CREATION OF RADIACTIVE C-14 UNDER THUNDERSTORM ATMOSPHERIC FLASHES

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LXXI International conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies"

Sep 20 – 25, 2021.

Thunderstorm flashes. 1.

The main purpose of the work – to evaluate production of the radiocarbon C-14 in conditions of the thunderstorm.

Radiocarbon is created in the atmosphere under cosmic fluxes in 14N(n,p)C14 with yield ~ 472 g-mole per year [1] . The isotope C-14 ($T_{1/2}$ = 5700 years) is important "instrument" for radiochronology.

Steps in history of the problem of C14 creation:

1) secular fluctuations of radiocarbon in tree rings [2];
   (do we understand C14 creation on the Earth ?)
1) The hypothesis of fusion $D+D \rightarrow 3He+n$ (E_n=2.5 MeV);
2) Evidence of neutron excess at thunderstorms [3];
3) The model of relativistic electron avalanche [4].

The typical altitudes of the thunderstorm clouds are 4-6 km. But the maximum height is determined by tropopause and can reach 17 km [6]

$< \Delta Q >$ = ~ 20 coulombs and more

The typiical strength of electric fields in clouds U = 100-300 kV/m

The most largest registrated fields reached ~ 1000 kV/m [7,8]

For our task (14C production) the key processes are: escape of x- and γ-rays at e^- decelerated in coulomb atom fields (bremsstraglung), photoproduction of neutrons (γ, n) and (n,p)-reaction on N-14: 14N(n,p)14C

[1] Roth, R., Joos F. (2013). A reconstruction of radiocarbon production and total solar irradiance from the Holocene 14C and CO2 records: implications of data and model uncertainties. Clim. Past, 9, p.1879.

[2] Suess, H.E. (1965). Secular variations of the cosmic-ray-produced carbon C14 in the atmosphere and their interpretations. J. Geophys. Res., 70, p.5937.

[3] Shah, G.N., Razdan, H., Bhat, C.L., Ali, Q.M. (1985). Neutron generation in lightning bolts. Nature, 313. p.773

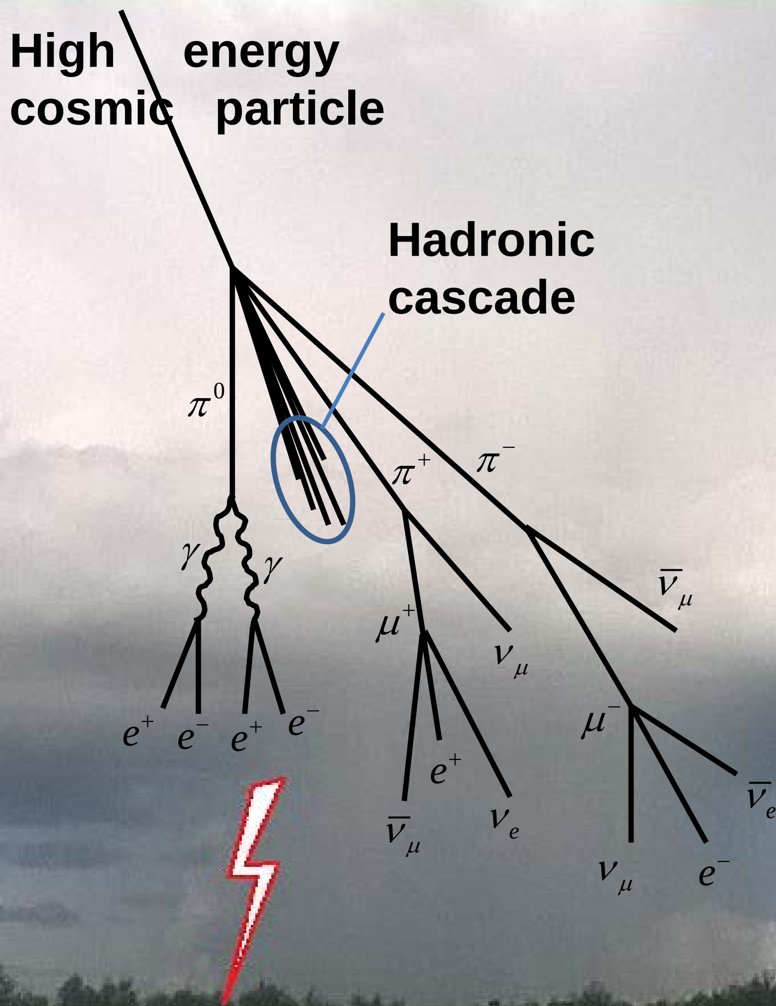
[4] Gurevich, A.V., Milikh, G.M., and Roussel-Dupre R. (1992). Runaway electron Mechanism of air breakdown and preconditioning during a thunder storm. Phys. Lett. A, 165, 463

[6] Pan, L. L., and L. A. Munchak (2011), Relationship of cloud top to the tropopause and jet structure from CALIPSO data, J. Geophys. Res., 116, D12201,

[7] Gunn, R. (1948). Electric field intensity inside of natural clouds. J. Appl. Phys. 19, p.481.

[8] Winn,W.P., Schwede,G.W., Moore, C.B. (1974). Measurements of electric fields in thunderclouds. J. Geophys. Res. Oceans and Atmospheres, 79. p.1761

Thunderstorm flashes. 2.



The most discussed model for origin of the thunderstorm flash is generation of the electron avalanche by means the very energetic cosmic particle
(as in case of extensive atmospheric showers).
The necessary condition for the flash is the presence of the strong electric fields [1]
with Ethreshold = 284 kV/m (at the sea level).
The most fast electrons move along the electric field direction, creating the leader group of MeV-energy. The next propagate the electron with intermediate energy and the last slow electron (with energy below several keV). Along the path the avalanche is strongly multiplicated.

Another widely known theory is the "thermal theory" of creation, evolution and increasing of electron population in the avalanche. The average energy of such "thermal" avalanche is about ~ 200 keV. But for the more strong electric fields are requested for realization of this scenario [2]

[1] Joseph R. Dwyer · David M. Smith · Steven A. Cummer. High-Energy Atmospheric Physics: Terrestrial Gamma-Ray Flashes and Related Phenomena. Space
Sci Rev (2012) 173:133–196. DOI 10.1007/s11214-012-9894-0
[2] A.V. Gurevich, On the Theory of Runaway Electrons // Sov. Phys. JETP 12(5), 904–912 (1961).

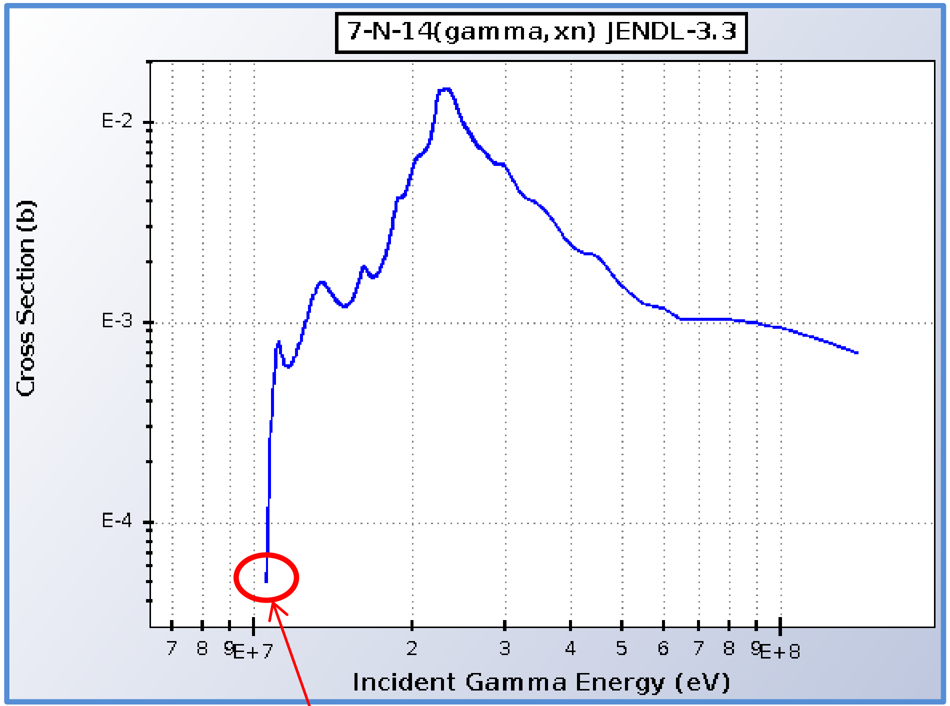
Creation of C-14 under condition of flashes.

The processes which led to C-14 creation:

- **Bremsstraglung** of γ–radiation at the electron slow down (electron avalanche);

- **photonuclear**
- **production of neutrons**;
  the main reactions are N-14(γ,Xn);
  (N-14 is the main air isotope - 78% , in volume)

- **Creation of C-14**
  in the reaction N-14(n,p)C-14



$E_{threshold}$ = 10.6 MeV

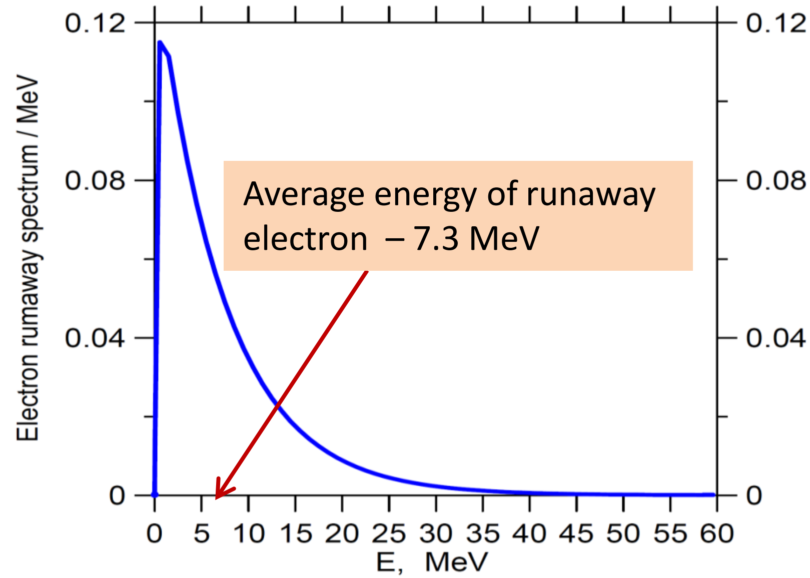
The item of some isotope creation under condition of thunderstorm flashes were stated earlier (the evidence of isotopes creation was reported in the work [Enoto, T. et al. Nature 551, 481–484 (2017)], discussion of the problem is presented in the work [Babich, L. P. Geophys. Res. Lett. 44, ttp://dx.doi.org/10.1002/2017GL075131 (2017)]).

Energetic electrons in the flash avalanche. Spectrum. Part of energetic electrons in the avalanche

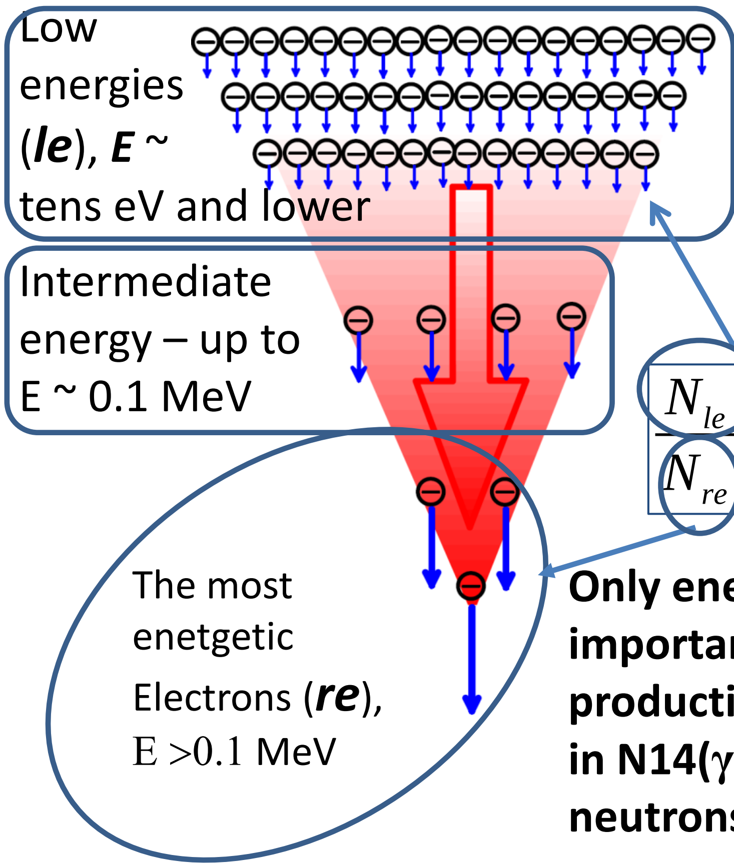
For the task of C-14 production (in (γ,n)- **threshold** reaction and then in (n,p)-reaction) the key point is the spectrum of the runaway **energetic** electron (***relativistic***) in the avalanche. This electron model spectrum was [1]:

$$f_{runaway} \sim \exp\left(\frac{-\varepsilon}{7.3\ \mathrm{MeV}}\right),$$

where ε is the electron runaway energy.



Scheme of the electron avalanche in the flash



$$\frac{N_{le}}{N_{re}} > \sim 1E+4$$ x ρ(*H*)/ρ(*H*=0)

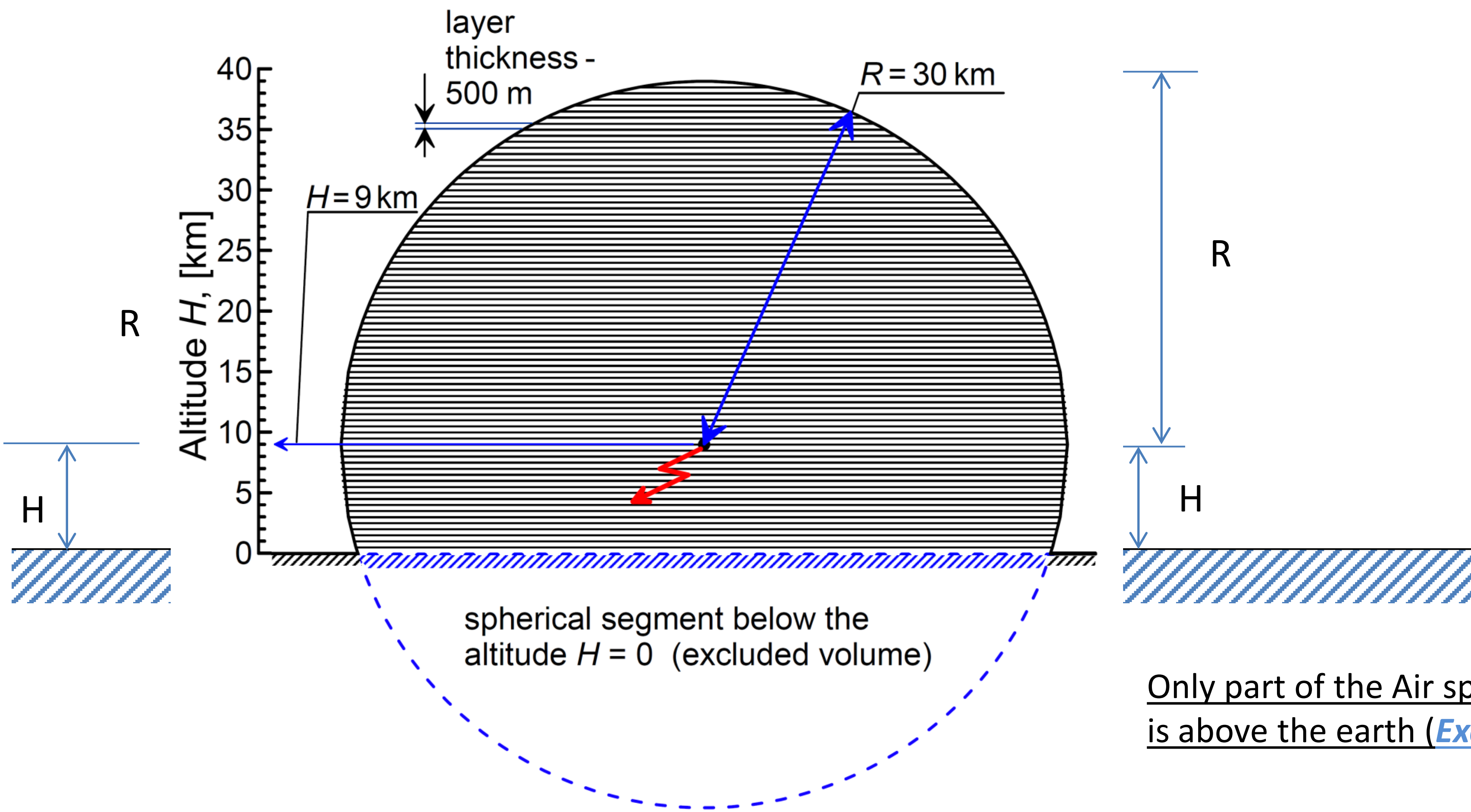
ρ(H) – density at the altitude *H*

Only energetic electrons important for hard photon production. Hard photons in N14(γ ,Xn)-reaction give neutrons ! (E_{thr} ~ 10.6 MeV)

[1] Dwyer, J. R., and L. P. Babich (2011), Low-energy electron production by relativistic runaway electron avalanches in air, J. Geophys. Res., 116, A09301, doi:10.1029/2011JA016494

GEOMETRY (PLANE LAYERS in the SPHERE)

The center of the air sphere corresponds the geometrical **origin of the flash** (with pressure corresponding to the altitude H [km])



Only part of the Air sphere is above the earth (***Example)***

Approaches in the task of C-14 isotope modeling

- For neutron [produced in the key reaction N-14(γ, Xn)] transport we used the data of ENDF/B-VIII and FENDL libraries; (also we use the data of TENDL, EAF libraries).

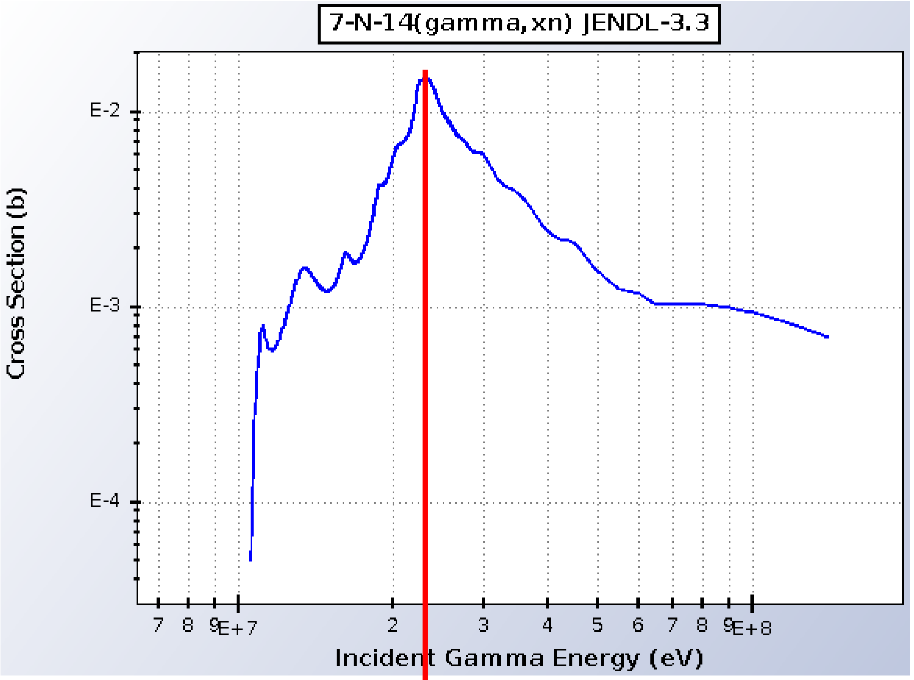
Basing on the task (to evaluate C-14 production) we allow the next approach:

- The electrons slow down in the air without connection with the discharge channel (this assumption is based on the key role of the energetic γ-radiation (with energy from about $E_{threshold}$ of N-14(γ, Xn)-reaction 10.6 MeV);
- The electrons are escaped isotropically.

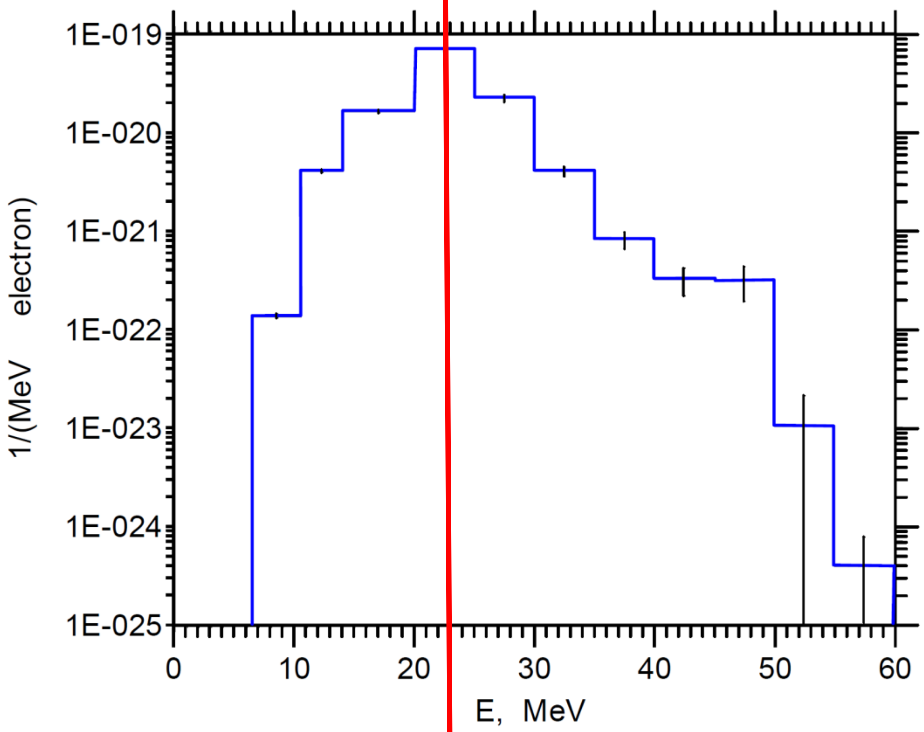
For the modeling of processes of bremsstrahlung creation of x-rays and propagation of the photons, pair production, Compton scattering, Rayleigh scattering et. al., production of neutrons, them interaction and moderation it was used the MCNPX code.

The modeling was realized at different altitudes (taking into calculation change of the atmospheric pressure) for height up 15 km (that correspond and cover the most number of thundestorms).

Spectrum of producing neutrons



Spectrum of neutron origin in the air (in N14(γ,Xn)-reaction)

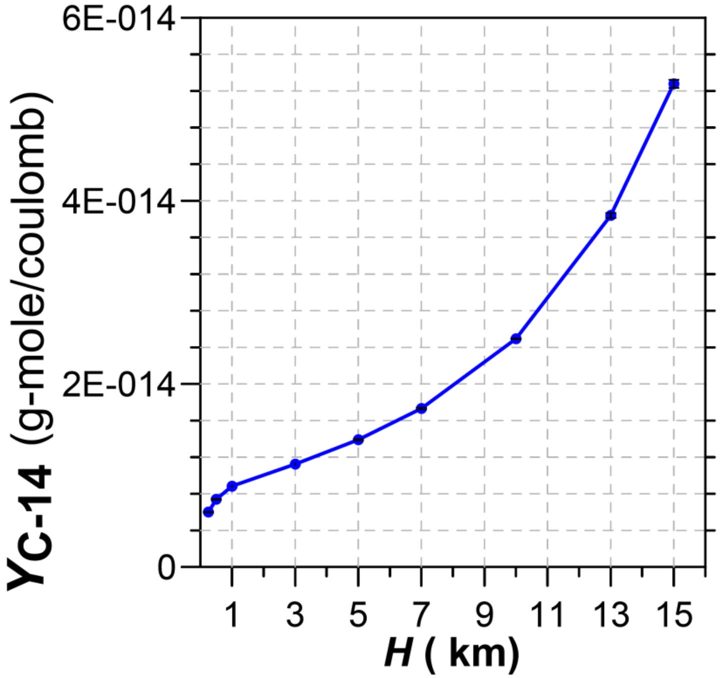


Maximum of Cross Section at E=23.35 MeV ⟷ Maximum of Cross Section at E=23 MeV

In calculation of the producing neutron spectrum it were taken into account also addition the neutron creation in (γ,n)-reaction 16O ($E_{threshold}$ = 15.7 MeV) and 40Ar ($E_{threshold}$ = 10.0 MeV).
It is obtained: 14N, 16O and 40Ar are responsible for 75.3%, 15.7% and 9% of total neutrons yield.

Yield of the isotop C-14 under conditions of flashes

Yield of C-14 (from the flash of charge 1 coulomb) depending on the altitude of the flash



The total yield of C-14 per year is:

$$Y_{C-14} = \int_H F'(H)dH$$

where *F*(H) is complicated function (of solar activity, atmosphere condition, geographical coordinates).

We don't know *F*(H) !

But it is possible to obtaine the top limit for C-14 production from flashes:

number of flashes per year -~ 1.4E+9 [1];

if the charge of the flash – 10 coulombs (really the charge can be larger, [2]), then the **top limit for Yield of C-14 per year** is ~

~ $1.7 \cdot 10^{-14} \cdot 1.4 \cdot 10^{+9} \cdot 10 =$

$2.4 \cdot 10^{-4}$ [g-mole/year] (evaluation for H=7 km)

[1] Hugh J. Christian, Richard J. Blakeslee, Dennis J. Boccippio et al. Global frequency and distribution of lightning as observed from space by the Optical Transient Detector // JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. D1, 4005, doi:10.1029/2002JD002347, 2003.

[2] Pritindra Chowdhuri, MASARU Ishii, William Chisholm, Michael Marz et al. Parameters of lightning strokes: A review // Article in IEEE Transactions on Power Delivery · February 2005

Ionization to Bremssraghlung loss relation

<u>Slowing down of electrons</u>. In order to exclude the dependence on the matter density the rate of energy loss is given as (dE/dx)/ρ , where ρ - density of the matter (MeV · cm^2/g). (dE/dx)/ρ – is called (in terminology of ICRU Report 37) as **mass collision stopping** power and denoted as S_c / ρ .The mean energy loss per unit of pathlength includes the density parameter δ.

The realation of Ionization loss to Bremsstraghlung irradiation:

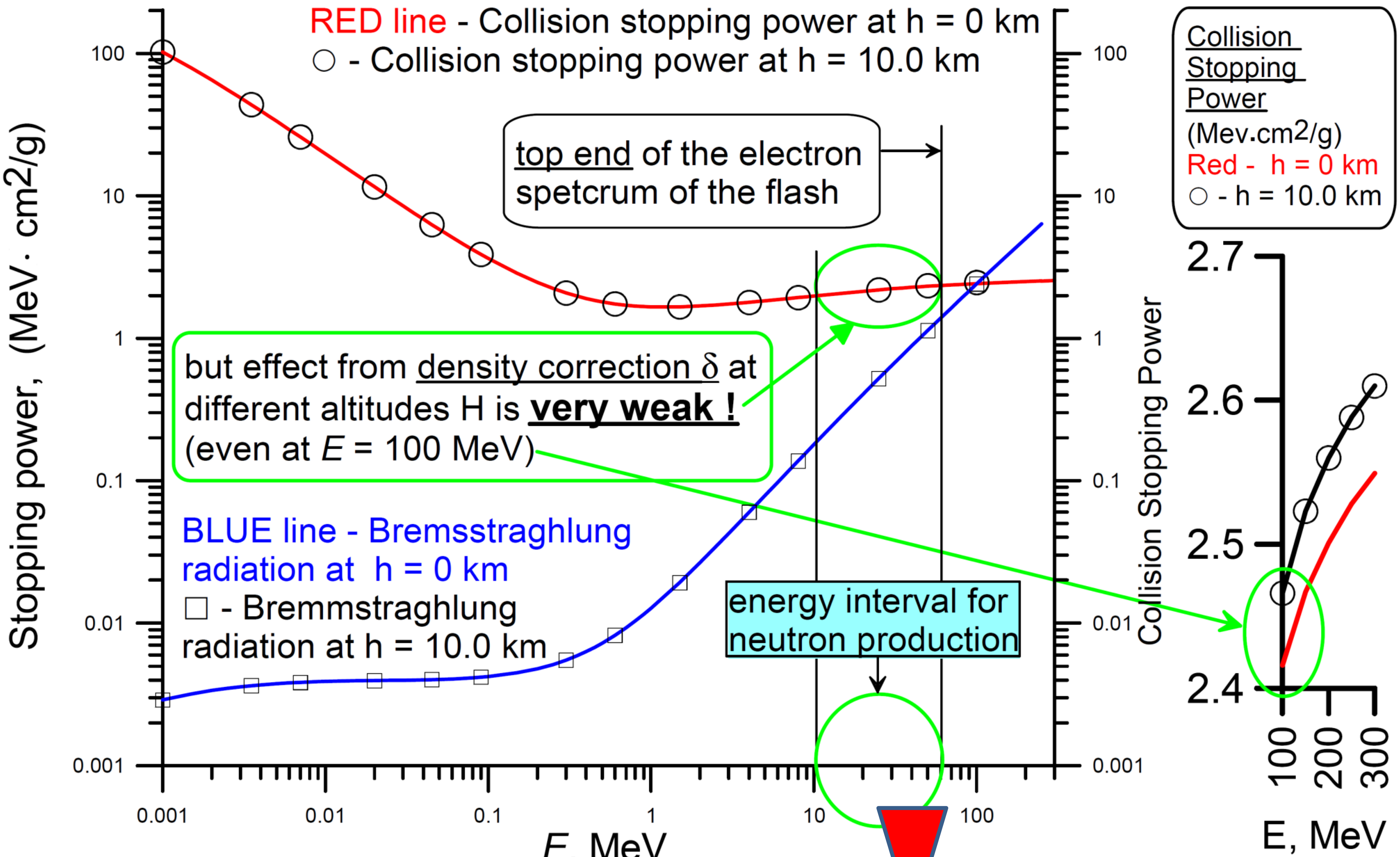
$$\frac{S_{collision}(T,\ \delta)}{\rho} \Big/ \frac{S_{radiative}(T)}{\rho},$$

where the density value ρ in ionization and bremsstraghlung loss is reduced.

But the weak dependence on matter density exists in $S_{\text{collision}}$ (T, δ) on correction density effect δ.

In gases the values of density effect δ is **<u>significant</u>** [about (several units) •0.1 at the pressure 1 atmosphere] and increase with pressure.

Ionization and Bremssraghlung loss. Density effect correction

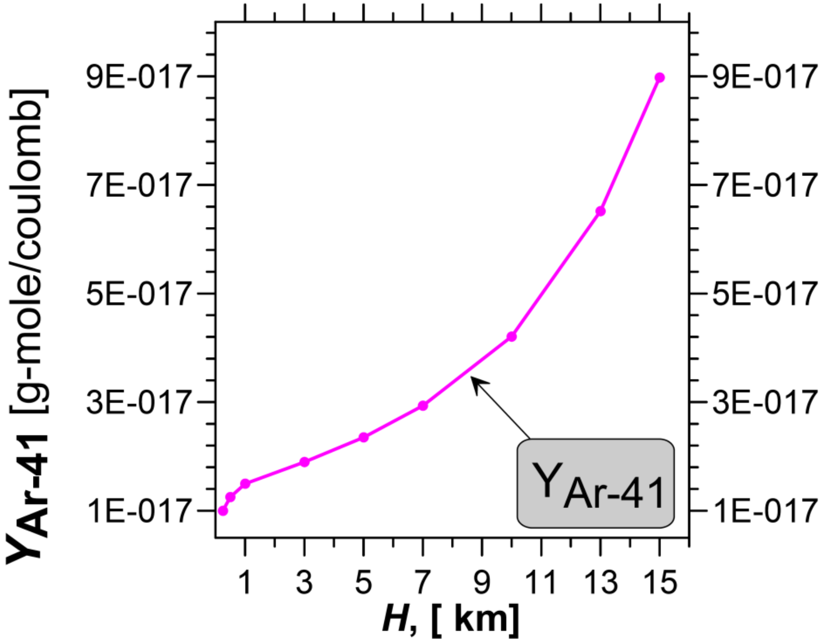


The yield of density effect correction on neutron production ! is very small

Yield of the isotop Ar-41 under conditions of flashes

Ar-40(n,γ)Ar-41; $T_{1/2}$ = 109.34 m, β^-(100%). [Argon – 0.934% (in volume) in the atmosphere, stable isotopes: 36Ar (0,337 %), 38Ar (0,063 %), 40Ar (99,600 %)]

Yield of Ar-141 (from the flash of charge 1 coulomb) depending on the altitude of the flash:



The yield evaluation of Ar-41 (and C-14 too) is obtained for relation of number of slow to relativistic electrons in the avalanche N_{le}/N_{re} >1E+4 (for relation N_{le}/N_{re} >1E+6 [according to alternative avalanche model] the yields will be in two orders smaller) [1,2].

Note that monitoring of the Ar-40(n,γ)Ag-14 reaction is well organized on the reactors and accelerators [3].

[1] Dwyer, J. R., and L. P. Babich (2011), Low-energy electron production by relativistic runaway electron avalanches in air, J. Geophys. Res., 116, A09301.
[2] Gurevich A.V., Zybin K.P., Medvedev Yu.V. 2006 Phys.Lett. A 349 331-339.
[3] Oyama, T., Nagaguro, S., Hagiwara, M., et al., Measurements and Characterization of Air Activation in J-PARC Main Ring. JPS Conf. Proc., (2021) 011147-1 - 011147-6.

Conclusion

It was obtained (in the simple model) the top limit for yield of the radiocarbon C-14 under the condition of the flash thunderstorm:

The top limit is evaliated as 2.4E-4 [g-mole/year], i.e. ~ 0.5E-4 % from C-14 production from cosmic irradiation.

On the discussed question of C-14 production in the atmosphere under conditions of thunderstorm it is possible to answer that the yield of radiocarbon C-14 from flashes is small (and can not change the total yield in the atmosphere).

The result allows to take off the problematic question on C-14 valuable yield in the additional channel of radiocarbon production.

Note, that the time decay of Ar-41 ($T_{1/2}$ = 109.34 m) is very attractive to consider it as convenient indicator (tracer) for C-14 production. But it is an exclusively complicated experimental task due to its very small yield.

Dear colleagues,
thank you a lot
for attention !