuclear testing in the Earth's atmosphere was finished in 1962

$\leq 6 \cdot 10^{-24}$ atoms of ^{42}Ar / ^{nat}Ar atoms

$^{40}Ar(\alpha,2p)^{42}Ar$ (1)

α-particles ~ 14% of proton flux of cosmic ray

$$\lambda\cdot N(42) = \sigma\cdot\varphi\cdot n(40)\cdot S$$

Where

- $\sigma(\alpha,2p) = 2.5$ mb (? uncertainty $k = 2$)
- $\varphi(\alpha$ particles$) = 0.1\ \mathrm{m^{-2}\ sec^{-1}}$ (200 MeV – 1 GeV)
- $S = 4\cdot\pi\cdot R^2 = 5.15\cdot 10^{14}\ \mathrm{m}^2$ (R – the Earth' radius)
- The range of α particles in the air:

$$R(E) = 2.9\ \mathrm{g\cdot cm^{-2}}\cdot(E/200)^{1.8} = 30\ \mathrm{g\cdot cm^{-2}}$$

then $n(40) = 4.316\cdot 10^{21}\ \mathrm{at\cdot cm^{-2}}$

$$N(40) = 5.15\cdot 10^{14}*10^{4}*4.316\cdot 10^{21} = 2.2*10^{40}$$

^{40}Ar(α,2p)^{42}Ar (2)

$$\lambda \cdot N(42) = 2.5 \text{ mb}^* \, 0.1 \text{ m}^{-2} \text{ sec}^{-1} \, {}^*2.2^*10^{40} \text{ at} =$$

$$= 6^*10^{12} \text{ sec}^{-1}$$

$$N(42) = 9 \cdot 10^{21} \text{ atoms}$$

$$9 \cdot 10^{21} / 10^{42} = 9 \cdot 10^{-21} \sim 10^{-20} \text{ at } {}^{42}\text{Ar/at Ar}$$

CONCLUSION (1)

1. Bomb testing:

$\leq \quad 6 \cdot 10^{-24}$ atoms ^{42}Ar / ^{nat}Ar

2. Spallation reactions from the cosmic ray nucleon component: $^{40}Ar(\alpha,2p)^{42}Ar$

$\leq \quad 9 \cdot 10^{-21}$ atoms ^{42}Ar / ^{nat}Ar

3. From experiment (A.Barabash, TAUP2001):

$\leq 3 \cdot 10^{-21}$ atoms ^{42}Ar / ^{nat}Ar

CONCLUSION (2)

If

$\leq 3\cdot10^{-21}$ atoms ^{42}Ar /Ar → ≤ 26 μBq/kg

→ ~ 2.2 decay/day

How to measure the ^{42}Ar content?

→ 42Ar (beta)

→ 42K (beta + γ)