Relativistic Be^7: A Probe of Cosmic-Ray Acceleration?

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We have observed the cosmic-ray Be^7/Be ratio to be 0.6 below 500 MeV/nucleon, as expected from spallation reactions, but then to drop sharply to 0.4 by 1500 MeV/nucleon. This measurement suggests that primary cosmic rays traverse some material at their sources, producing Be^7 which picks up electrons and decays by K capture during or after the acceleration to relativistic energies. All cosmic rays then enter interstellar space, where further pickup is negligible.

Beryllium has provided a stimulus to cosmic-ray isotope measurements because radioactive Be^{10} can be used as a "clock" to measure the cosmic-ray age. Several groups have already reported beryllium isotope separations at low energies.[1-3] This Letter describes measurements made at higher energies, to reduce potential uncertainties from solar modulation and energy-dependent spallation–cross-section corrections. These measurements have disclosed an unexpected sharp drop in the Be^7 flux above about 500 MeV/nucleon.

The detector, a balloon-borne superconducting magnetic spectrometer (Fig. 1), measured cosmic-ray isotopes from lithium to oxygen for kinetic energies below about 1500 MeV/nucleon.[4,5] A combination of scintillators and optical spark chambers recorded dE/dx and rigidity R (momentum/charge). Since both of these are functions only of particle velocity, mass, and charge Z, the mass can be calculated, because Z is generally determined unambiguously through the discrete nature of charge. Mass resolution was limited by the several percent accuracy of the spectrometer's rigidity measurement, and comparable accuracy in the dE/dx measurements due to Symon-Landau fluctuations. A mass resolution of about 0.3 amu was achieved for beryllium isotopes below 2 GV/c (about 500 MeV/nucleon). The resolution worsened at higher rigidities, reaching 1.5 amu at 4.5 GV/c (about 1500 MeV/nucleon). A trigger threshold allowed events to be recorded with more than about 14 times the dE/dx of a minimum ionizing $Z=1$ particle in scintillator S_1, more than 11 times in S_2, and more than one time in S_4. The flight took place from Aberdeen, South Dakota, on 28 May 1977 at a residual atmosphere of 5.9 g/cm^2 and at a geomagnetic cutoff of 1.5 GV/c. The exposure factor was 1640 m^2 sr sec.

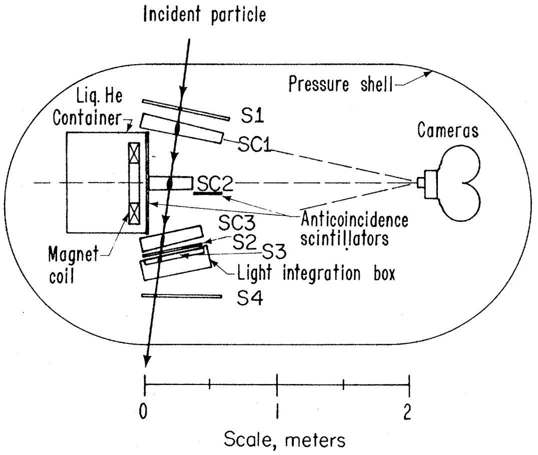

FIG. 1. Schematic diagram of the apparatus. A particle incident from above had its trajectory bent by the field of the superconducting magnet. Scintillators S_1, S_2, S_3, and S_4 measured the dE/dx and provided the trigger for three optically viewed spark chambers, which recorded the trajectory.

The spark positions for each of 28 552 events satisfying scanning criteria for a single trajectory through the spectrometer were measured on a film-plane digitizing machine. The trajectory through the magnetic field was fitted to yield a rigidity value. The scintillator pulse information was corrected for incident angle and position, and for scintillator light saturation, to yield dE/dx values. These, with the rigidity value, were fitted by a minimum-χ^2 technique simultaneously to eliminate fragmentations and yield isotope masses.[5] Of 17 652 events passing all selection criteria, 631 were best fitted to beryllium below 4.5 GV/c. Figure 2 shows the mass distributions for these events, together with the fits derived from Monte Carlo–generated events. Note that there is very little Be^{10} and a rapidly varying Be^7/Be ratio with increasing rigidity. The fit in the lowest-rigidity histogram would be improved by a shift of -0.1 amu in the data. This shift is compatible with the residual systematic error in determining the scintillator light saturation correc-

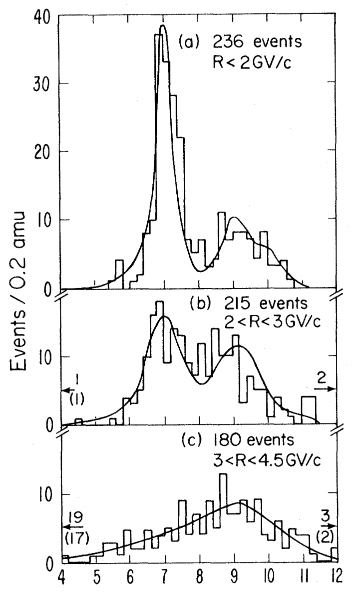

FIG. 2. Mass distributions for beryllium in rigidity bins (GV/c). The smooth curves represent Monte Carlo fits to the data. Underflow and overflow are indicated for data and Monte Carlo (parentheses).

tions, which were established independent of Be using the Li and C data. Correcting this shift changes none of the results to be reported in this Letter.

The events of Fig. 2 were observed under an average 7.2 g/cm^2 of atmosphere and gondola shell, which both attenuated the cosmic beryllium and added extra beryllium from spallations above the instrument. In addition, 7.9 g/cm^2 of apparatus material, mostly scintillator, attenuated the beryllium signal but added no extra beryllium secondaries, since fragmentations within the apparatus were eliminated by the fitting criteria. Table I shows how the event counts of Fig. 2 were corrected for the effects of interactions and dE/dx losses in the material in and above the apparatus. A detailed description of the correction factors, as well as a discussion of the Be^{10} results, is given in Ref. 5.

Figure 3 shows that our low-energy Be^7/Be ratio, corrected to the top of the magnetosphere, is in good agreement with previous balloon[1,2] and satellite[3] measurements. The two experiments[6,7] utilizing the geomagnetic cutoff method of Peters[8] measured only mean Be mass, and hence were not recognized as giving prior hints of the changing Be^7/Be ratio reported here.

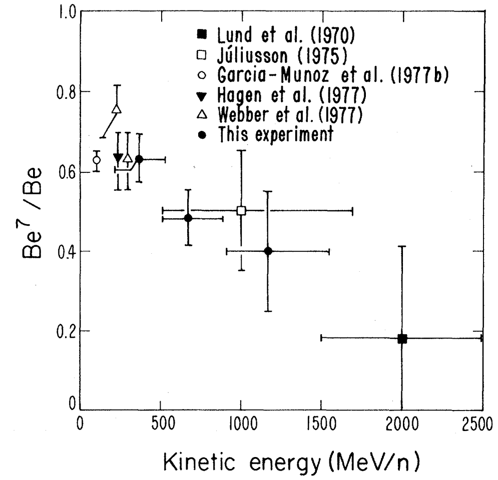

FIG. 3. A plot of the Be^7/Be ratio at the top of the atmosphere as a function of kinetic energy per nucleon. The mean mass data of Ref. 6 and of Júliusson (Ref. 7) have been plotted without atmospheric correction and assuming complete absence of Be^{10}. If a value of Be^{10}/Be = 0.1 were chosen, both mean mass data points would move upward by about 0.05. The significance of the raw Be^7/Be data relative to an assumed constant low-rigidity value of 0.65 [Figs. 2(b) and 2(c) compared with 2(a)] is 4 to 5 standard deviations, depending on how systematic error estimates are included. The significance is about one standard deviation less here due to the T/N factor in Table I. The error bars here and in Table I, which include full systematic contributions at the 1-standard-deviation level, may overestimate the errors at the 3-standard-deviation level.

Since the Be^9/C ratio is much more constant than the Be^7/C ratio,[5] we conclude that Be^7 is responsible for the changing Be^7/Be ratio, Solar modulation seems unable to account for the change because (1) at low energies where solar modulation should have its greatest distorting effect, the Be^7/Be ratio is as expected from spallation reactions (see, for example, Raisbeck and Yiou[9]); (2) calculations of solar modulation[1,3] indicate a change of only (5–10)% in the Be^7/Be ratio, and of the opposite sign to explain the observed change; and (3) if solar modulation were responsible, the B^{10}/B ratio might show about half the change of Be^7/Be whereas no such change was observed.[5]

It is possible that energy dependence of spallation cross sections might cause changing isotope ratios. However, most of the data presented here lies safely above the regime of strong energy dependence even if the effect of the solar modulation's adiabatic deceleration (estimated to be ≈200 MeV/nucleon) is neglected.

We attribute the diminishing Be^7/Be ratio to

TABLE I. Corrections for gondola, atmosphere, and dE/dx losses.

Isotope	Measured rigidity (GV/c) in gondola	Equiv. rigidity top of atmosphere	Kinetic energy (MeV/N), top of atmosphere[a]	Events[b]	Correction factors				Events
					Gond. atten.	Bin edges[c]	Atmos.	T/N factors[d]	
Be^7	0.83–2.00	1.19–2.12	330–640	151	1.34	1.00	0.87	0.93	163 ± 25
	2.00–3.00	2.12–3.09	640–1090	113	1.34	0.91	0.74	1.03	105 ± 20
	3.00–4.50	3.09–4.58	1090–1860	69	1.34	0.98	0.70	1.13	72 ± 33
Be^9	1.01–2.00	1.41–2.15	210–425	52	1.40	1.04	0.83	1.03	65 ± 19
	2.00–3.00	2.15–3.10	425–745	92	1.40	0.94	0.87	1.03	108 ± 23
	3.00–4.50	3.10–4.59	745–1320	82	1.40	0.97	0.89	0.92	91 ± 26
Be^{10}	1.09–2.00	1.52–2.19	175–355	28	1.43	1.07	0.63	1.16	31 ± 11
	2.00–3.00	2.19–3.12	355–635	17	1.43	0.98	0.22	1.03	5 ± 12
	3.00–4.50	3.12–4.59	635–1130	30	1.43	0.99	0.62	0.83	22 ± 19

[a] Energy values correspond to carbon-12's rigidity bin edges (Ref. 5).

[b] Six events were added to the 2–3-GV/c bin, and eighteen to the 3–4.5-GV/c bin, to correct for the S_1 trigger threshold inefficiency: Not included here are 21 events which were rare, atmospherically produced Be isotopes.

[c] Correction to coincide data with carbon-12's rigidity bins (1.49, 2.22, 3.14, and 4.62 GV/c).

[d] Correction to coincide data with carbon-12's kinetic energy bin edges (260, 510, 895, and 1550 MeV/N).

K-capture decay occurring prior to the entry of the cosmic rays into interstellar space, because interstellar electron pickup at these energies appears to be negligible.[10] Since about half of the expected Be^7 is not observed at high energies, we propose that the primary cosmic rays, after preacceleration to energies above spallation threshold, pass through roughly half of the 4–5 g/cm^2 they typically encounter in their lifetime. Spallations in this source material produce about half of the total Be^7. Energies above ~500 MeV/nucleon are then attained only by experiencing a yet-unknown process for acceleration to relativistic energies. We propose that either the relativistic acceleration or a "drift time" following it involves a comoving electron gas which permits partial recombination (and Be^7 decay). Finally, the cosmic rays enter the interstellar medium, making further Be^7 secondaries with no chance for decay.

It is not presently apparent to us how the above description fits in with current (e.g., supernova-remnant) theories of cosmic-ray origin, and why the energy dependence begins near 500 MeV/nucleon (β^2 ~0.5). It does seem difficult, however, to reconcile the present measurement with any theory which invokes numerous energy-changing interactions after the Be^7 decay. Such processes, whether producing a net energy shift or not, would tend to obscure the rather sharply defined change that we have observed (a factor-of-3 change in Be^7/Be^9 over an energy range of a factor of 3). Also, isotope measurements for lithium and beryllium above about 5 GeV/nucleon are now of very great interest for future experiments, since they would be able to tell us whether the changing L/M ratio above this energy is due to changing properties of interstellar space (Be^7/Be remains ~0.4), or of regions associated with the source (Be^7/Be returns to 0.6 above about 50 GeV/nucleon).

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