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Cosmic-ray astrophysics with the AMS-02 experiment

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Abstract

Precise knowledge of the hadronic component of cosmic rays (CRs) is needed to describe the CR production, acceleration and propagation mechanisms in our galaxy. Present measurements suffer from limitations coming from short exposure time, intrinsic instrumental limitations and restricted energy range. The AMS-02 experiment is a large acceptance magnetic spectrometer designed to perform high statistics studies of CRs in space. The detector will operate on the International Space Station (ISS) for a minimum of 3 years. AMS-02 will precisely measure the CR fluxes of individual elements up to $Z = 26$ in the rigidity range from 500 MV to few TV. AMS-02 will allow to test propagation models through the precise measurements of secondary-to-primary ratios as d/p, ^{3}He/^{4}He in the energy range up to 10 GeV/n, and B/C, sub-Fe/Fe up to TeV/n. In particular the measurements of ^{10}Be/^{9}Be will be performed with high accuracy allowing for the understanding of the age of the CR confinement and constraining models of the size of the galactic halo.

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1. Cosmic rays nuclei

Cosmic rays (CRs) are charged particles striking Earth atmosphere isotropically. They are mainly composed by protons (~90%), alpha particles (~9%), electrons and completely ionized stable nuclei with charges larger than Helium.

CRs with energy between 10^{9} eV/n and 10^{18} eV/n are assumed to originate in the Milky Way being accelerated in supernova explosions occurring in the Galaxy [1]. In this picture, particles are scattered across the shock fronts of the SN, gaining energy at each crossing by the first order Fermi process. This acceleration model is strongly supported by recent observations of γ-ray emission from SN remnants revealing the presence of energetic particles near these objects [2]. After acceleration particles propagate in the Galaxy confined by the randomly oriented galactic magnetic fields (~3 μG), for an average time of ~15 Myr before reaching Earth.

The primary galactic CRs nuclei energy spectra and chemical composition are modified from the astrophysical sources to the Earth by the spallation processes on the inter-stellar medium (ISM) producing secondary CRs. Electrons, protons and helium, as well as carbon, oxygen, iron and other nuclei synthesized in stars, are mostly primaries. Nuclei such as lithium, beryllium, and boron (which are not abundant end-products of stellar nucleosynthesis) and antimatter particles as positrons or antiprotons are mostly secondaries.

Detailed information on the composition at the source can be obtained from measurements of the abundance of refractory nuclei (Mg, Al, Si, Ca, Fe, Co and Ni) that appear to have a minimal elemental fractionation [3]. These abundances are in a very good agreement with the solar system values [4], indicating in the stellar flares the origin of most of all CRs species before acceleration. An exception to this similarity between solar and CRs abundances is the ratio ^{22}Ne/^{20}Ne. In CRs the ^{22}Ne abundance, respect to ^{20}Ne, is about 5 times more than in the solar system. This overabundance is due mainly to primary production and only a little by spallation of heavier elements. This is the

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consequence of the origin of a CRs fraction in high metallicity sources, as the Wolf–Rayet stars [5].

The scale time for the acceleration can be evaluated with unstable primary isotopes. In supernova explosions, nucleosynthesis of elements above Iron occurs and the unstable ^{59}Ni is produced. ^{59}Ni is an unstable primary decaying for K-capture with half-life of 76 kyr. At CR energies the atoms are stripped of all their atomic electrons and ^{59}Ni becomes stable. However no presence of ^{59}Ni in CRs has been measured. This is compatible with a lower limit on the delay time between production and acceleration of the order of 10 kyr [6].

Secondary isotope abundance depends on the origin primary composition and on the all-species galactic CRs propagation mechanism. In the context of the diffusion models [11], the secondary-to-primary ratios, as boron-to-carbon and sub-iron-to-iron, are used to evaluate the diffusive coefficient of CRs in the Galaxy. An increment of the diffusion coefficient corresponds to faster escaping of primary nuclei from the Galaxy and to smaller amount of secondaries produced, and vice versa. The peak structure observed in these ratios (left of Fig. 1) is explained as a diffusive reacceleration of CRs due to the scattering of charged particles on the magnetic turbulence in the interstellar hydrodynamical plasma. The precise measurement of the B/C ratio in the high energy range can distinguish among different propagation models [17].

The confinement time of CRs in the Galaxy is evaluated with *cosmic clocks*, long-lived β-decay secondary isotopes. In particular beryllium isotopes, ^{9}Be and ^{10}Be, have a complete secondary origin (beryllium is completely burned in stars). While ^{9}Be is stable, ^{10}Be has an half-life of 1.5 Myr. Their production cross-sections are very similar, however the observed ^{10}Be/^{9}Be is $\simeq 0.2$ (right of Fig. 1). This indicates that most of the beryllium has decayed in propagation constraining the time of confinement to 15 Myr [18].

2. Galactic CRs direct measurements

The chemical composition of Galactic CRs has been measured starting from the sixties by several instruments flying on balloons [7,19–24]. The most precise absolute flux measurements till today, however, have been obtained by two space-borne experiments: C2 on the High Energy Astrophysics Observatory 3 (HEAO-3) satellite, taking data for 3 years starting from 1979 [8]; Cosmic Rays Nuclei (CRN) instrument on-board of the Spacelab-2 mission on the Space Shuttle *Challenger* flown in 1985 [10].

C2 was able to discriminate among nuclei from beryllium up to nickel in the energy 0.6–35 GeV/n. This high statistics measurement was extended by CRN up to TeV/n energy for the most abundant elements.

The isotopic composition, instead, is mostly matter of space experiments as the High Energy Telescopes (HET) flying with the Voyager 1, Voyager 2 [15] and Ulysses [25] spacecrafts, or the Cosmic Rays Isotope Spectrometer (CRIS) instrument on the Advanced Composition Explorer (ACE) satellite [12]. All these instruments are characterized by solid-state Silicon detector able to distinguish a wide number of isotopes (almost all the species in CRs up to Iron) in a narrow energetic range, ~100 MeV/n. An exception to this picture is the magnetic spectrometer ISOMAX flown in 1998 able to give some detail on the shape of the ^{10}Be/^{9}Be ratio (right of Fig. 1).

The present generation of experiments measuring the chemical composition is devoted to reveal the composition toward the knee energies following the road opened by the

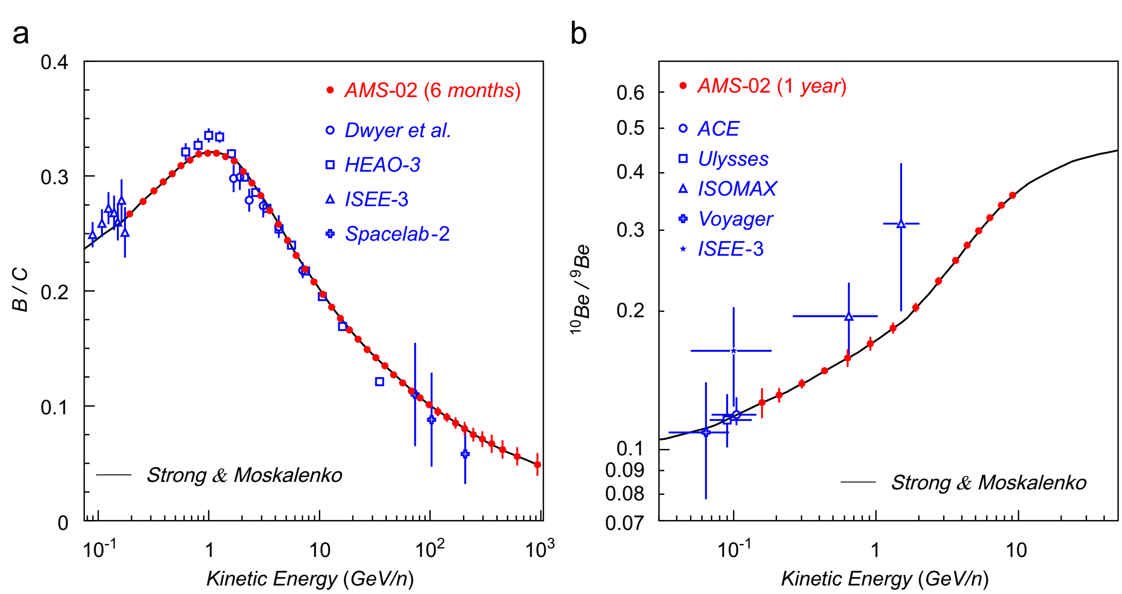

Fig. 1. On the left the boron-to-carbon ratio measured by several experiments [7–10]. The Strong and Moskalenko diffusion model [11] and the expected measurement for 6 month of data taking of AMS-02 are superimposed. On the right the isotopic ratio ^{10}Be/^{9}Be for the available data [9,12–15] is presented. The prediction for 1 year of AMS-02 is superimposed [16].