# The Beryllium Age Observable at the Boundary of the Solar Cavity

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**Abstract**

The measurement of the unstable-to-stable isotopic ratio, $^{10}Be/Be$, allows the determination of the beryllium age and the delimitation of the ages of other stable spallation secondaries. A calculation of the beryllium age observable in the local galactic zone is presented. The calculation utilizes the observational data on the galactic magnetic field and the dimension of the disk. A uniform source distribution of the parent ions generating beryllium isotopes in the disk and a uniform interstellar gas density are relevant assumptions of the calculation.

The ages of stable beryllium isotopes, $^{7}$Be and $^{9}$Be, resulting from this calculation are less than $4 \times 10^6$ years above 1 GeV/u in the spiral field. This value disagrees with the longer age of about $15 \times 10^6$ years, derived from the measured $^{10}Be/Be$ ratios elaborated in the context of the Leaky Box Model . An explanation for the origin of this difference is attempted.

## 1 Introduction:

The age and the matter thickness interleaved between the sources and the solar cavity (grammage) are some of few fundamental properties of cosmic rays that have been measured to date. The age has been measured (Connell, 1997; Lukasiak et al. 1994; Garcia-Munoz et al., 1981; Wiedenbeck et al., 1980) by using the radioactive clocks of various species (like $^{10}$Be, $^{26}$Al, $^{36}$Cl and $^{54}$Mn) and other methods. The commonly accepted value of grammage, which is believed to be between 5 and 10 g cm$^{-2}$ around the mean energy of galactic cosmic rays (Webber, 1996), is based on many experiments that have measured the boron-to-carbon flux ratio versus energy in a large interval between 50 MeV/u and 100 GeV/u and other measurements. The experimental data available as flux ratios require a rather complex elaboration in order to determine the age, the grammage and the residence time in the disk. Traditionally, this elaboration is made by Leaky Box Models and in a few cases, by the simple diffusion model.

A new computational method that differs from those mentioned above determines the age and grammage of cosmic rays in the galactic volume by using cosmic ray trajectories which are the deformed helixes. The method has been applied to protons and to two beryllium isotopes, $^{7}$Be and $^{10}$Be in a circular magnetic field (Brunetti and Codino, 1997 referred to as Paper I).

In this contribution to the conference, new results of the beryllium age and grammage in a spiral magnetic field of the Galaxy are presented.

## 2 Approximations in the calculation of beryllium trajectories:

The calculation has been made by a simulation program (CORSA) described elsewhere (Brunetti and Codino, 1998; Codino, 1999). Major simplifications involved in the calculation are here repeated. Cylindrical, galactocentric coordinates $r$, $z$ and $\phi$ are used. The galactic disk is a cylinder of radius 15 kpc and half-thickness of 250 pc. The magnetic field in the disk is described in terms of a regular and a chaotic component with field strengths of 3 and 10 $\mu$G, respectively. The interstellar gas density is uniform with 1 hydrogen atom per cm$^3$.

Beryllium is generated by the nuclear collisions of carbon nuclei and heavier species with interstellar hydrogen. The beryllium-proton cross section, $\sigma(Be\,p)$, is taken from a classical compilation and interpolation of experimental data (Silberberg et al., 1985). The source distributions of parent nuclei in the disk volume are taken uniform in $r$, $\phi$ and normal along the $z$ axis with a standard deviation of 80 pc. The resulting source distribution of beryllium is also uniform in $r$, $\phi$ but normal along the $z$ axis with a larger standard deviation of 106 pc.

Many details of the calculation are described in the papers cited above where some specific notions peculiar to this computational method such as the local galactic zone, the partition of cosmic ray populations in three classes and others are introduced and discussed. Note also that the effect of the solar modulation is neglected.

## 3 The age and grammage of the beryllium:

Samples of $10^7$ Beryllium trajectories in the galactic disk have been generated and those intercepting the local galactic zone analyzed. The local galactic zone is a sphere of 100 pc in radius concentric with the solar cavity ($r$=8500 pc, $z$=+14 pc, $\phi$=$90^0$) used to compute the appropriate average values for age and grammage.

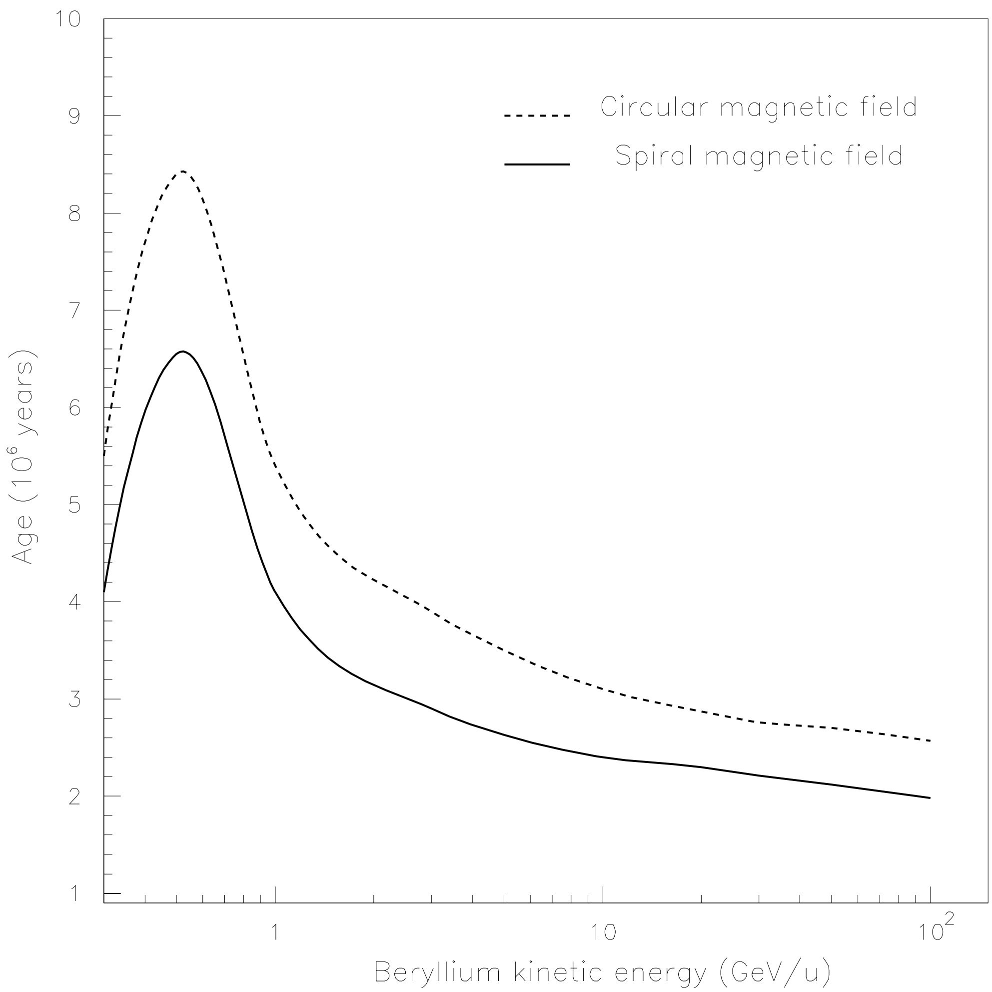


Figure 1: Beryllium age versus kinetic energy per atomic mass unit of the isotope $^9$Be for two magnetic field shapes.

The results of the calculation are shown in figure 1 where the age of the isotope $^9$Be is given as a function of the kinetic energy per atomic mass unit (u) and in figure 2 where the corresponding grammage is also given. The beryllium age for the spiral field above 5 GeV/u is nearly constant amounting to less than $3\times10^6$ years and the corresponding grammage less than 5 g cm$^{-2}$. The peak around 1 GeV/u is generated by different beryllium populations suffering strong rising and decreasing effects of the ionization energy losses, nuclear interaction cross sections and escape probabilities from the disk (see figures 1 and 2 of Paper I). The isotope $^9$Be instead of the $^{10}$Be is selected because it is stable and simplifies the discussion of the results. If the isotope $^{10}$Be is injected in the disk with the same abundance of $^{9}$Be and with the same parameters of the simulation, except of course, for cross sections and ionization energy losses, the surviving fraction arriving at the boundary of the local galactic zone is 57% at 0.5 GeV/u in the spiral field.

## 4 Discussion of the results:

In order to determine the dependence of the results on the parameters of the calculation the following quantities have been varied within plausible limits from their standard values. The variations pertain:

(A) the interstellar gas density;
(B) the thickness of the disk;
(C) the halo size;
(D) the source distribution in the disk volume;
(E) the magnetic field strength of the regular and the chaotic component;
(F) the configuration of the magnetic field and,
(G) the dimension of the magnetic cloudlets.

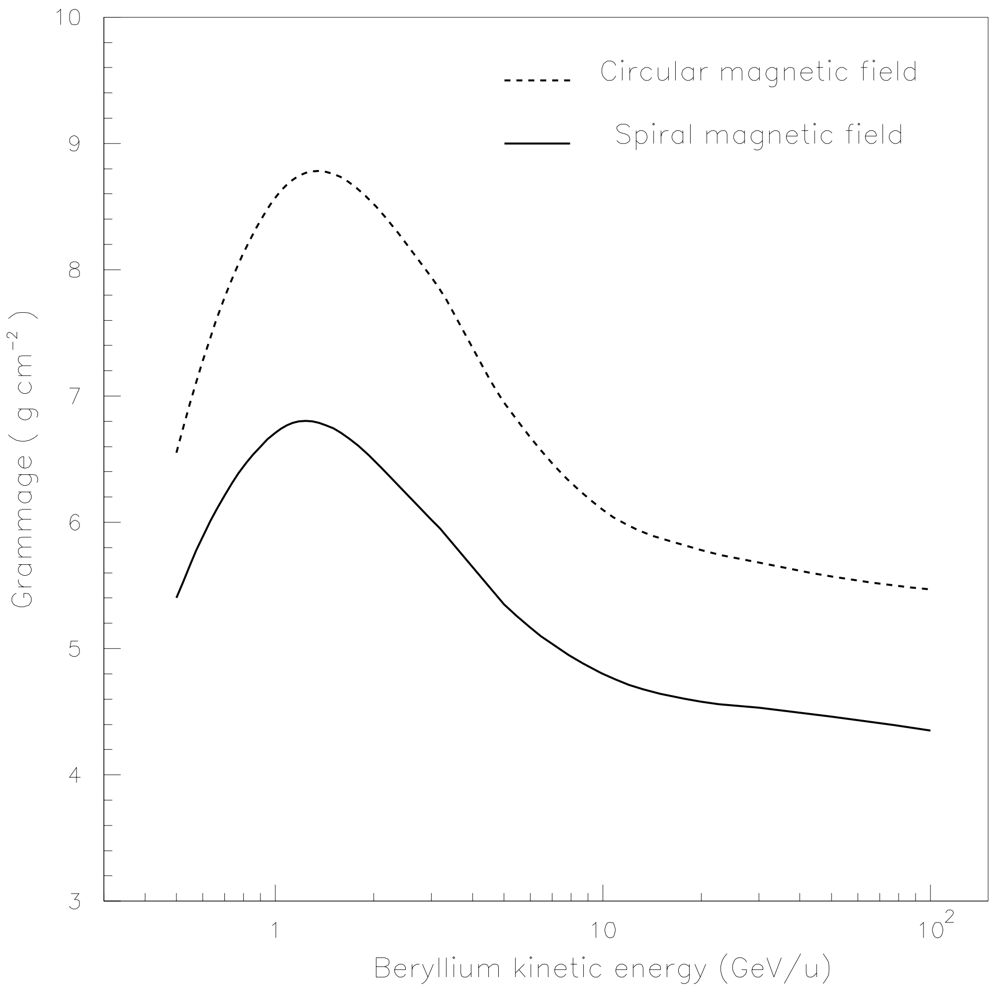


Figure 2: Grammage versus kinetic energy per atomic mass unit of the isotope $^{9}$Be for two magnetic field shapes in the disk.

Also the dimension of the local galactic zone has been varied and its effect on the age of cosmic protons computed (see figure 13 in Brunetti and Codino, 1998). For beryllium it is expected the same dependence computed for protons. If the cosmic ray sources are located in the disk with a uniform distribution or with that of the supernovae remnants, the variation of the parameters (A), (B), (C), (D), and (E) do not alter, within $\pm$30%, the age and grammage of beryllium. The variation of these quantities versus the magnetic field shape for two configurations is reported in figure 1 and 2. The critical parameter is the dimension of the magnetic cloudlets (Brunetti and Codino, 1995).

It is interesting to compare the grammage and age of protons with those of beryllium in exactly the same magnetic building, hydrogen density, galactic dimensions and method of calculation. The comparison is not perfect because protons, unlike beryllium, produce secondaries that are not distinguishable from primaries but, we believe, still instructive. The proton age in the spiral field above 5 GeV is $6.7 \times 10^6$ years and the corresponding grammage 14 g/$cm^2$ which significantly differ from those of beryllium. Both the age and grammage are approximately constant above 5 GeV/u.

If the beryllium and proton sources are located in the disk, as generally assumed, both species sweep the same gas columns. Since the helix length for the two species is necessarily the same, the grammages differ in the two cases because the cross sections $\sigma(pp)$ and $\sigma(Be\ p)$ are different. For example, if the cross section $\sigma(Be\ p)$ would be artificially lowered to 40 mbarn, the beryllium age and grammage increase attaining values close to those of protons except at low energies where the difference in the ionization energy losses for the two species is large. As a consequence, due to higher cross section of $\sigma(Be\ p)$ with respect to $\sigma(pp)$, beryllium trajectories originate, on average, in sites closer to the local galactic zone than those of protons. This effect gives beryllium a shorter age and lower grammage.

In Leaky Box Models, the same grammage for all the species with the same rigidity is assumed. In some respects, if this hypothesis were embedded in the calculation presented here, it would be equivalent to displacing cosmic-ray sources to different average distances from the solar cavity which ultimately produces shorter age for heavier nuclides.

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