GENERATION OF RADIOCARBON C-14 IN THE AIR IN CONDITIONS OF THUNDERSTORMS

V.I. Lyashuk [1, 2, §]

[1] *Institute for Nuclear Researches of the Russian Academy of Sciences, Moscow, Russia*

[2] *National Research Center "Kurchatov Institute", Moscow, Russia*

The synthesis of isotopes is possible under conditions of power electric discharge in the atmosphere. It is extremely important to know the radioactive ^{14}C yield under thunderstorm conditions as additional channel of ^{14}C production relative to the main – cosmogenic one. Here we propose the gross model for evaluation of the upper limit of the ^{14}C yield, which creation was simulated for the altitudes up to 15 km. It is presented the results for yield of radioactive isotope ^{41}Ar which synthesis goes along with ^{14}C creation under thunderstorm conditions. It was obtained that the possible thunderstorm mechanisms of ^{14}C creation cannot compete with production originated from cosmogenic sources.

1. Introduction

The main mechanism of radiocarbon ^{14}C creation on the Earth is ensured by cosmogenic irradiation [1] with yield of 472 g-mole/year in the reaction of thermal neutrons with atmospheric nitrogen: ^{14}N(n,p)^{14}C. The generated isotope of ^{14}C is assimilated in the biomass (in the form of dioxide CO_2) and decays within it ($T_{1/2}$ =5700 y) that allows to date the age of the investigated organic materials.

Along with such cosmogenic generation it is possible the synthesis of the isotope ^{14}C under conditions of atmospheric thunderstorm: the electrons in the avalanche of the flash discharge slow down and escape bremsstrahlung *x*-rays; the escaped *x*-radiation produces the flux of photo-neutrons in interactions with air nitrogen in ^{14}N(γ,Xn)-reaction ($E_{threshold}$ = 10.6 MeV), where Xn – emission of X=1, 2 or more neutrons with maximal cross section at $E_\gamma \approx$ 23 MeV according to JENDL-3.3 nuclear reaction library [2]); the produced neutrons slow down and intensively create the radiocarbon in reaction ^{14}N(n,p) ^{14}C (cross section according to ENDF/B-VIII [3] is given in Fig.1; thermal cross section $\sigma_{np} \approx$ 1.8 b).

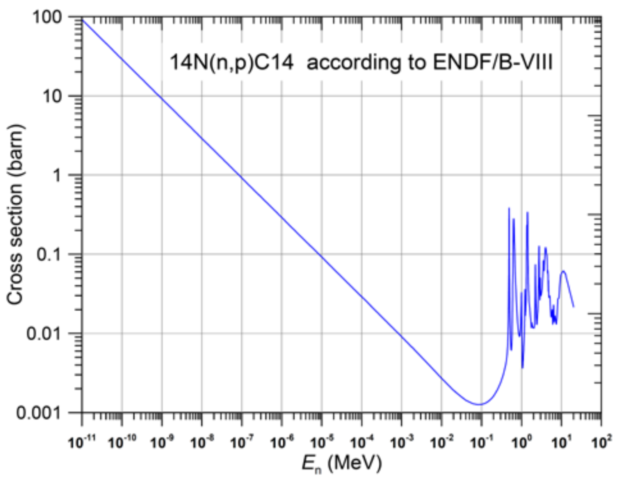

Fig. 1. Cross section of radiocarbon C-14 production in ^{14}N(n,p)^{14}C reaction according to the nuclear reaction library ENDF/B-VIII [3].

§ lyashuk@itep.ru

As neutron production is the threshold process, the ^{14}C synthesis can be realized only by means the relativistic electrons with energy higher than threshold of the reaction. The spectrum of these energetic electrons was applied as $f \sim \exp(-\varepsilon[\text{MeV}]/7.3)$ [4], where ε is the energy of the runaway electrons (i.e., electrons accelerated in the electric fields; the process was investigated by Wilson [5]). The spectrum spreads up to ~60 MeV ensuring the multiplication of the avalanche under condition of atmospheric electric fields in the thunderclouds. Namely relativistic electrons (E >1 MeV) move in the forward part of the flash discharge producing the low energy electrons in interactions (via ionization of the media), drawing them into the avalanche propagated and accelerated in the thundercloud electric field. In opposite the electrons, which energy decreases below the threshold about 100 eV, fall out the avalanche and form the dynamical equilibrium between involved and lost electrons. In the avalanche the number of low energy electrons N_{le} strongly exceed the relativistic ones N_{re}, the relation is $N_{le}/N_{re} \approx (1.3\times10^4)\times n$, where $n = \rho(H)/\rho(H=0)$ is the relation of the air density $\rho(H)$ at the altitude H to the density at the sea level (H = 0) [4]. So, the total charge of flashes is ensured namely by low energy electrons which part in the avalanche decreases for higher altitudes.

2. The Gross Model for Simulation of Isotope Creation

Taking into account the dependence of relation N_{le}/N_{re} from the air density the simulation was realized for the altitudes from the sea level up to the H =15 km (i.e., including approximately the upper charge layer at typical elevation H=(10–14) km) as the most of thunderclouds are distributed at these heights [6]. We use the spherical geometry with centers (the point source of energetic electrons of isotropic f-spectrum) at the indicated altitudes. The spheres are divided into plane layers (of 500 m thickness) with air density corresponding to their heights. In order to exclude the escape of the valuable part of neutrons (which were born in the sphere) the radii were increased up to 30 km. The scheme of geometry is given in the Fig. 2.

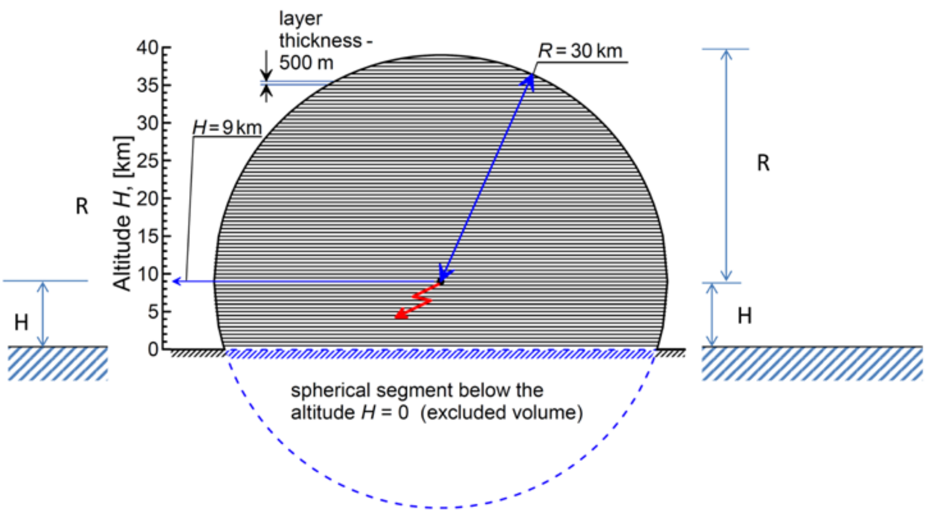

Figure 2. Geometry of the spherical-layers model for simulation of the particles transport and calculation of radiocarbon ^{14}C creation in the air under conditions of thunderstorms lightning (examples for lightning [indicated as arrow] origin at the altitude H = 9 km on the sea level). The spherical segment below the sea level (H =0) is excluded from ^{14}C accumulation.

As a result the percent of the escaping neutrons was lower than 1%. An example of the spectrum of generating neutrons at H=10 km is presented in the Fig. 3 (a). The maximum of the obtained spectrum ~ 23 MeV in Fig. 3 (a) is in good agreement with maximum of neutron production in $^{14}N(\gamma,Xn)$ reaction in Fig. 3 (b). Such a spherical-plane-layers formalism allowed to specify the yield of relativistic electrons N_{re} in the total $(N_{le} + N_{re})-$flux that was necessary for correct evaluation of ^{14}C production.

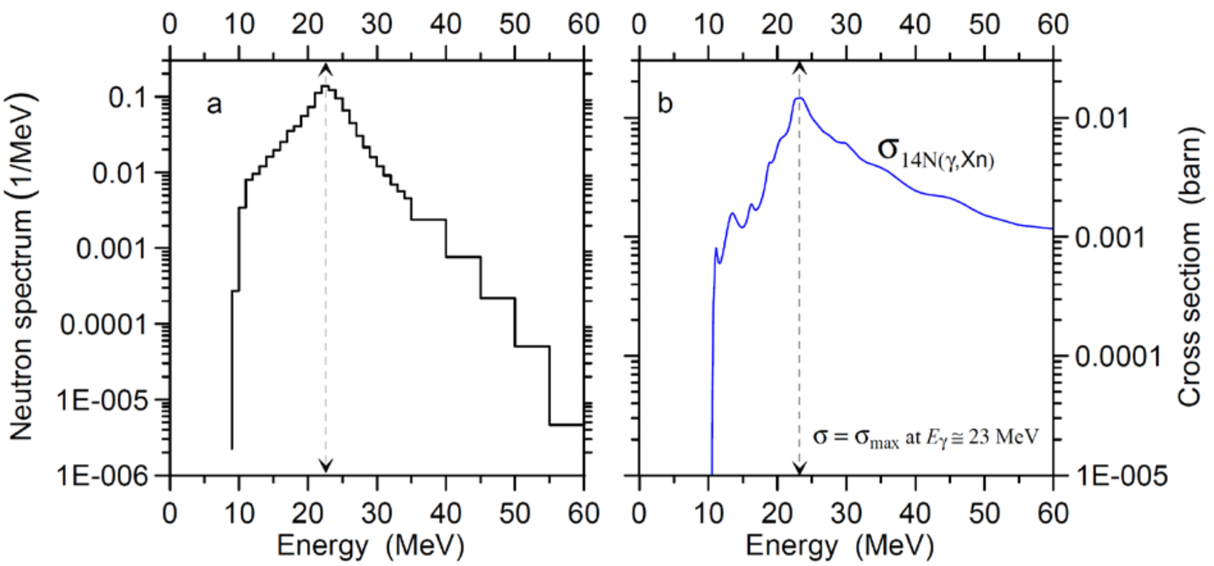

Figure 3. (a) Spectrum of neutrons produced in air under thunderstorm conditions. Generation of neutrons is accounted in the reactions: $^{14}N(\gamma,Xn)$, $^{16}O(\gamma,n)$ ^{15}O and $^{40}Ar(\gamma,n)^{39}Ar$. (b) Cross section of the main channel of neutron production $^{14}N(\gamma,Xn)$ (according to JENDL-3.3 [2]) by bremsstrahlung from electrons under thunderstorm flashes. The spectrum maximum is in good agreement with the maximum cross section of the main channel of neutron production $^{14}N(\gamma,Xn)$ (see (a)).

The modeling results (by means the code [7]) for radiocarbon ^{14}C yield depending on the altitude are shown in the Fig. 4.

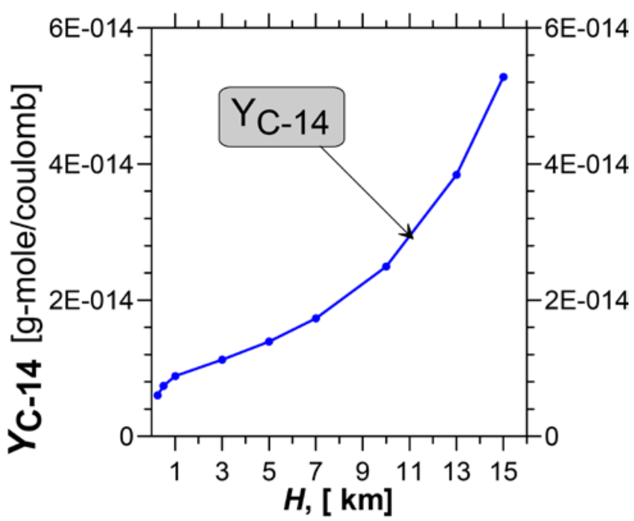

Figure 4. Yield of ^{14}C (in gram-molecules) depending on the altitude H (km) above the sea level. The yields correspond to one coulomb flash discharge under thunderstorm conditions.

For the equal discharges the drop of the low energy population N_{le} in the avalanche at increase of the altitude ensures rise of the ^{14}C yield. The results of isotope generation (in gramme-molecules) are normalized on the flash charge 1 coulomb. If the discharge occurs between thunderclouds in the horizontal plane (idealized case) then the normalized yield corresponds the function *Y*(*H*) in the Fig. 4. In common case the discharge goes between some altitudes *H1* and *H2*. The ^{14}C yield is calculated then as the integral along the discharge path and normalized yield will be between *Y(H1)* and *Y(H2)*.

3. The Upper Limit for Radiocarbon C-14 Production. Creation of Argon-41 under Thunderstorm Conditions

Let us evaluate the upper limit of ^{14}C production per year under the flash condition (knowing the number of flashes on the Earth per 1 year – 1.4×10^9 [8] and considering that the average flash charge is ~ 20 coulombs [6] and mean *H* = 7 km [6]): then production during the year is $Y_{C\text{-}14} = 1.7\times10^{-14}\times20\times1.4\times10^9 \simeq 5\times10^{-4}$ (g-mole/year) for the relation *R1*.
Creation of neutron flux ensures simultaneously also the production of ^{41}Ar isotope by the reaction $^{40}Ar(n,\gamma)^{41}Ar$ with significant cross section (see Fig.5).

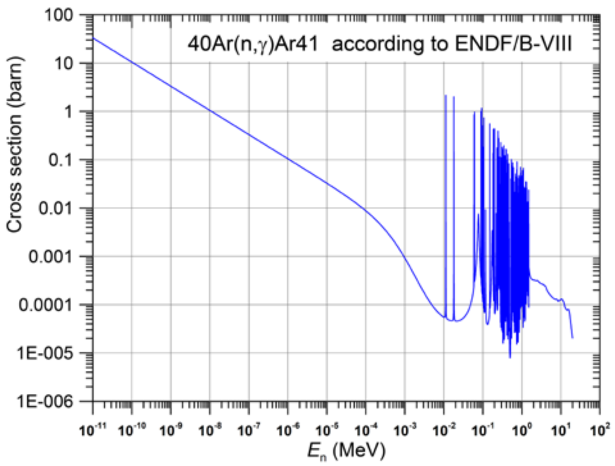

Figure 5. Cross section (barn) of the $^{40}Ar(n,\gamma)^{41}Ar$ reaction according to ENDF/B-VIII library.

In the similar way (as ^{14}C production) it was obtained the yield of radioactive ^{41}Ar (produced at neutron activation of the main argon isotope: $^{40}Ar(n,\gamma)^{41}Ar$) – see Fig. 6. The upper limit of ^{41}Ar production per mean flash (20 coulombs) will be: $Y_{Ar\text{-}41} = 2.9\times10^{-17}\times20 \simeq 5.8\times10^{-16}$ (g-mole).

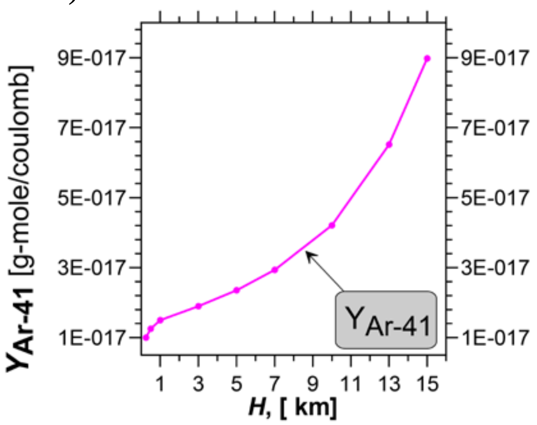

Figure 6. Yield of ^{41}Ar (in gram-molecules) depending on the altitude *H* (km) above sea level. The yields correspond to one coulomb flash discharge under thunderstorm conditions.

The curves of yields for ^{14}C and ^{41}Ar are very similar as: the main yield occurs at the thermal energy; $(N_{le}/N_{re}) \propto n$. As a result, $Y_{C-14,\,Ar-41} \propto \sigma_{C-14,\,Ar-41} \times n$. Note that cross sections for ^{14}C and ^{41}Ar production $\sigma \propto 1/v$ (at $E < 2\times10^{-2}$ MeV for ^{14}C and $E < 1\times10^{-4}$ MeV for ^{41}Ar; v – neutron velocity).

The obtained upper limits for yields of ^{14}C and ^{41}Ar were evaluated basing on the relation $N_{le}/N_{re} \approx 1.3\times10^4$. According to the alternative model of electron avalanche this relation is more than factor of order larger: $N_{le}/N_{re} \approx 3\times10^6$ [9]. In case of this relation the yields for ^{14}C and ^{41}Ar will be smaller in $(3\times10^6/1.3\times10^4)$ times. Taking into account two alternative theories, then for evaluation of the possible upper limits of ^{14}C and ^{41}Ar creation we have to use the first N_{le}/N_{re} relation.

Under thunderstorm condition the isotope ^{41}Ar is created in the atmosphere simultaneously with ^{14}C. Owing to relevant ^{41}Ar decay characteristics ($T_{1/2}$ = 109.34 m, β^-(100%)) it will be attractive to consider this isotope as an appropriate tracer of the radiocarbon ^{14}C generation. But the detection of such low and changing ^{41}Ar concentration is a very complicated task. In spite of debugged technique of ^{41}Ar monitoring (for example on the accelerators [10] and reactors) the detection of ^{41}Ar may be possible in cases of significantly larger atmospheric discharge phenomena (may be when population of neutrons reaches ~ 1E+15 as in case of large “terrestrial” gamma flashes [11]).

4. Conclusion

It was considered the synthesis of radiocarbon ^{12}C creation under the condition of thunderstorm flashes. We propose the gross model to evaluate the upper limit of isotope ^{14}C creation. The synthesis of ^{14}C is ensured by relativistic electrons in the flash avalanche. The yield of relativistic electrons in the total number of electrons is strongly model dependent. In case of $N_{le}/N_{re} \approx 1.3\times10^4$ (relation of low energy to relativistic electrons number) [4], the upper limit of ^{14}C creation on the Earth per year during the thunderstorm is evaluated as 5×10^{-4} (g-mole/year). Compared to ^{14}C isotope creation from the cosmogenic radiation (472 g-mole/year [1]) the production at the thunderstorm gives about 1×10^{-4} %. In case of realization of the alternative avalanche model [9] the relative number of relativistic electrons in the avalanche will be in two orders smaller (according to this theory the relation $N_{le}/N_{re} \approx 3\times10^6$) and ^{14}C synthesis on the Earth during the thunderstorm per year will be in two orders smaller too.

It was also shown [12] that dependence of bremsstrahlung yield (the bremsstrahlung is responsible for generation of neutron flux in (γ,n) reaction and generation of ^{14}C under neutron irradiation) on the air density (with change of the altitude) is very small.

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