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Origins of Chiral Life in Interstellar Molecular Clouds

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Keywords: galactic chemical evolution, molecular dust clouds, spin-polarized proton-proton scattering, element abundances, chirality, origin of life, LUCA

Abstract

The phenomenon of life is discussed within a framework of its origin as defined by the following assumptions. Life, as we know it, is (H-C-N-O) based and relies on the number of bulk (Na-Mg-P-S-Cl-K-Ca) and trace elements (Li-B-F-Si-V-Cr-Mn-Fe-Co-Ni-Cu-Zn-As-Se-Mo-I-W). It originated when the element abundance curve of the living matter and of the universe coincided. By studying the chemical evolution of the solar neighborhood we have obtained the best agreement between the two curves for $(4 \pm 1) \times 10^9$ years after the Big Bang.

The dust-forming planetary system and stars already contained an excess of L- type amino acids and D- type sugars when incorporated into proteins and primitive organisms. Therefore, the emerging life had to be chiral. Because of the universe's aging, life originated only once.

Introduction

To shed some light on the problems where and when life originated, we can hypothesize that life originated when the element abundance curve of the living matter and of the cosmic environment in which life originated coincided. This coincidence occurring at a particular space/time region of the universe can indicate when life originated, T_{origin} . In T_{origin} the chemical abundance ratios of selected elements for a particular cosmic environment and living matter, corrected by the values of concentration factors, should be close to one. The life abundance curve that we have considered is of the only life we know: that on the planet Earth. In our considerations we have taken the estimated essential elements abundances of the Last Universal Common Ancestor (LUCA) ignoring the fact that we do not know its essential elements concentration factors.

When looking into the interstellar medium (ISM) of the universe as the possible environment of the origin of primitive life form, our attention is on interstellar molecular clouds (IMCs) and circumstellar envelopes which are places of complex molecular synthesis (1-3). In addition to gas, interstellar material also contains small micron-sized particles. Gas-phase and

gas-grain interactions result in the formation of complex molecules. Surface catalysis on solid particles enables molecule formation and chemical pathways that cannot proceed in the gas phase because of reaction barriers (4-5). Thus, interstellar dust appears to play a critical role in the formation of interstellar molecules. Molecules may be formed on or in grain surfaces. The existence of interstellar molecules suggests that such molecules support, or are the metabolic products of an interstellar micro-biota. These molecules and micro-biota, participating in planetary condensation from the ISM, can initiate and sustain planetary life and its subsequent evolution. A high number of molecules that are used in contemporary biochemistry on the Earth are present in the ISM on surfaces of comets, asteroids, meteorites, and interplanetary dust particles.

It is reasonable to suppose that life will not depend on resources that are scarce in its environment. The living matter needs only some chemical elements for its existence. Life, as we know, is (H-C-N-O) based and relies on the number of bulk elements (Na-Mg-P-S-Cl-K-Ca) for its existence. All existing organisms use a number of elements for providing proteins with unique coordination, catalytic, and electron transfer properties. This group of elements is called trace elements and it includes some (or all) of the following chemical elements: Li-B-F-Si-V-Cr-Mn-Fe-Co-Ni-Cu-Zn-As-Se-Mo-I-W. One can put in question the essentiality of some of these trace elements for life emerging. For example boron, which is depleted in the solar system, played an essential role in the process of life forming since its primary purpose has been to provide thermal and chemical stability in hostile environments (6). The fact that boron is not depleted in the ISM is yet another indication that life probably originated at a place different than Earth and the solar system.

Chirality phenomenon

Together with a problem of trace element essentiality, we should consider a closely related problem of chirality. A living organism is an organized system of molecules having specific handedness, called chirality. Chiral molecules are designated D (dextrorotatory) or L (levorotatory) according to the right or left direction, respectively, in which the crystalline forms

rotate polarized light. Biological polymers (e.g. nucleic acids and proteins) use almost exclusively D- sugars and L- amino acids. The exception is glycine as it has two (indistinguishable) hydrogen atoms attached to its alpha (central) carbon. Laboratory synthesis made from optically inactive starting materials yield racemic (1:1) mixtures of L- and D- isomers. Nineteen of the 20 amino acids used in the synthesis of proteins can exist as L- or D- enantiomorphs. The function of a protein is determined by its shape. Fig. 1 shows examples of D- and L- amino acids and sugars.

Fig. 1

The mechanism that influenced the choice of enantiomers when life began is still not identified. There have been several suggestions, including 1) polarized light, 2) optically active quartz, and 3) natural radioactivity. We propose a new mechanism that might result in chirality excess, assuming that amino acids were synthesized on dust particles in interstellar space. This is the bombardment by cosmic ray high-energy protons polarized in magnetic fields. Polarized proton cosmic rays preferentially destroy one isomer because of significant asymmetry in proton (in cosmic rays) - proton (in amino acid/sugar) scattering on the surface of ISM dust particles aligned by the magnetic fields. Such dust particle alignment has been observed for solar magnetic field and it is assumed to be the reason why the light scattered by cometary dust becomes circularly polarized (CP) (7). Actually, the most popular explanation of the CP formation is the scattering of light on aligned/irregular dust particles, or on the particles that contain homochiral molecules.

Considering the chemical composition of dust in interstellar molecular clouds (8) and recent findings in the field of prebiotic solid-state chemistry (9) showing that the evolution from molecular clouds to stars and planets provides a suitable environment for nucleobase synthesis in space, we can hypothesize that life arose chiral because originated in the interstellar molecular clouds with the critical role of dust particles, magnetic fields, and exposure to cosmic rays. The arguments supporting the hypothesis are put forward based on numerous astrophysical observations and physics laws.

Results and discussion

The estimation of T_{origin}

For the determination of time of the life origin, T_{origin} , we have to consider only well characterized cosmic environments such as the solar neighborhood, for which the elemental abundance curves for elements of our interest could be constructed from the measured data or existing models. Recently, Kobayashi *et al.* (10) constructed Galactic Chemical Evolution (GCE) models in the solar neighborhood for all stable elements from ^{12}C to ^{238}U from first principles by using theoretical nucleosynthesis yields and event rates of all chemical enrichment sources. This enables the prediction of the origin of elements as a function of time and environment. The basic equations of chemical evolution are described by Kobayashi *et al.* (11). The code follows the time evolution of elemental and isotopic abundances in a system where the ISM is instantaneously well mixed.

Considering the life abundance curve, we have assumed that all organisms on the tree of life have a common ancestor, i.e. tree is rooted in the LUCA. Therefore, to establish an average elemental composition of life one needs to estimate the relative abundance of elements in LUCA. One such effort has been undertaken by Chopra *et al.* (12) and Chopra and Lineweaver (13). Their compilation samples eukaryotic, bacterial, and archaeal taxa across the extant tree of life taking into account elemental abundances and phylogenetic relationship between the taxa. The idea of LUCA of all cells, or the progenitor, is the most important for the study of early evolution and life's origin, yet information about when, where and how LUCA originated is still lacking. Namely, considerable time and extinct organisms might have existed between the origin of life and the root of the tree, as defined by extant organisms. All these considerations are done by assuming that Earth's present day three existing domains of life define the LUCA's capabilities and characteristics. However, as pointed out by Cockell (14), we cannot be sure that there were not domains that went extinct early in the history of life and took with them crucial information.

Figure 2 presents concentrations of selected essential elements relative to iron in LUCA, compared to the same for the Sun (15). It has been recently shown by Obhodaš *et al.* (16) that preconcentration factors can be different in very low magnetic fields. *Bacillus subtilis* grown in magnetic fields of 100 nT, which are intensities found in IMCs (17), required 5.5 times less potassium compared to control culture growing in the Earth magnetic field. Magnetic, as well as gravitational fields, are orders of magnitude weaker in IMCs compared to the Earth. Thus, the abundances derived for LUCA may be severely misleading. If potassium abundance in LUCA is corrected by factor 5.5 inferred from the experiment with the *Bacillus subtilis* grown in the magnetic field of 100 nT (16), the LUCA abundance curve resembles the Sun abundance curve more closely. The essential elements concentration factors of primitive life forms for intensities of magnetic and gravitational fields found in IMCs will be systematically studied in our future research.

Fig. 2

Figure 3a and 3c present the χ^2 and R^2 estimates, respectively, for a set of 19 life-essential elements abundances (C, N, O, Na, Mg, Al, Si, P, S, K, Ca, V, Cr, Mn, Co, Ni, Cu, Zn, and Mo) in the solar neighborhood stars, and those inferred for LUCA. The χ^2 estimates calculated for abundances of selected 7 trace elements (V, Cr, Mn, Co, Ni, Cu, and Zn) are shown in Fig. 3b. In all cases, T_{origin} of $3 - 5 \times 10^9$ years is observed. However, the large uncertainty of age determination derived from the age - [Fe/H] metallicity model, as well as uncertainties derived by extrapolation and interpolation of solar neighborhood abundances of elements from graphical diagrams presented in Kobayashi *et al.* (10), should be taken into account. On the other hand, the corrections for concentration factors in LUCA would shift the χ^2 and R^2 curves presumably towards the better agreement between two data sets, those for LUCA and the abundances of elements in stars, but it would not change the shape of the curve. For example, the correction for potassium in LUCA for a factor of 5.5 (16) shifts up the R^2 estimates

for 0.035 (i.e. 3.5 % better agreement was observed between abundance curves for LUCA and stars throughout the chemical galactic evolution).

Fig. 3

The estimation of T_{origin} lower boundary of 3×10^9 years can be further supported by the trends in dust composition as presented for the solar neighborhood by Zhukovska *et al.* (8). The evolution of the dust composition is closely related to the stellar injection of the elements in ISM and therefore to the galactic chemical evolution, although slight differences can be observed with respect to volatile elements. In particular, one should pay attention to the C/O ratios found in ISM dust particles, stars of the solar neighborhood, and our planet, compared to the C/O ratio inferred for LUCA. Throughout the galactic evolution, the C/O ratio is <1 for most stars of the solar neighborhood (see Supplementary Information). The C/O ratio for the Earth's crust is also less than 1 (18). Yet, the C/O ratio for LUCA is above 1 and also for ISM dust particles in the solar neighborhood starting from 3×10^9 years after BB (8) suggesting that life most probably originated on the carbonaceous dust particles of IMCs.

IMCs - Environment where life might have originated

Interstellar dust is coupled to gas clouds and, as such, carried around the Milky Way. These clouds come in a wide variety of shapes, sizes, densities, and temperatures. They can, however, be qualitatively classified into two basic categories: interstellar diffuse clouds and IMCs. The diffuse clouds are not distinguishable and are limited to a density less than about 300 hydrogen atoms per cm^3 with a temperature of 50–100 K. The molecular clouds can have temperatures of 20 K (even 10 K) and a density of hydrogen atoms above 300 per cm^3 including the densities at which clouds collapse to form stars. Diffuse clouds contain hydrogen in atomic form, whereas molecular hydrogen is a dominant component of molecular clouds. Molecular clouds can be very dark, as illustrated by the Horsehead nebula, and by isolated blank regions in the sky widely called Bok globules. These latter are probably concentrations of dust and gas, which are collapsing to form stars (19-21).

It appears that solid-state chemistry is more relevant in the prebiotic context than thus far anticipated (22-25). It has been shown (9) that nucleobases methylated at the glycosidic nitrogen atom achieve DNA-specific self-assembly upon heating in the solid-state. This pairing of nucleotides in the DNA via specific hydrogen-bonding interactions constitutes the most famous example of supramolecular recognition. Oba *et al.* (26) reported the simultaneous detection of all three pyrimidine (cytosine, uracil, and thymine) and three purine nucleobases (adenine, xanthine, and hypoxanthine) in interstellar ice analogs composed of simple molecules including H₂O, CO, NH₃, and CH₃OH after exposure to ultraviolet photons followed by thermal processes, that is, in conditions that simulate the chemical processes accompanying star formation from molecular clouds.

The findings of Obhodaš *et al.* (16) demonstrated that magnetic fields below 400 nT significantly enhance the growth of *Bacillus subtilis* compared to controls growing in the Earth's magnetic field. This might suggest that microorganisms favor extremely low magnetic fields. The Earth's magnetic field of the approximately same intensity as presently (between 33 μ T at the magnetic equator, and 67 μ T at the magnetic poles), formed 4.2×10^9 years ago, almost immediately after the lunar-forming giant impact (27). Moreover, it has been shown that microorganisms in a very similar way favor microgravity (28). These findings of microorganisms favoring the low magnetic and gravitational fields, evident as 10 times increase in their multiplication rate, strengthen the assumption that life originated in IMCs, where maximum magnetic field intensities are ~ 100 nT (17) and strong gravitational fields are not yet formed.

Spin-polarized proton-proton scattering

Primary cosmic rays are stable charged particles that have been accelerated to enormous energies by astrophysical sources somewhere in our universe. They must be stable in order to survive the long trips through interstellar (or intergalactic) space. They are charged because the accelerating mechanism is probably electromagnetic and because their charge is what interacts with matter and produces the effects that we can observe. They have a range of

energies, 10^9 eV (1 GeV) up to 10^{20} eV (10^8 TeV). For comparison, the latest accelerators here on earth can achieve only about 7 TeV. The most common primary cosmic ray particle is the proton or hydrogen nucleus. 95% of all cosmic rays are protons, 4% are helium nuclei, and the 1% balance is made up of nuclei from elements up to iron. Protons in the cosmic rays get scattered off different targets on their path through the universe and along with the magnet field force, including individual atoms in the molecules in molecular clouds and on the dust particle surfaces. Among other processes, the one process of interest which has been overlooked in the scientific literature concerning pre-biotic chirality is elastic spin-polarized proton-proton (p-p) scattering as shown in Fig. 4. Either proton (beam or target) can be polarized.

Fig. 4

Analyzing power $A_N(t)$ for p-p elastic scattering in the energy range of energetic cosmic ray protons has been studied by several groups (29-31), some of this work is summarized by Bazilevsky *et al.* (32). The analyzing power (A_N) can be extracted from the asymmetry between the number of scatterings on the left versus on the right, corrected for the left and right detector acceptances, or from the asymmetry between the number of scattering (e.g. on the left) for target polarization “up” and target polarization “down”, corrected for the integrated luminosities for the corresponding target spin states. These two approaches can be combined in a so-called “sqrt” formula, which cancels contributions from different left-right detector acceptances and different luminosities in the measurements with “up” and “down” target polarization states to the asymmetry:

$$A_N = \frac{1}{P_T} \frac{\sqrt{N_L^\uparrow \times N_R^\uparrow} - \sqrt{N_R^\uparrow \times N_L^\downarrow}}{\sqrt{N_L^\uparrow \times N_R^\downarrow} + \sqrt{N_R^\uparrow \times N_L^\uparrow}}$$

where $N_{L(R)}^{\uparrow(\downarrow)}$ is the number of recoil protons selected from p-p elastic scattering events detected on the left (right) side of the beam. P_T is target polarization and the arrows give the direction of the target polarization. The A_N measurements were performed for the recoil proton kinetic energy

range $T_R = 1 - 4$ MeV corresponding to a momentum transfer $0.002 < -t < 0.008$ (10^9 eV/c)²;
 $-t = 2m_p T_R$, where m_p is the proton mass.

Single spin asymmetry up to 5% in polarized p-p elastic scattering has been observed at high energies, see, for example, Adamczyk *et al.* (33) for experiments done at Relativistic Heavy Ion Collider, RHIC. The RHIC is one of only two operating heavy-ion colliders, and the only spin-polarized proton collider ever built. It is located at Brookhaven National Laboratory (BNL) in Upton, New York. Polarization produced in p-p scattering has been observed even at low energies, 30 and 50 MeV (34).

Preferential destruction of enantiomers by spin-polarized cosmic ray protons

Although the two forms of a chiral molecule have identical physical and chemical properties, the interaction with other chiral molecules may be different. Chiral molecules in living organisms exist almost exclusively as single enantiomers, a property that has a critical role in molecular recognition and replication processes. Therefore, it is a prerequisite for the origin of life. Left-handed and right-handed molecules of a compound will be formed in equal amounts (a racemic mixture) when synthesized in the laboratory in the absence of some directing template.

Assuming that amino acids, and some sugars, could be synthesized on dust particles in interstellar space, the observed optical activity may be a result of cosmic ray bombardment. Two processes could be involved alone or combined: (i) The first process might arise from asymmetric dust grains aligned with the magnetic field. Interstellar medium polarization by aligned dust grains has been probed from the diffuse medium in the UV to heavily obscured sightlines in the near-IR and into dense clouds and heavily embedded sources using far-IR emission (35). It should be kept in mind, that not all environments produce the same amount of polarization. Although, the dust mainly consists of silicates, amorphous carbon, and small graphite particles in various simple shapes, in the dark cold parts of molecular clouds grain aggregates and mantles of volatile ice might form. Only a limited number of relatively large grain sizes ($\sim 0.01 - 1$ μm) contribute to the polarization. This situation corresponds to a polarized target in the p-p elastic scattering

process. (ii) Alternatively, polarized beam interaction could be considered. High energy polarized protons in cosmic rays may be able to preferentially destroy one isomer on the dust particle surface because of significant asymmetry in proton (in cosmic rays) - proton (placed next to chirality center in amino acid or sugar) scattering. See Fig. 5. for the schematic presentation of the process leading to preferential destruction of L-sugars and D-amino acids.

Fig. 5

If a sufficient enantiomeric excess existed in life's primordial molecular reservoir, it would almost certainly push life toward the extreme bias of actual living beings (36). Meteoritic samples suggest that such an enantiomeric excess has been generated before Earth formation. The source of their molecular material can be traced to the cloud of gas and dust from which our solar system formed. The process shown in Fig. 5 could have generated an enantiomeric excess in the primordial cloud, thus linking the origins of life's enantiomeric bias to processes that occurred billions of years ago before the solar system existed. Since the life on planet Earth is chiral, it is reasonable to assume that dust that formed our solar system contained already this information. All of these findings support our hypothesis that chirality is a *sine qua non* condition for the emergence of life.

Conclusions

We have presented numerous examples of observations, experiments, and theoretical considerations which we have used to synthesize our hypothesis concerning the origin of life on interstellar dust particles. The universe was born only with plenty of hydrogen isotopes, some helium, and lithium, while all other elements were formed as the universe aged through star formation processes, their lives, and deaths, which resulted in dust clouds as a birthplace of a new generation of stars. During this process of the universe aging, the chemical element abundance curve has been changing in such a manner that at the time T_{origin} coincided with the abundance curve of living matter. Our hypothesis defines T_{origin} as a time when conditions were right for life to originate in the primitive form and that happened only once in the history of the

universe. Exposure to cosmic rays and magnetic fields as well as nuclear physics laws made life chiral. Our preliminary considerations of the solar neighborhood as a part of the Milky Way galaxy indicate $(4 \pm 1) \times 10^9$ years after BB for the origin of life on the carbonaceous dust particles in the IMCs. The same could be expected for similar zones in other spiral galaxies. Such a life form could have survived the planet formation processes and evolve in habitable zones of stars. During this process, the primitive organisms had to adjust their essential element concentrations to adapt to new environments. This should be seen in concentration factors dependence of environment properties, in particular, due to adaptation to different magnetic and gravitational fields, and the availability of essential elements.

Methods

The elemental abundances for the solar neighborhood have been obtained from the experimental values summarized in (10). The elemental abundances for LUCA have been taken from (13) and expressed relative to iron. The agreement between life essential bulk and trace elements in LUCA and the solar neighborhood as a function of metallicity [Fe/H] have been calculated for different [Fe/H] values corresponding to different times, T-values, according to the age-[Fe/H] model presented in (10). Only those essential elements available for the evaluation of the solar neighborhood chemical evolution presented in (10) have been selected (C, N, O, Na, Mg, Al, Si, P, S, K, Ca, V, Cr, Mn, Co, Ni, Cu, Zn, and Mo).

Two approaches have been used to estimate the time of the life origin, T_{origin} . First, we calculated the minimum of χ^2 (best agreement) as defined by

$$\chi^2 = \frac{1}{N} \sum_{i=1}^N (C_{i,LUCA} - C_{i,environment})^2 / C_{i,environment} ,$$

where C_i is the abundance of essential element i in LUCA and in the solar neighbourhood environment where LUCA originated. In the second approach, we have calculated the maximum coefficient of determination (R^2), i.e. the percentage of the variance explained by the linear regression model between logarithmic values of abundances of essential elements in LUCA and

the environment of its origin. The χ^2 and R^2 have been calculated for 19 essential elements, and χ^2 also for the subgroup of trace elements (V, Cr, Mn, Co, Ni, Cu, and Zn). Row data used for χ^2 and R^2 calculations are presented in Supplementary Information. Uncertainties expressed as a standard deviation of a mean were calculated by bootstrapping using software Resampling Stats Addin for Excel of The Institute for Statistics Education, An Elder Research Company, Arlington, Virginia, United States.

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Figures

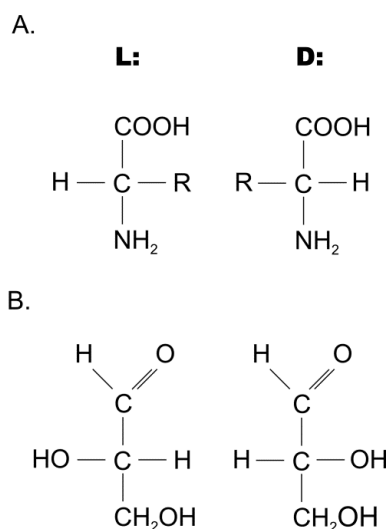


Fig. 1: Two enantiomers (L- handed and D- handed) of A.) generic amino acid and B.) glyceraldehydes.

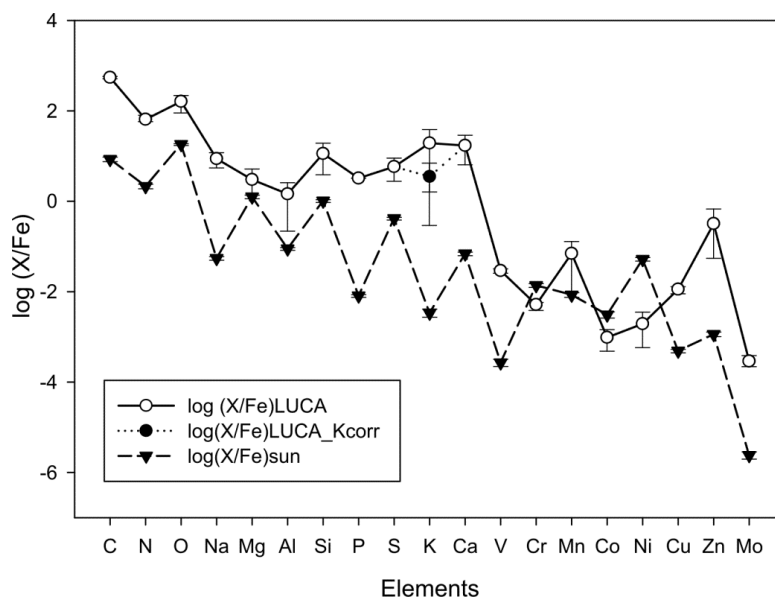


Fig. 2: The abundance curves of LUCA (after 12) and the Sun (after 15) for selected essential elements. The closed circle presents the correction for the abundance of potassium measured in *Bacillus subtilis* for the 100 nT magnetic field (16).

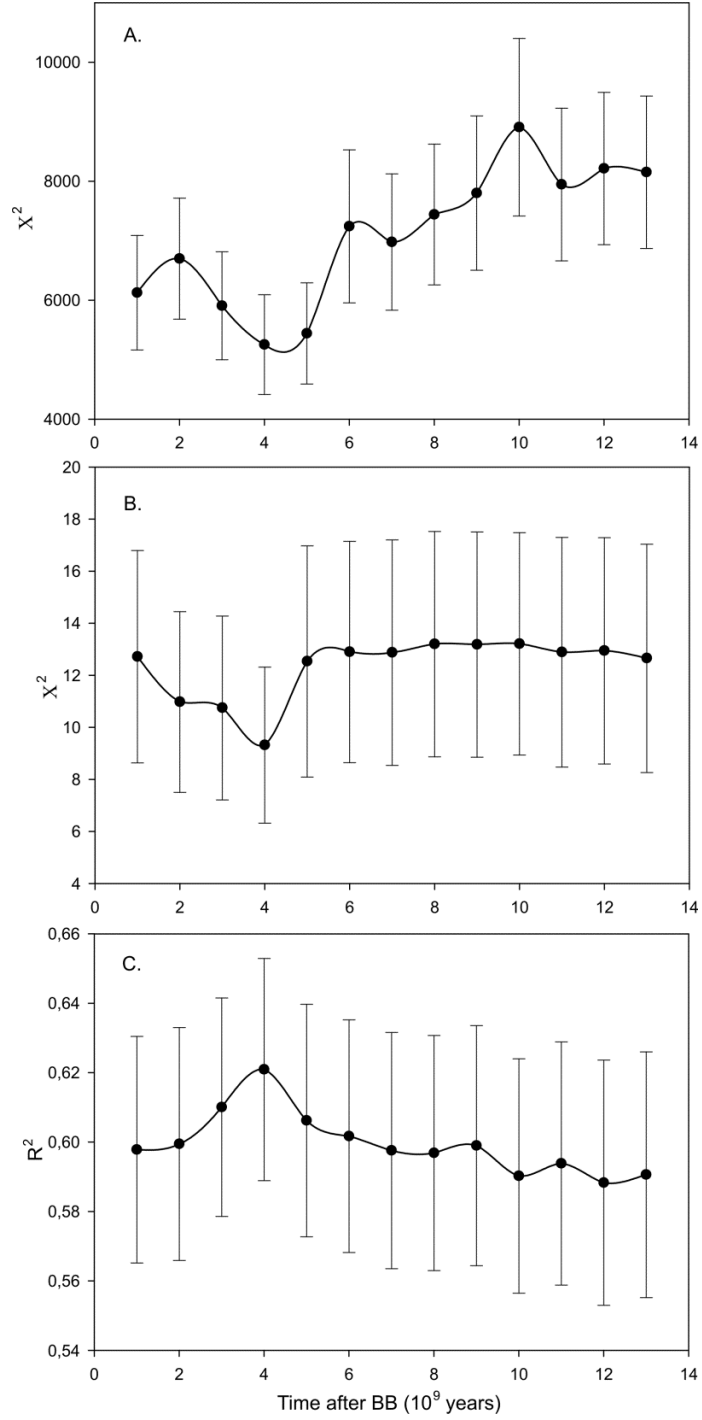


Fig. 3: The χ^2 and R^2 estimates for the solar neighborhood data and LUCA, 19 essential elements (A. and C.), and the subgroup of 7 essential trace elements (B.) have been taken into consideration. The uncertainties shown are the standard error of the mean.

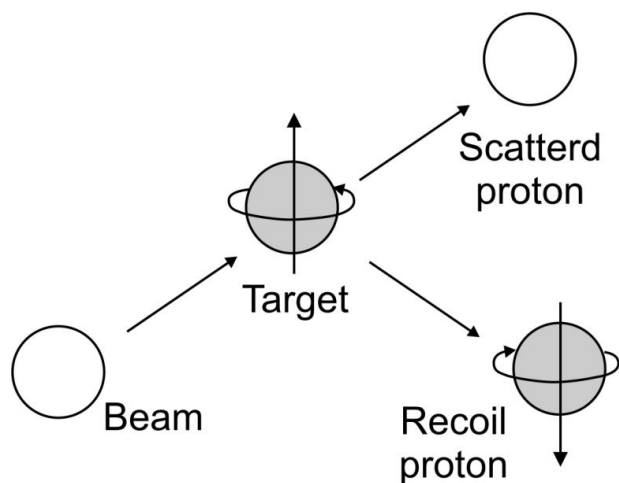


Fig. 4: The elastic scattering process. A_N arises from the interference between a spin-flip (coulomb) and spin non-flip (nuclear) amplitude.

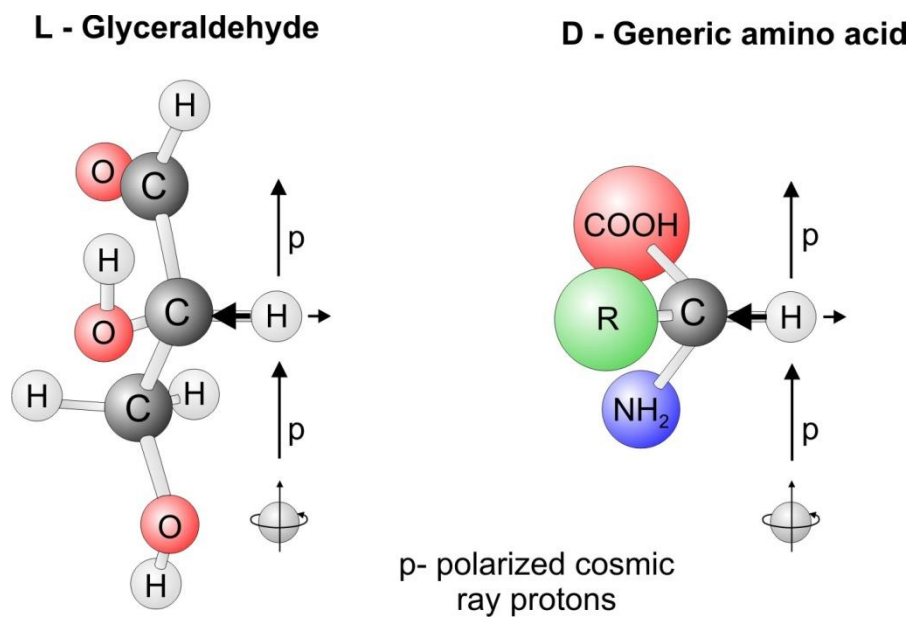
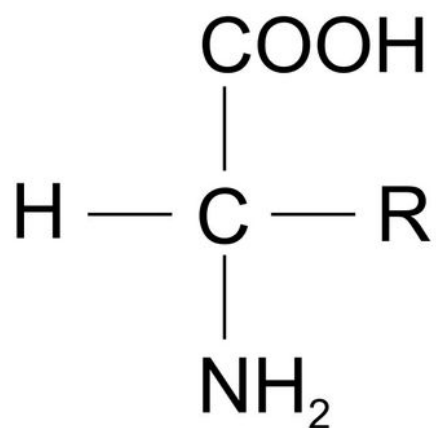


Fig. 5: Schematic presentation of the process of preferential destruction ($A_N = 5\%$) of L-sugars and D- amino acids.

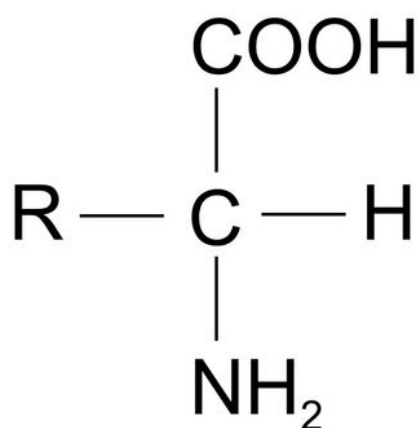
Figures

A.

L:



D:



B.

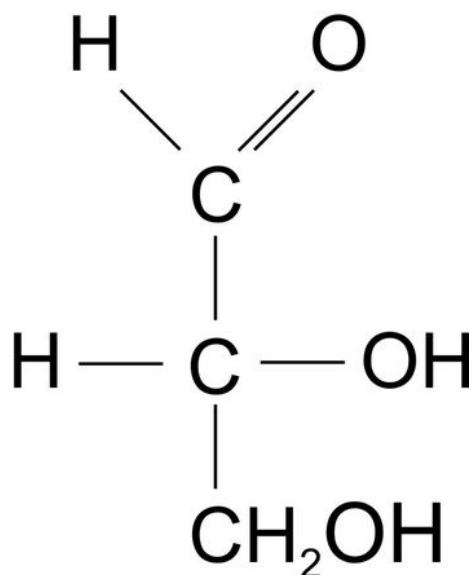
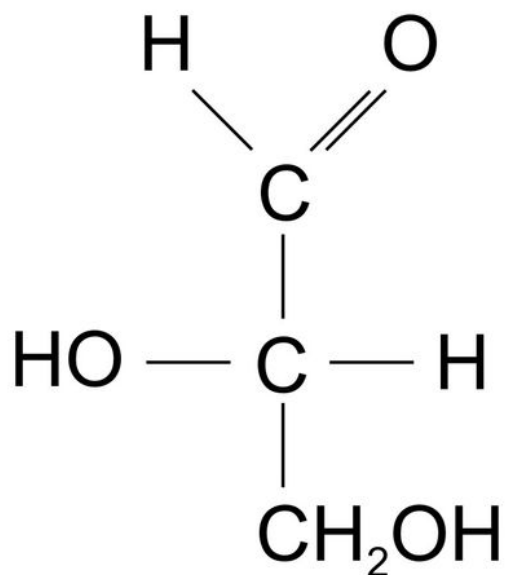


Figure 1

Two enantiomers (L- handed and D- handed) of A.) generic amino acid and B.) glyceraldehydes.

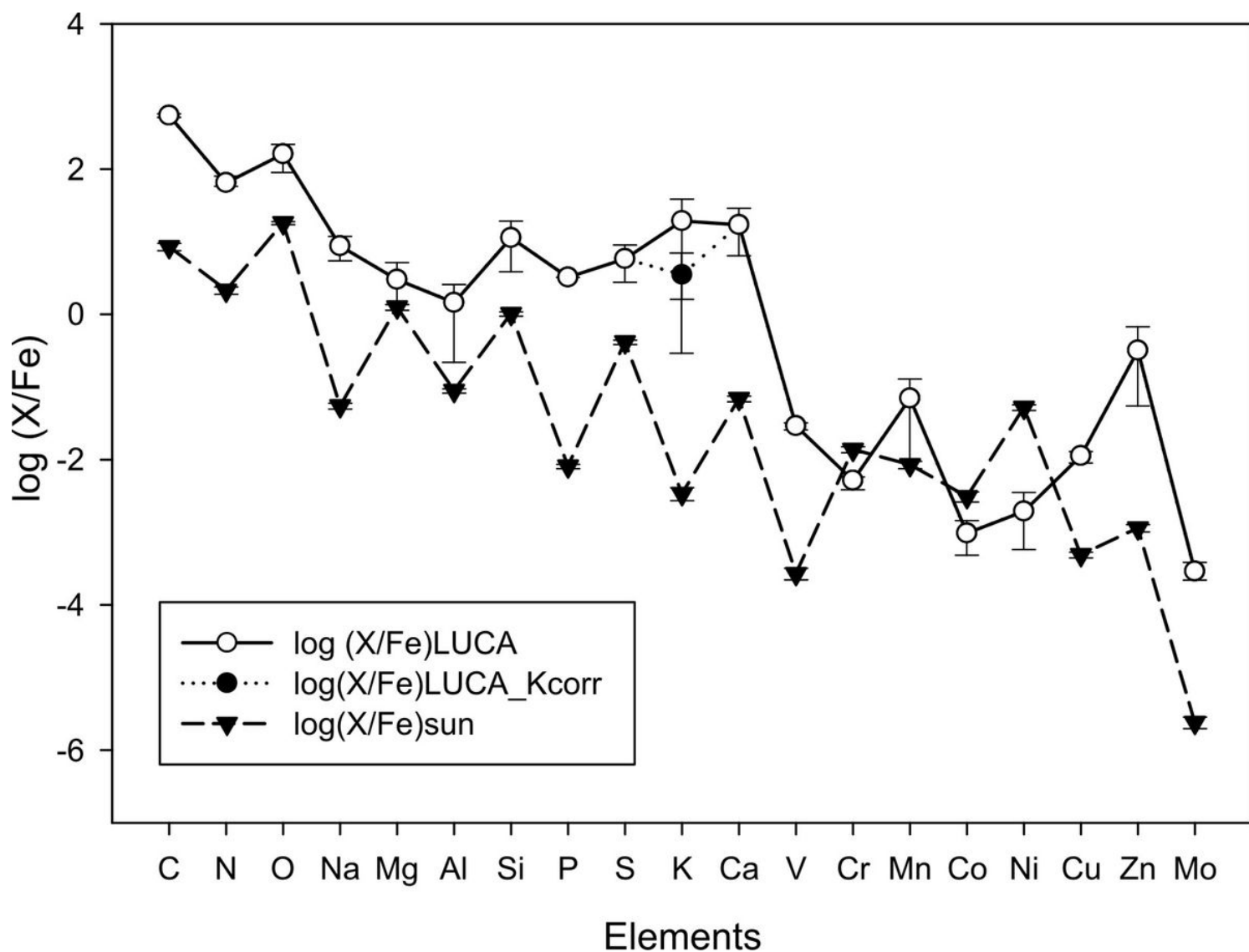


Figure 2

The abundance curves of LUCA (after 12) and the Sun (after 15) for selected essential elements. The closed circle presents the correction for the abundance of potassium measured in *Bacillus subtilis* for the 100 nT magnetic field (16).

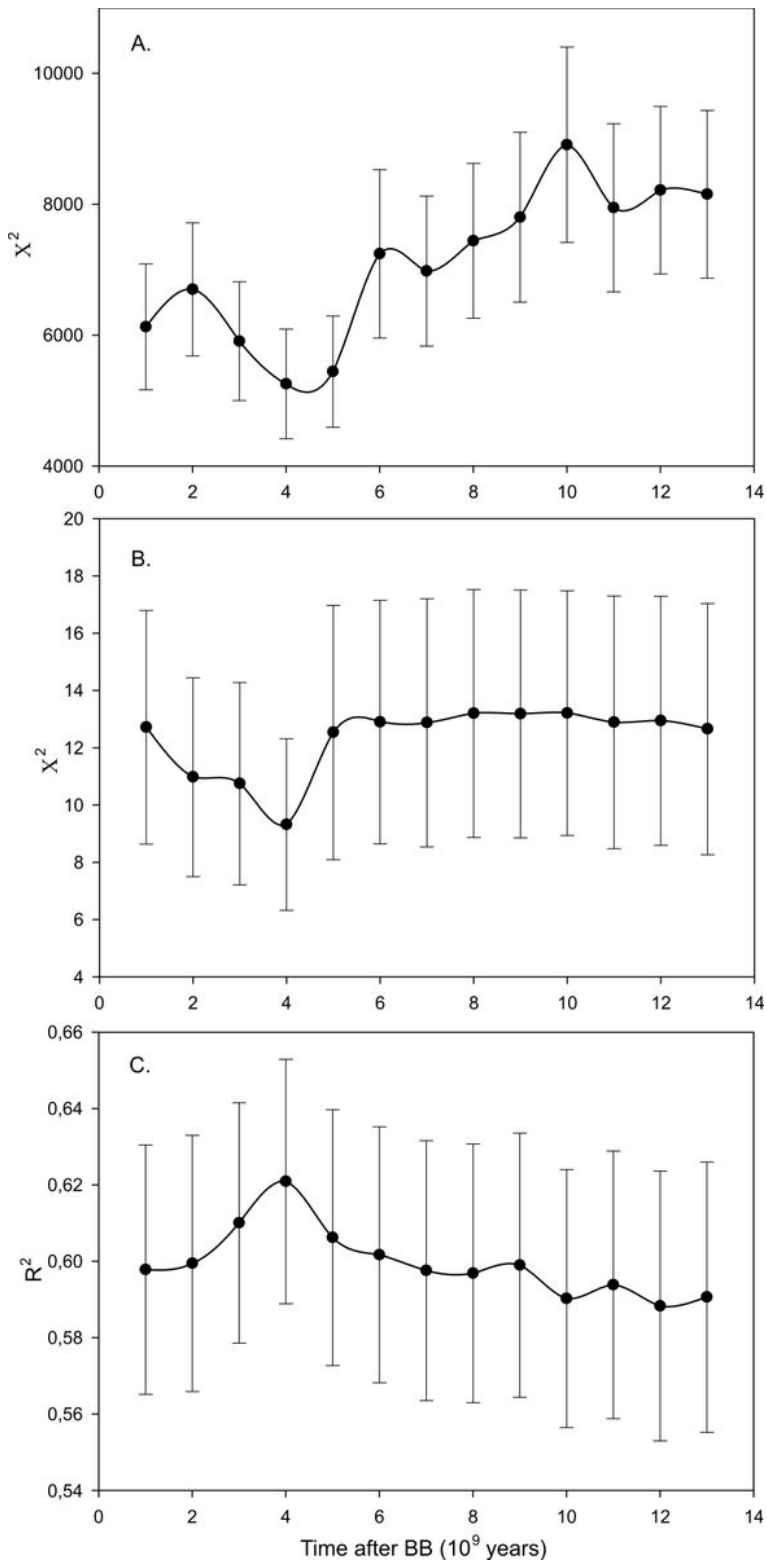


Figure 3

The χ^2 and R^2 estimates for the solar neighborhood data and LUCA, 19 essential elements (A. and C.), and the subgroup of 7 essential trace elements (B.) have been taken into consideration. The uncertainties shown are the standard error of the mean.

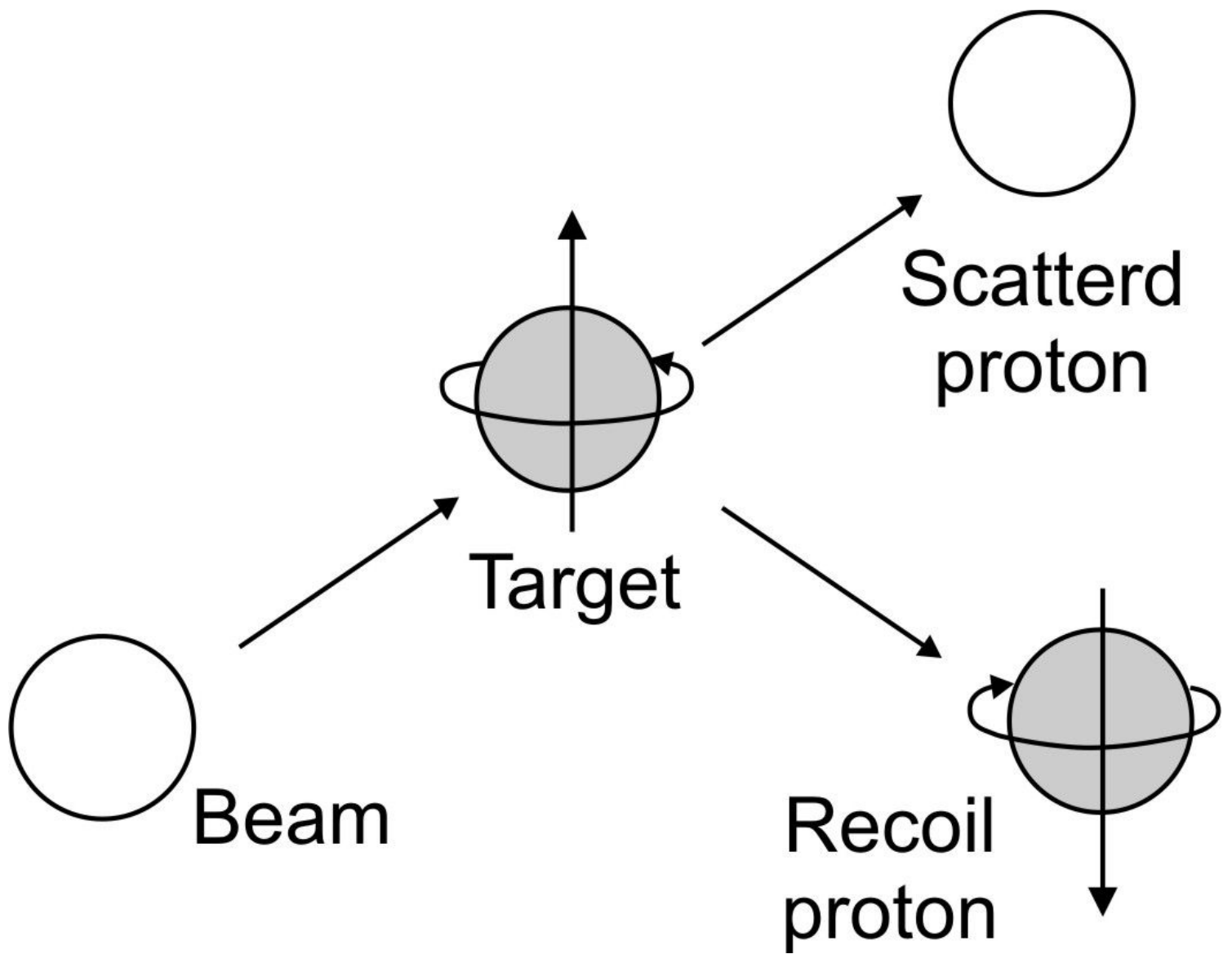
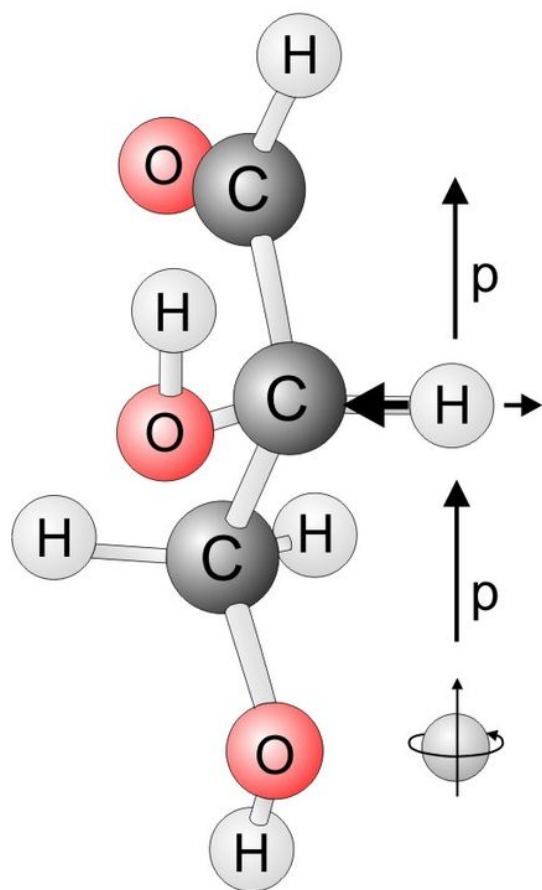


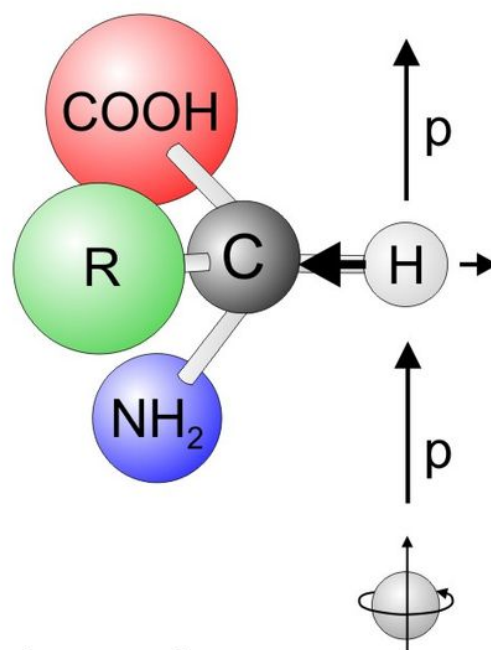
Figure 4

The elastic scattering process. AN arises from the interference between a spin-flip (coulomb) and spin non-flip (nuclear) amplitude.

L - Glyceraldehyde



D - Generic amino acid



p- polarized cosmic
ray protons

Figure 5

Schematic presentation of the process of preferential destruction (AN = 5%) of L-sugars and D- amino acids.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformation.xlsx](#)