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^{10}Be/^{9}Be ratio up to 1.0 GeV/nucleon measured in the ISOMAX 98 balloon flight

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Abstract. The Isotope Magnet Experiment, ISOMAX, a balloon-borne superconducting magnet spectrometer was built with the capability to measure the isotopic composition of the light isotopes ($3 \leq Z \leq 8$) of the cosmic radiation up to 4 GeV/nucleon by using the β vs. rigidity technique with a mass resolution better than 0.25 amu, employing a combination of time-of-flight (TOF) system and silica-aerogel Cherenkov counters for the velocity determination. One of the primary scientific goals of ISOMAX was the accurate measurement of radioactive ^{10}Be with respect to its stable neighbor isotope ^{9}Be conveying information on the age of the cosmic rays in the galaxy. ISOMAX had its first flight on August 4-5, 1998, from Lynn Lake, Manitoba, Canada. It provided 13 h of data with a residual atmosphere of less than 5 g/cm^2. This paper reports the results of the beryllium ratio $^{10}\mathrm{Be}/^{9}\mathrm{Be} = 0.195 \pm 0.036$ at the top of atmosphere in the energy range from 0.261 – 1.030 GeV/nucleon using the TOF in the 1998 flight. The high energy results of the beryllium ratio up to 2 GeV/nucleon in the Cherenkov regime as well as the lithium results in the TOF energy range are also reported in these proceedings.

1 Introduction

The "secondary" constituents of the cosmic rays, e.g. lithium, beryllium, and boron, are produced by spallation in interactions of heavier "primary" cosmic ray nuclei, mainly carbon, nitrogen, and oxygen, with the ambient gas in our galaxy. Thus, by comparing the secondary to primary ratio in cosmic rays for a given propagation model one can derive the amount of mean matter cosmic rays encounter during their propagation. However, the measurement of radioactive "clock"-isotopes, such as ^{10}Be with a half-life of 1.6×10^6 years, which is entirely secondary, are of particular interest allowing the age of cosmic rays to be deduced. The measurement of this clock-isotope provides a stronger constraint to propagation models if it is carried out at high energies from 1 – 10 GeV/nucleon where the relativistic time dilation becomes significant to the ^{10}Be decay.

2 Instrument & Flight Performance

The Isotope Magnet Experiment, ISOMAX, was a balloon-borne superconducting magnet spectrometer. It was conceived and built to measure the isotopic composition of the light elements from lithium to oxygen in the cosmic radiation up to 4 GeV/nucleon in multiple flights. A special interest of the ISOMAX balloon program was the accurate measurement of radioactive ^{10}Be with respect to its stable neighbor isotope ^{9}Be (Streitmatter et al., 1995).

Incoming cosmic ray particles were identified by measuring their charge, velocity and magnetic rigidity (momentum/charge) using the velocity-rigidity technique with a mass resolution better that 0.25 amu. To achieve this excellent mass resolution ISOMAX was comprised of three detector subsystems: a magnetic rigidity spectrometer, and the velocity measurement of a state-of-the-art time-of-flight (TOF) system and two silica-aerogel Cherenkov counters. The rigidity was obtained from the curvature of a particle in the field of the superconducting magnet measured by a stack of three high-resolution drift chambers (DC). The middle DC was located in the high-field region between the two coils of the Helmholtz-like magnet. The coils had a separation of 80 cm and were operated for the 1998 flight at 120 A, yielding a field of 0.8 T in the center between the coils and a mean field integral of 0.54 Tm. The DC were composed of 480 hexagonal drift cells arranged in 24 layers (16 in bending and 8 in non-bending plane). The overall height of the DC stack was 150 cm. The drift gas was pure CO$_2$. The drift chamber demonstrated a spatial resolution of 54 μm for relativistic helium and 45 μm for beryllium using in-flight data. With the given field strength of the magnet and the spatial resolution of the DC we obtained a mean maximum detectable

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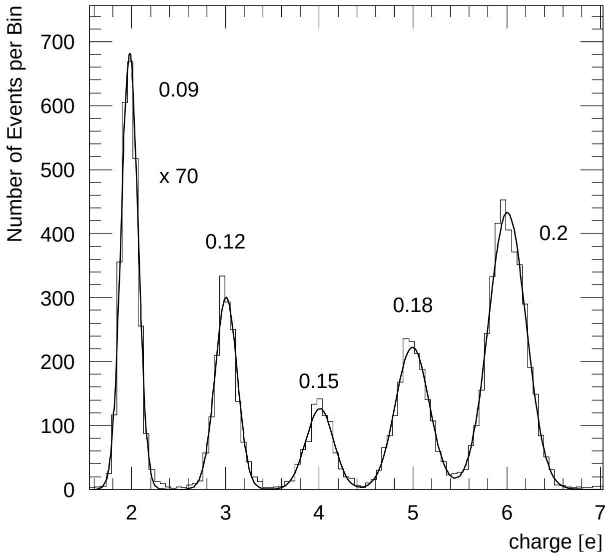

Fig. 1. In-flight charge separation in the top TOF by requiring a 3σ cut on charge in the other two scintillators and $\beta > 0.6$. The helium peak was scaled by a factor of 70. The values close to the charge peaks quote the charge resolution, which is better than 0.2 charge units for He – C.

rigidity (MDR) of 970 MV/c for in-flight helium. Further details on the magnetic rigidity spectrometer are reported by Hams et al. (1999). The TOF system consisted of three layers of fast Bicron BC420 scintillator with a separation from the top to middle and top to bottom scintillator of 206.8 cm and 260 cm, respectively. The time resolution of the TOF system was found at 70 ps for helium and 60 ps for beryllium. In addition, the TOF scintillator provided a multiple charge measurement using dE/dx. Figure 1 shows this charge separation in the top scintillator with a 3σ cut on charge in the other two scintillators and $\beta > 0.6$. The charge resolution for helium through carbon is better than 0.2 charge units. Further details of the time-of-flight system can be found in Geier et al. (1999). To extend the velocity measurement of the TOF system (beyond 1 GeV/nucleon for beryllium) two large-area Cherenkov counters were used. In the 1998 flight these counters were each equipped with a nominal index-of-refraction $n = 1.14$ silica-aerogel radiator resulting in an energy threshold of 1.08 GeV/nucleon. For relativistic single-charged particles ($Z = 1$, $\beta = 1$) a total of 22 photoelectrons were obtained for both counters (de Nolfo et al., 1999). The geometry factor of the instrument was 450 cm^{2}sr for particles that had penetrated the sensitive area of the TOF and the DC.

The ISOMAX experiment had its first flight on August 4-5, 1998, from Lynn Lake, Manitoba, Canada. After the flight the instrument was recovered in perfect condition near Peace River, Alberta, Canada. In this successful flight, the instrument was able to measure the beryllium isotopes in the energy range from 0.2 – 2.0 GeV/nucleon with a mass resolution better than 0.25 amu. We used ascent data transmitted via telemetry to optimize the detector settings for beryllium ($Z = 4$). During this flight we obtained 13 hours of data at a residual atmosphere of less than 5 g/cm^2 as well as a few hours of low-altitude data. A detailed general instrument performance during flight can be found in Mitchell et al. (1999) and Hof et al. (2000).

$0.2 \leq E_{kin} \leq 1.0$ GeV/nucleon
$\rho_{alt} \leq 5$ g/cm^2
DC single-track fit: $N_x \geq 8$ and $N_y \geq 4$
$\lvert Z_i - 4 \rvert \leq 0.5$

Table 1. Applying these cuts to the flight data 424 beryllium events were detected.

3 Data Selection

In this section the cuts applied to the flight data are discussed and the obtained beryllium mass histogram is presented. To reduce the effects of atmospheric interaction, only events recorded at less than 5 g/cm^2 residual atmosphere were considered for the analysis. From this subsample of events a successful track reconstruction in the drift chamber was required. A DC fit was successful if at least 8 of the 16 layers in the bending plane, N_x, and 4 of the 8 layers in the none-bending plane, N_y, were incorporated into the track fit. In addition, multi-track events where rejected. We chose a fairly loose DC cut to avoid a bias in the isotopic ratio due to rigidity-dependent cuts. The DC fit efficiency for beryllium with this constraint was found at 95% and was independent of the rigidity. The beryllium events were then identified by requiring a measured charge $Z = 4$ in all three scintillator layers. Specifically, a cut requiring $|Z_i - 4| \leq 0.5$ was imposed, where i denotes the different scintillator layers. The velocities of incident particles up to 1 GeV/nucleon were determined with the timing of the top and bottom scintillator arrays. Account was taken of energy losses within the instrument and the subsequent increase in local dE/dx. By requiring a consistent charge measurement in all three TOF paddles, $Z = 4$, within $\sim 3\sigma$ the contamination of the beryllium events by misidentified charge is less than 10^{-6} and can be neglected while the efficiency of this cut was determined at 95%. In the discussed energy range from 0.2 – 1.0 GeV/nucleon, 424 beryllium events were detected by applying the cuts discussed above and summarized in Table 1. Figure 2 shows the mass histogram for these beryllium events. From this mass histogram the relative abundances of the beryllium isotopes were obtained by a least-square fit using a Monte-Carlo simulation which accounts for in-flight detector performance. This fit of the measured ratio in the instrument is also shown in the figure and was found to be $^{10}\mathrm{Be}/^{9}\mathrm{Be} = 0.249 \pm 0.046$ for the energy range 0.2 – 1.0 GeV/nucleon.

	^{10}Be/^{9}Be Ratio	Energy
Instrument	0.249 ± 0.046	$0.200 - 1.000\,\mathrm{GeV/nuc.}$
Top of Instrument	0.259 ± 0.048	$0.233 - 1.016\,\mathrm{GeV/nuc.}$
Top of Atmosphere	0.195 ± 0.036	$0.261 - 1.030\,\mathrm{GeV/nuc.}$

Table 2. Beryllium ratios and energy ranges at different stages of the analysis. The quoted uncertainty of the beryllium ratios are statistical errors only.

4 Instrumental & Atmospheric Correction

The charge consistency in all three TOF scintillator layers and the single-track requirement in the DC reject interacting beryllium events in the detector stack. The mean instrumental correction which accounts for the interaction probability of beryllium isotopes propagating through the instrument ($\rho = 11.2\,\mathrm{g/cm^2}$) is found at 1.04 using the method of Kox (Kox et al., 1987) for the inelastic cross section. The corrected beryllium ratio at top of instrument with the corresponding energy range is shown in Table 2. The beryllium ratio at the top of instrument needs to be corrected for interactions in the atmosphere above the experiment. The average residual atmosphere for the high altitude data was 4.4 $\mathrm{g/cm^2}$. Taking the geometrical aperture of the instrument into account, the mean incident zenith angle is 15°, resulting in an average grammage of 4.6 $\mathrm{g/cm^2}$ which was used for atmospheric correction. The spectra of the elements from boron through nickel measured by the ACE-satellite (ACE/CRIS, 2000) and by Engelmann et al. (1990) were demodulated and thereafter adopted to a solar modulation of 430 MV/c experienced during the ISOMAX 1998 flight. In addition, a leaky-box model ($n = 0.3\,\mathrm{cm^{-3}}$) was used to derive an initial ^{9}Be spectrum at top of atmosphere (TOA). We assumed a similar spectral shape for the ^{10}Be flux. This set of spectra was then propagated through 4.6 $\mathrm{g/cm^2}$ of atmosphere using the partial cross sections of Silberberg et al. (1998) and Tsao et al. (1998) and the total inelastic cross sections of Kox et al. (1987). The mean atmospheric correction factor for our energy interval was found at 0.753 resulting a beryllium ratio at TOA of $^{10}\mathrm{Be}/^{9}\mathrm{Be} = 0.195 \pm 0.036$, see Table 2.

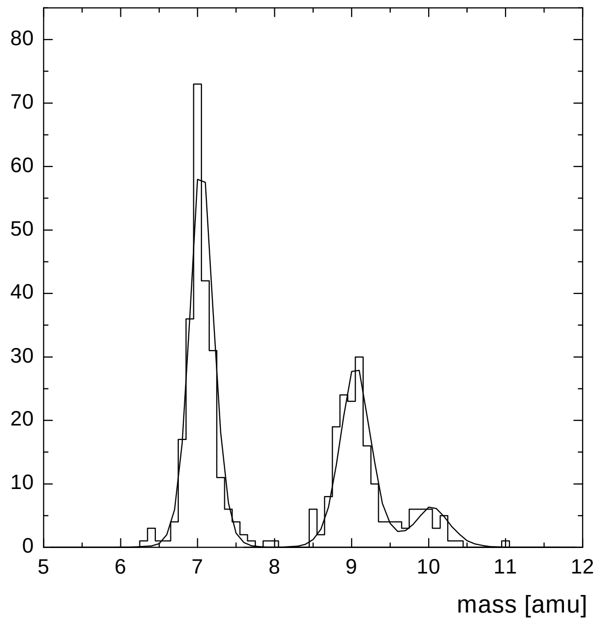

Fig. 2. Mass histogram of 424 beryllium events as measured in the instrument in an energy range from 0.2 – 1.0 GeV/nucleon. Solid curve is a least-square fit of a Monte-Carlo simulation. We obtained a beryllium ratio of $^{10}\mathrm{Be}/^{9}\mathrm{Be} = 0.249$ measured in the instrument.

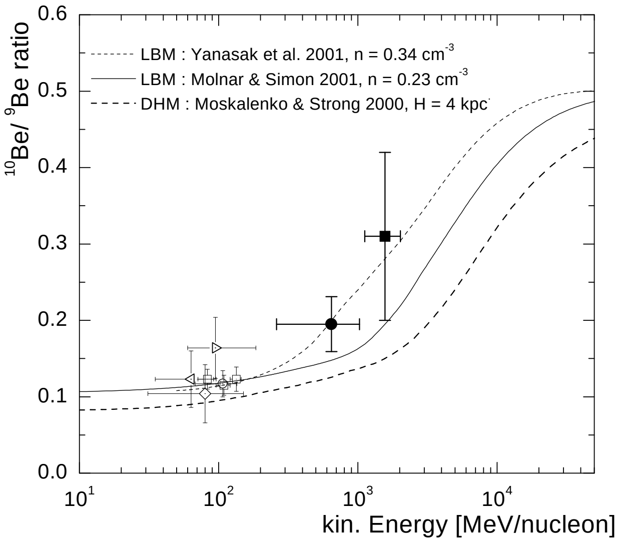

Fig. 3. Beryllium ratio at top of atmosphere of ISOMAX (● this work and ■ de Nolfo et al., 2001) compared with satellite measurements: □ ACE (Yanasak et al., 1999), ○ Ulysses (Connel, 1998), ◁ Voyager 1-2(Lukasiak et al., 1997), ▷ ISEE-3 (Wiedenbeck and Greiner, 1980), and ◇ IMP 7/8 (Garcia-Munoz et al., 1977; Garcia-Munoz & Wefel, 1981). The lines show the expected beryllium ratio in different propagation models. The two upper lines are leaky-box model (LBM) the lower one is a diffusive-halo model (DHM).

5 Results

Figure 3 shows the ^{10}Be/^{9}Be ratio at top of atmosphere in the energy range from 0.261 – 1.030 GeV/nucleon measured by the TOF together with satellite measurements at several 100 MeV/nucleon of ACE, Ulysses, Voyager 1-2, ISEE-3, and IMP 7/8. The figure also includes the ISOMAX ^{10}Be/^{9}Be ratio above 1 GeV/nucleon measured by Cherenkov detectors and discussed in detail in these proceedings (de Nolfo et al., 2001). The error bars represent the statistical errors of our measurement. The additional uncertainty from instrumental and atmospheric corrections are currently under investigation.

Our measurement does not confirm the apparent excess of ^{10}Be reported by SMILI (Ahlen et al., 2000). SMILI quoted the detection of nine ^{10}Be in a total of 26 beryllium events at an average energy of $\sim$1 GeV/nucleon resulting in a ratio of $^{10}\mathrm{Be}/\mathrm{Be} = 0.35$. Our measured ratio in the instrument covered by the TOF is $^{10}\mathrm{Be}/\mathrm{Be} = 0.09 \pm 0.02$, more than three times smaller. This low $^{10}\mathrm{Be}/\mathrm{Be}$ ratio is also confirmed by the ISOMAX Cherenkov data.

The two upper curves in Fig. 3 are different leaky-box models. The top dashed curve by Yanasak et al. (2001) is assuming an average density of 0.34 atoms/cm^3 of interstellar medium (ISM). The solid curve by Molnar & Simon (2001) takes a ISM density of 0.23 atoms/cm^3 into account. Finally, the lower dashed curve is a diffusive-halo model by Moskalenko & Strong (2000) with a halo size of 4 kpc and that accounts for the local galactic structure. The statistical uncertainties of the ISOMAX results, in combination with the spread in model predictions, preclude any final conclusions concerning cosmic-ray propagation at present. However, it is worthwhile mentioning that the steep increase of the $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratio as measured by ISOMAX is probably difficult to accommodate with the presence of reacceleration, since reacceleration has the general tendency to produce ratios, that are below those calculated in the corresponding model without reacceleration.

6 Conclusion

The beryllium measurements of ISOMAX (this work; de Nolfo et al., 2001) are the first of its kind extending the measurement up to 2 GeV/nucleon. Our data indicate a steep increase in the $^{10}\mathrm{Be}/^{9}\mathrm{Be}$ ratio but final conclusions on model predictions are not possible at present, although the steep rise of the ratio with energy might be difficult to accommodate with reacceleration. Future experiments with comparable features of ISOMAX and improved statistics are needed to impose stronger constraints on the comic-ray propagation models.

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