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**A REVIEW AND INTERPRETATION OF RECENT COSMIC RAY
BERYLLIUM ISOTOPE MEASUREMENTS**

**(Contribution to a Symposium of the Division
of Cosmic Physics, the American Physical Society,
presented in Washington D.C., on 26 April 1978)**

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ABSTRACT

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A Review and Interpretation of Recent Cosmic Ray Beryllium Isotope Measurements*

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Be^{10} has long been of interest for cosmic ray propagation, because its radioactive decay half-life is well matched to the expected cosmic ray age. Recent beryllium isotope measurements from satellites and balloons have covered an energy range from about 30 to 300 MeV/nucleon¹⁻³. At the lowest energies, most of the Be^{10} is absent, indicating a cosmic ray lifetime of order 2×10^7 years and the rather low average density of 0.2 atoms/cc traversed by the cosmic rays. At higher energies, a greater proportion of Be^{10} is observed, indicating a somewhat shorter lifetime. These experiments will be reviewed and then compared with a new experiment covering from 100 to 1000 MeV/nucleon⁴. Although improved experiments will be necessary to realize the full potential of cosmic ray beryllium isotope measurements, these first results are already disclosing interesting and unexpected facts about cosmic ray acceleration and propagation.

* Work supported by NASA and DOE

¹M. Garcia-Munoz, G.M. Mason, and J.A. Simpson, Ap. J. 217, 859 (1977).

²F.A. Hagen, A.J. Fisher, and J.F. Ormes, Ap. J. 212, 262 (1977).

³W.R. Webber, J.A. Lezniak, J.C. Kish, and G.A. Simpson, Astrophys. Lett. 18, 125 (1977).

⁴A. Buffington, C.D. Orth, and T.S. Mast, contributed paper this meeting.

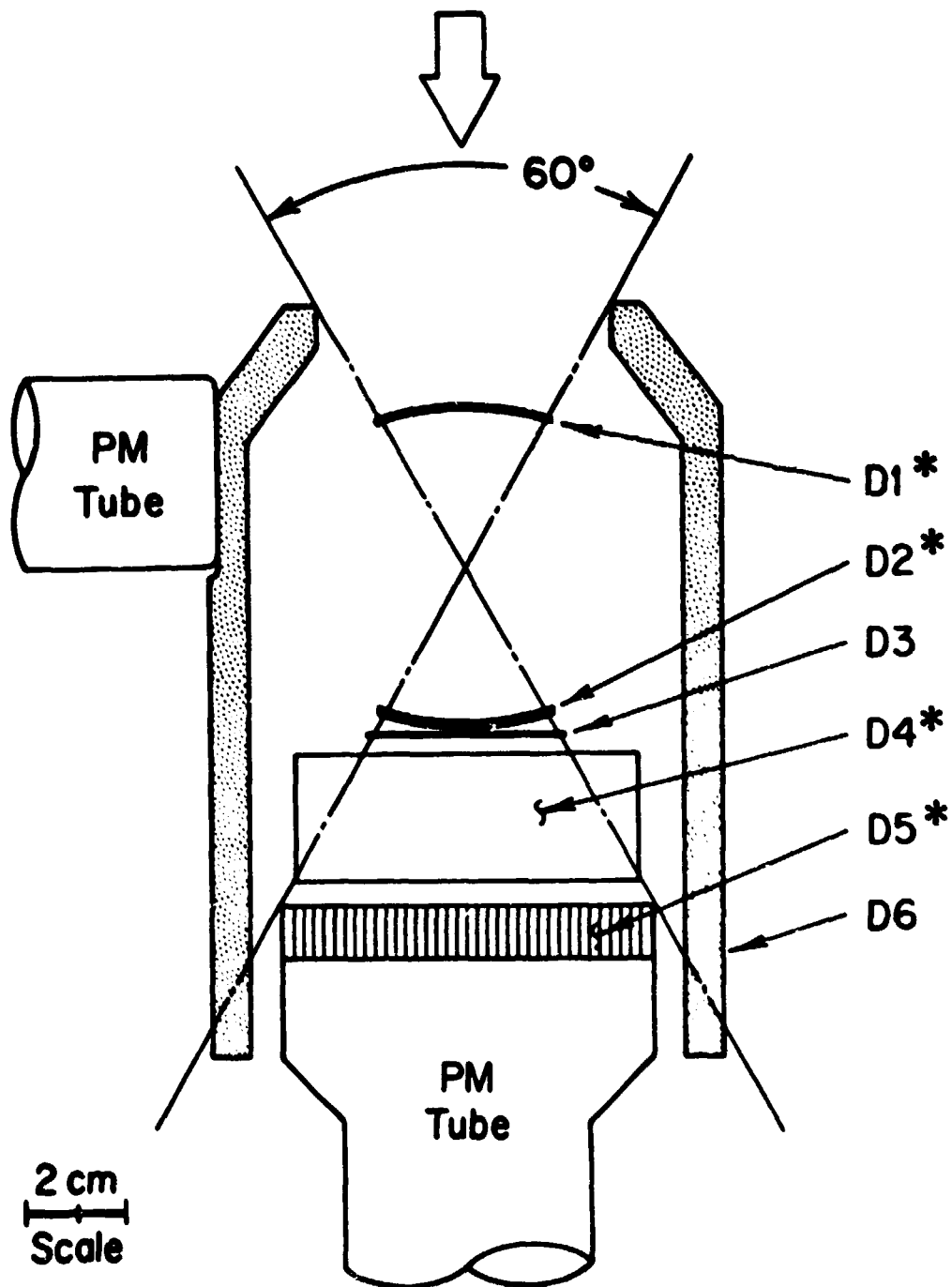
I am going to talk today about isotope measurements in the cosmic rays, in particular about beryllium isotopes, since these have recently been producing some interesting and unexpected results, which are already requiring considerable changes in our understanding of cosmic ray origin and history. But first, I will say a few words about why we're concentrating on beryllium. This element is secondary in the cosmic rays, which means that it is produced, presumably outside of the source region, by spallation reactions of primary cosmic ray nuclei such as carbon and oxygen with interstellar gas. Beryllium has a richness of isotopes which makes it particularly worthwhile to study. Be^7 is subject to K electron capture and decay in the laboratory with a 53 day half-life; stripped of all orbital electrons it is stable. Be^9 is stable. Be^{10} , with its 1.6×10^6 years half-life for β^- emission, has long been recognized as a "clock" suitable for dating the cosmic rays. Since beryllium isotopes are made in interstellar space, shorter-lived isotopes such as Be^6 or Be^{11} are all gone, although they may be observed in balloon experiments as atmospherically produced secondaries. Be^8 decays too quickly even for this, thus creating a convenient gap between Be^7 , and Be^9 and Be^{10} . The secondary nature of beryllium means that its study should tell us only about cosmic ray history, and not much about its origin. However, today I will be showing new data of a very unexpected kind which might show that measurements of beryllium isotopes in fact do tell us something about the nature of the cosmic ray sources.

I would like to review four experiments that have measured beryllium isotopes. Our consideration is limited to experiments above about 100 MeV/nucleon, so we won't have to worry too much about the effects of solar

modulation on the measurements and interpretations. Separation of isotopes is easiest when charge Z and energy-per-nucleon E/A are small; relative fluxes of nearby isotopes and absolute fluxes are also important, since one must gather a reasonable number of events in an experiment and not have a rare isotope buried beneath the tails of a nearby plentiful one. It is presently practical to measure velocity β (by dE/dx , Cerenkov light, or time-of-flight), magnetic rigidity R (by magnetic spectrometer or statistically using geomagnetic cutoff), and total energy E (by calorimeter or by range). Since specifying a particle requires Z , mass number A , and velocity β (or a combination of these) to be specified, one must measure three things to determine the mass. Quantization of charge Z usually reduces the number of measurements required to two. Mass number A is what we want to determine.

The four experiments I'm going to review today give a good exposure to the experimental techniques that are being applied presently to cosmic ray isotope measurements. I'll describe them in ascending order of energy covered. The first experiment is from the University of Chicago, with Garcia-Munoz, Mason, and Simpson as the experimenters. They used a small detector, only a few cm^2 ster, flown for many years on the IMP-7 and IMP-8 satellites. The energy was about 80 MeV/nucleon for beryllium isotopes and the technique used was the combination of dE/dx and total E measurements. Figure 1 shows the apparatus. The actual hardware is shown in figure 2, and figure 3 shows an artist's view of IMP-8. These satellites were operational for many years, so an impressive amount of data was gathered. Figure 4 shows a recent compilation of results, together with the Bevalac calibration of the backup instrument. This figure shows that $\text{Be}^7/\text{Be}^9 \approx 3$, and that only a little Be^{10} has survived, thus implying that the cosmic

UNIVERSITY OF CHICAGO
IMP-7/8



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Figure 1. Apparatus for the IMP-7 and IMP-8 satellite experiment for measuring beryllium isotopes (courtesy of M. Garcia-Munoz).

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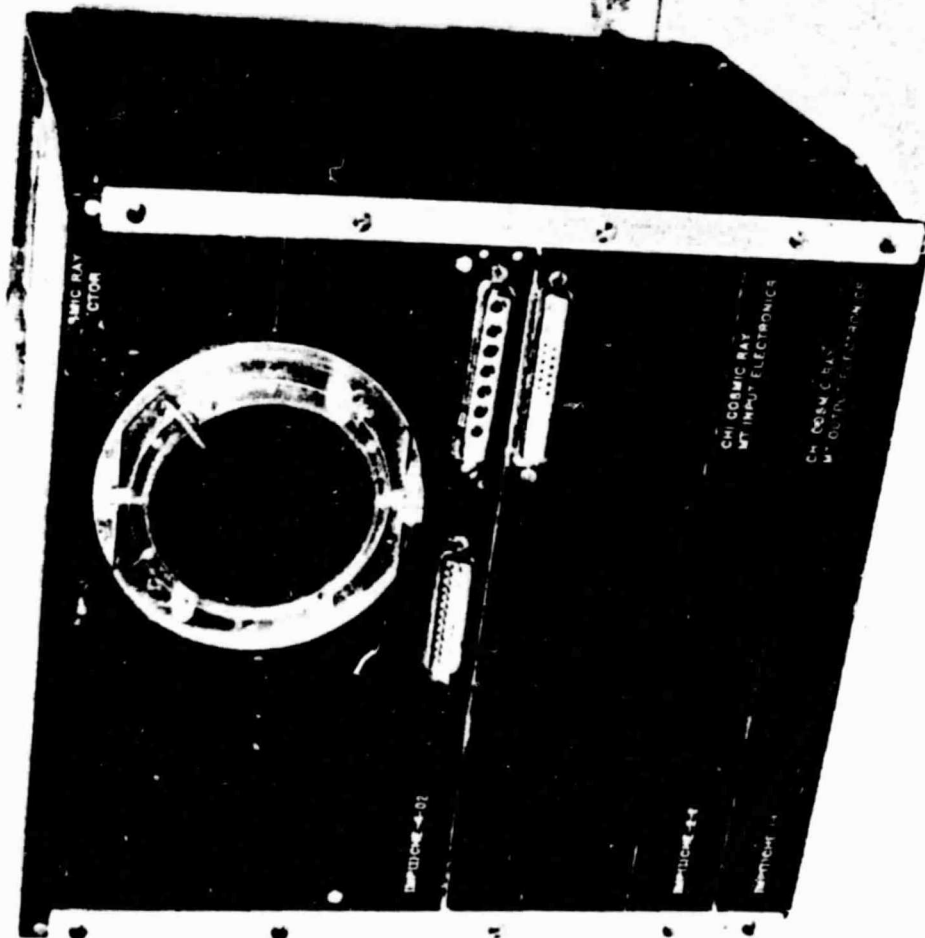
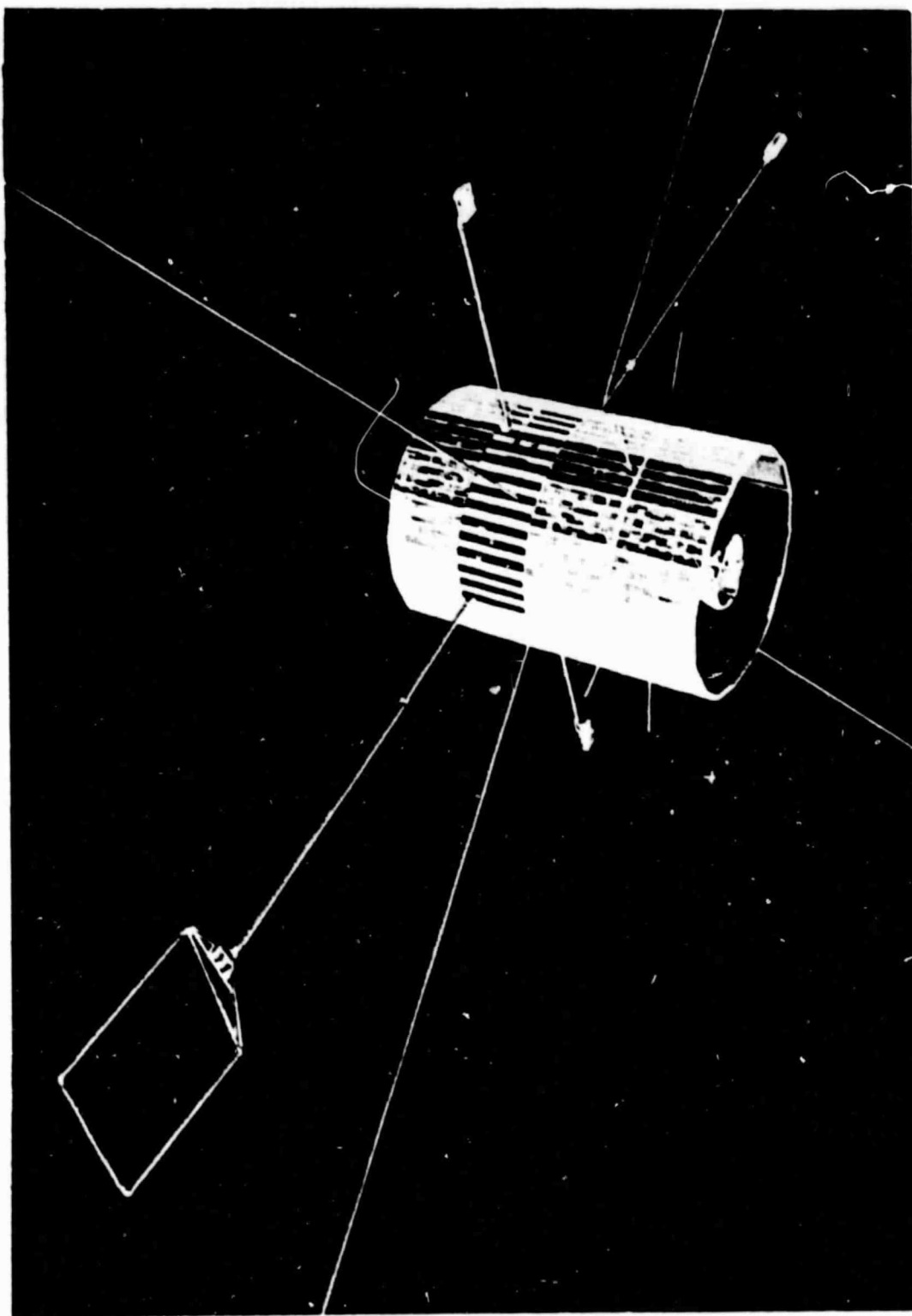


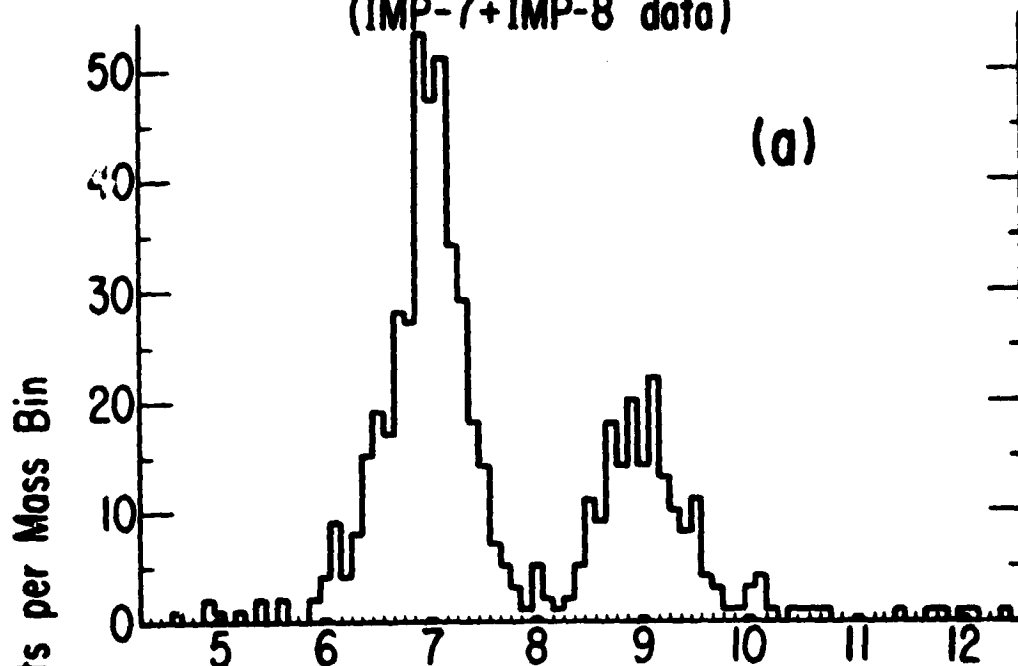
Figure 2. Flight hardware for the IMP-7 and IMP-8 satellite experiment (courtesy of M. Garcia-Munoz).



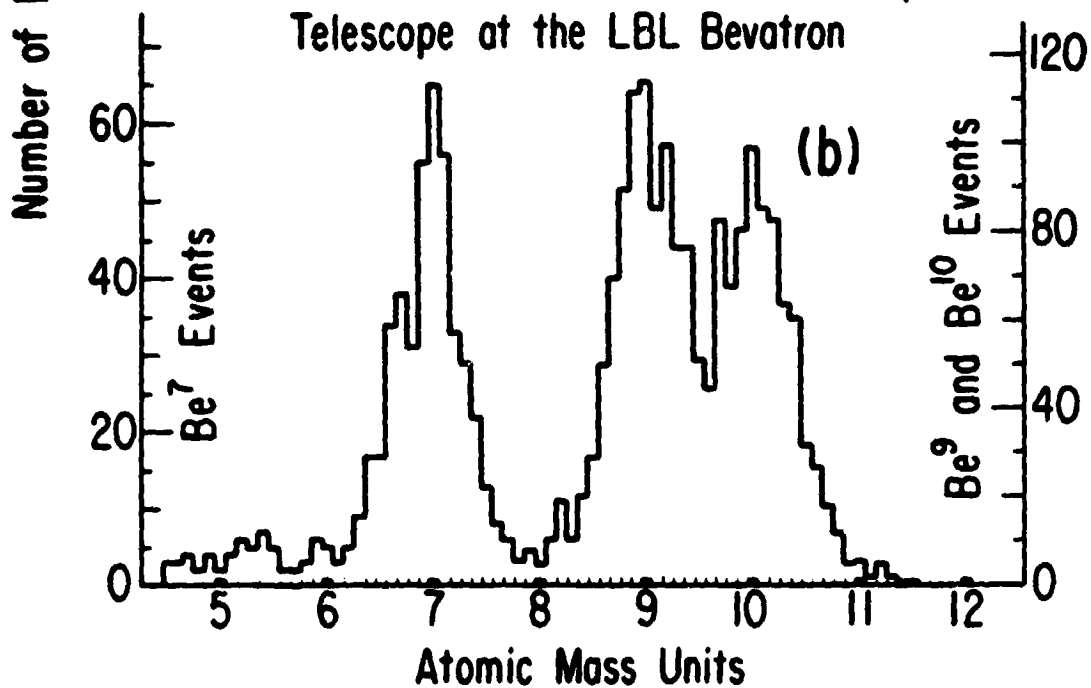
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Figure 3. Artist's conception of IMP-8 in flight (courtesy of M. Garcia-Munoz).

Isotopic Analysis Mass Histogram of Galactic Cosmic Ray Be (IMP-7+IMP-8 data)



Be Calibration of the IMP-7/8 Back-up Telescope at the LBL Bevatron



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Figure 4. Beryllium data from IMP-7 and IMP-8, with LBL Bevatron calibration (from reference 1, see abstract page).

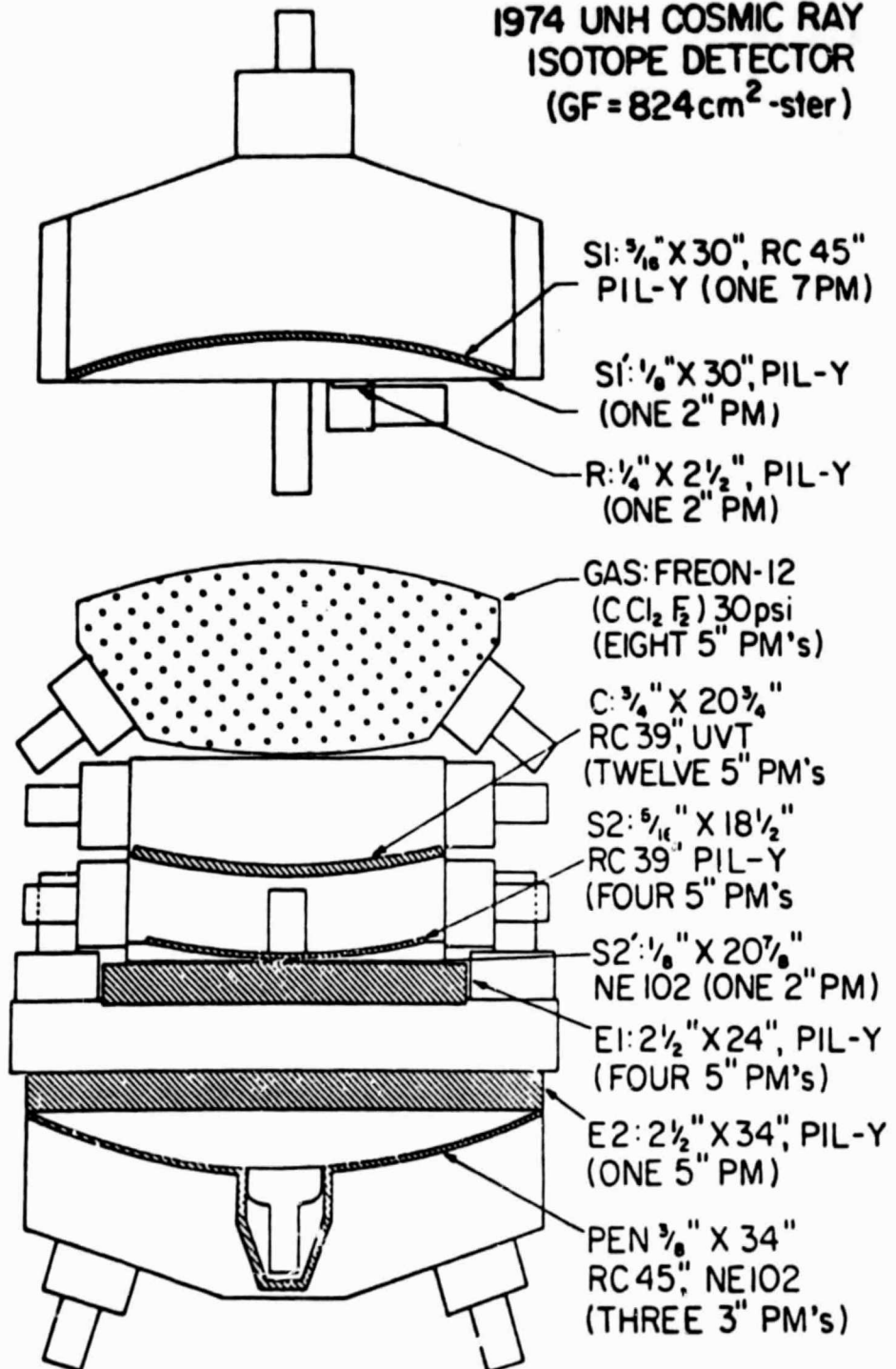
rays are old compared with 1.6×10^6 years.

The second experiment is from the University of New Hampshire, with Webber, Lezniak, Kish, and Simpson as the experimenters. Figure 5 shows the apparatus, which measures dE/dx and E also, and covers 100 to 250 MeV/nucleon. The experiment is flown by balloon, and (as is true for all the balloon-borne experiments) has a much greater geometry factor, to make up for the shorter flight times. Figure 6 shows the results: the picture is very similar to that of the University of Chicago, but there may be a bit more Be^{10} , as one would expect, since some Be^{10} is made in the overlying atmosphere and it doesn't get time to decay.

The third experiment is from the Goddard Space Flight Center, with Hagen, Fisher, and Ormes as the experimenters. Figure 7 shows the apparatus. Here many measurements of dE/dx follow the particle until it stops, as in a range measurement. The apparatus covers 150 to 350 MeV/nucleon, and is also flown by balloon. Figure 8 and 9 show the apparatus with its cover removed, and mounted on the balloon launch crane. Figure 10 shows the results, which again look like those of the Chicago group, but with more Be^{10} . Here the extra Be^{10} is a bit more than the overlying atmosphere could explain, as we'll see when we discuss the cosmic-ray Be^{10} lifetime shortly.

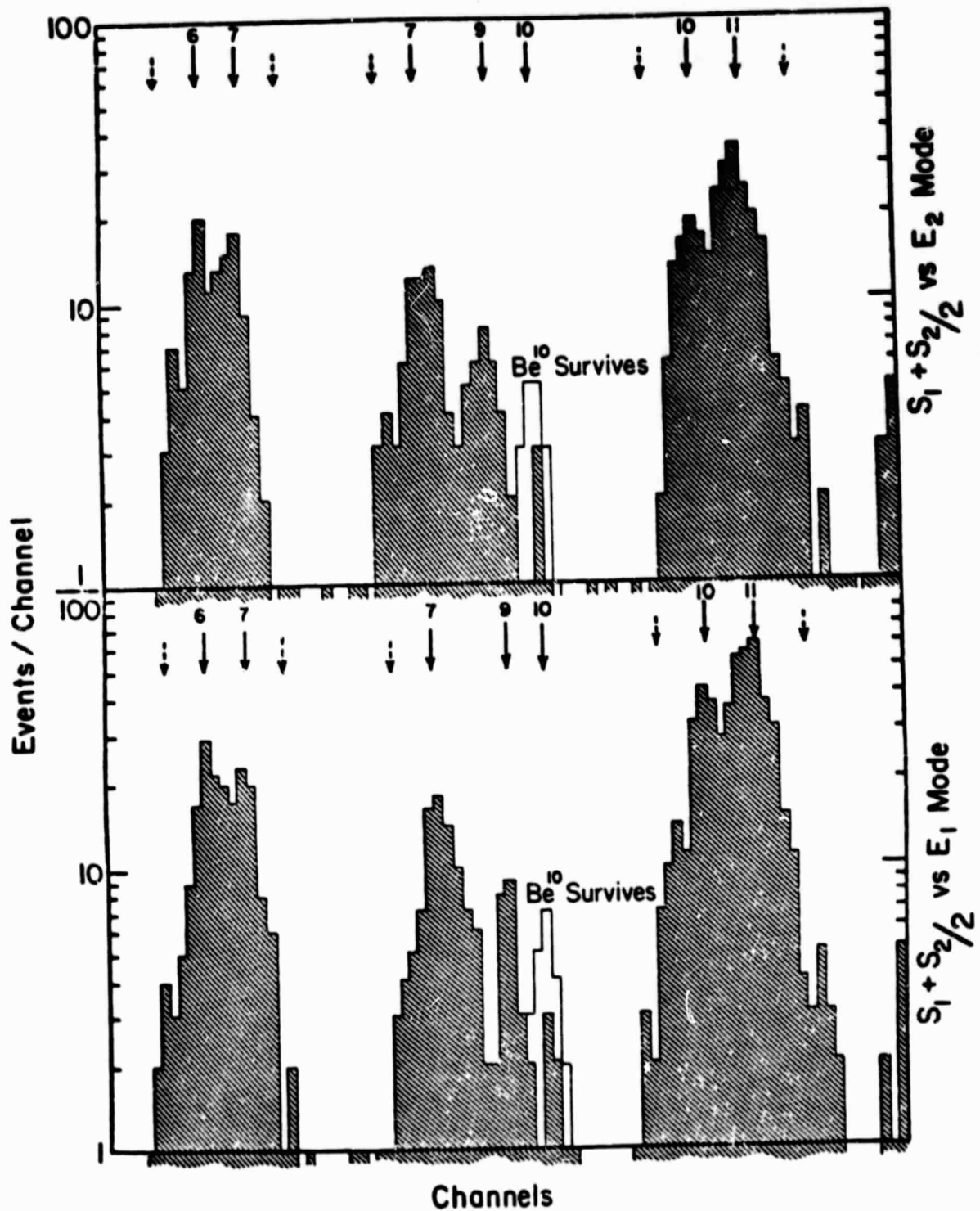
The final experiment I'll describe today is that of my own group at Berkeley. Beside myself, the group consists of Orth, Mast, Smoot, Muller, and Alvarez. The beryllium experiment uses a magnetic spectrometer to measure rigidity R (momentum per charge) and scintillators to measure dE/dx and is flown by balloon. Figure 11 shows the apparatus. The field from the superconducting magnet bends the particle trajectory, which is recorded optically. Figure 12 shows the apparatus on the launch crane, figure 13 is

1974 UNH COSMIC RAY
ISOTOPE DETECTOR
(GF = 824 cm²-ster)



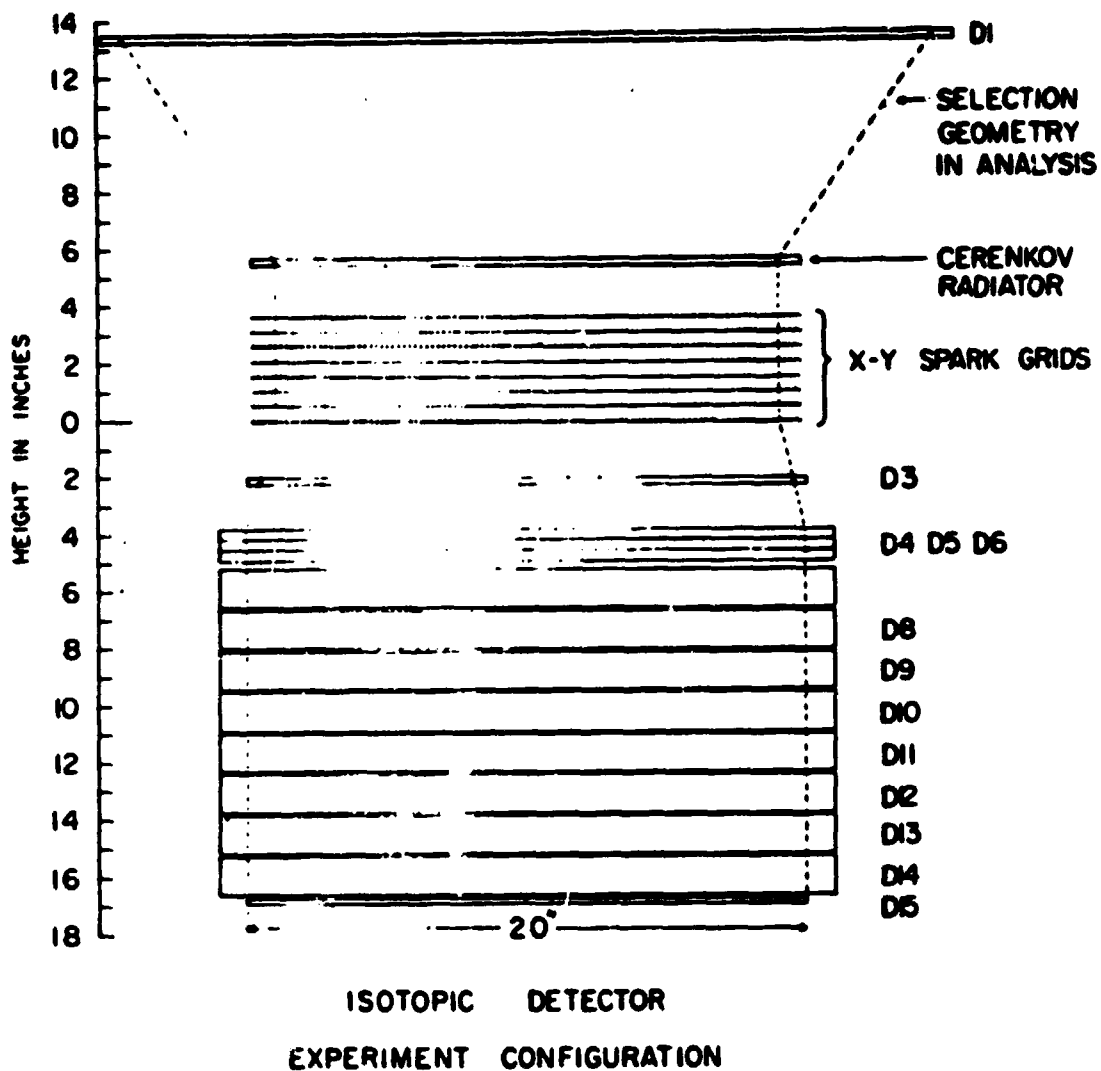
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Figure 5. University of New Hampshire apparatus for isotope measurements (from reference 3).



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Figure 6. Mass histograms of Li, Be, and B nuclei as measured by UNH group; arrows at top of histograms show the location of the principal isotope lines. The range of energy for the top histogram is approximately 150 to 200 MeV/nucleon, while the range of the bottom histogram is 200 to 300 MeV/nucleon (from reference 3).



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Figure 7. Schematic diagram of Goddard Space Flight Center cosmic ray isotope apparatus (courtesy of J. Ornes; see also reference 2).

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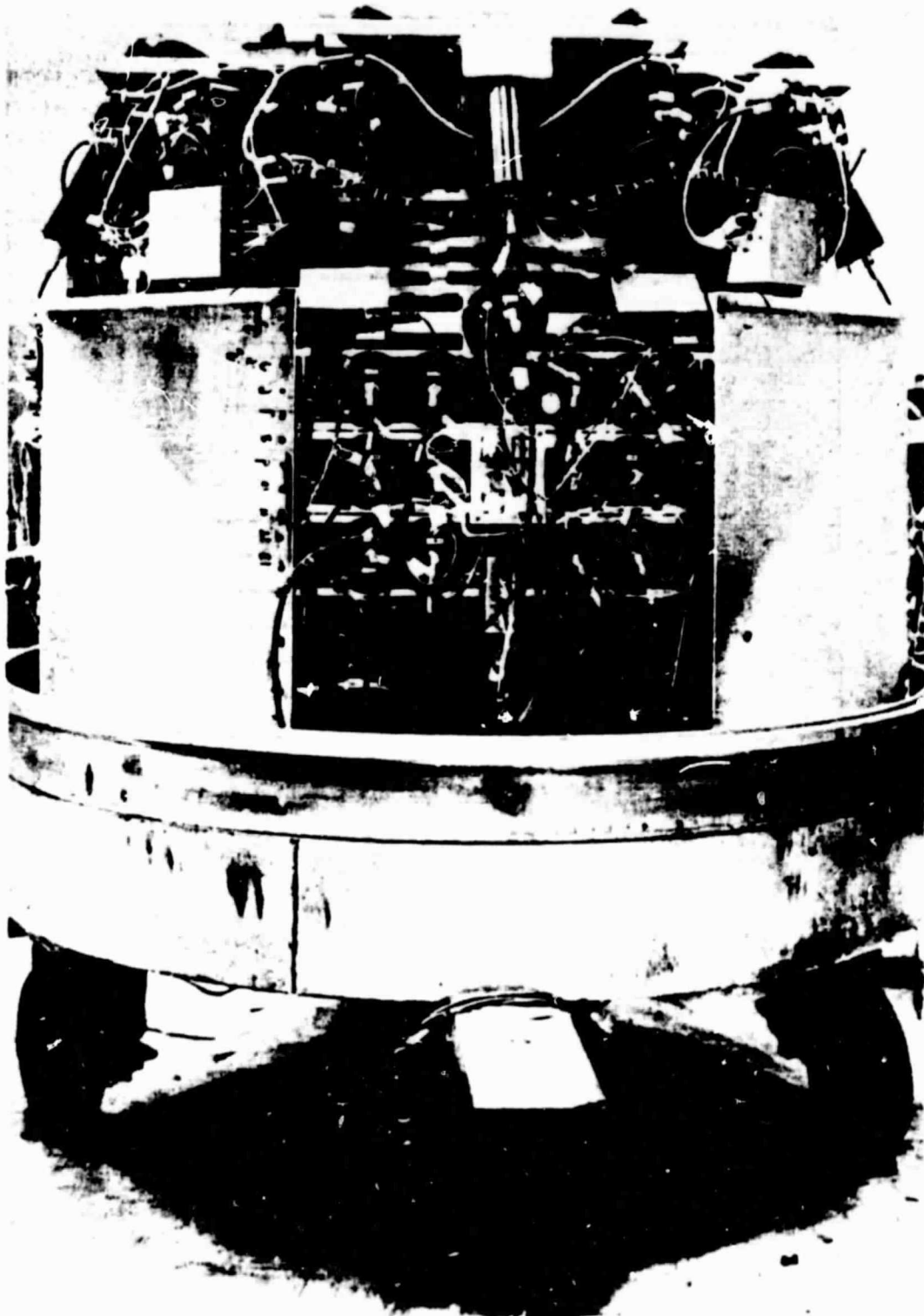
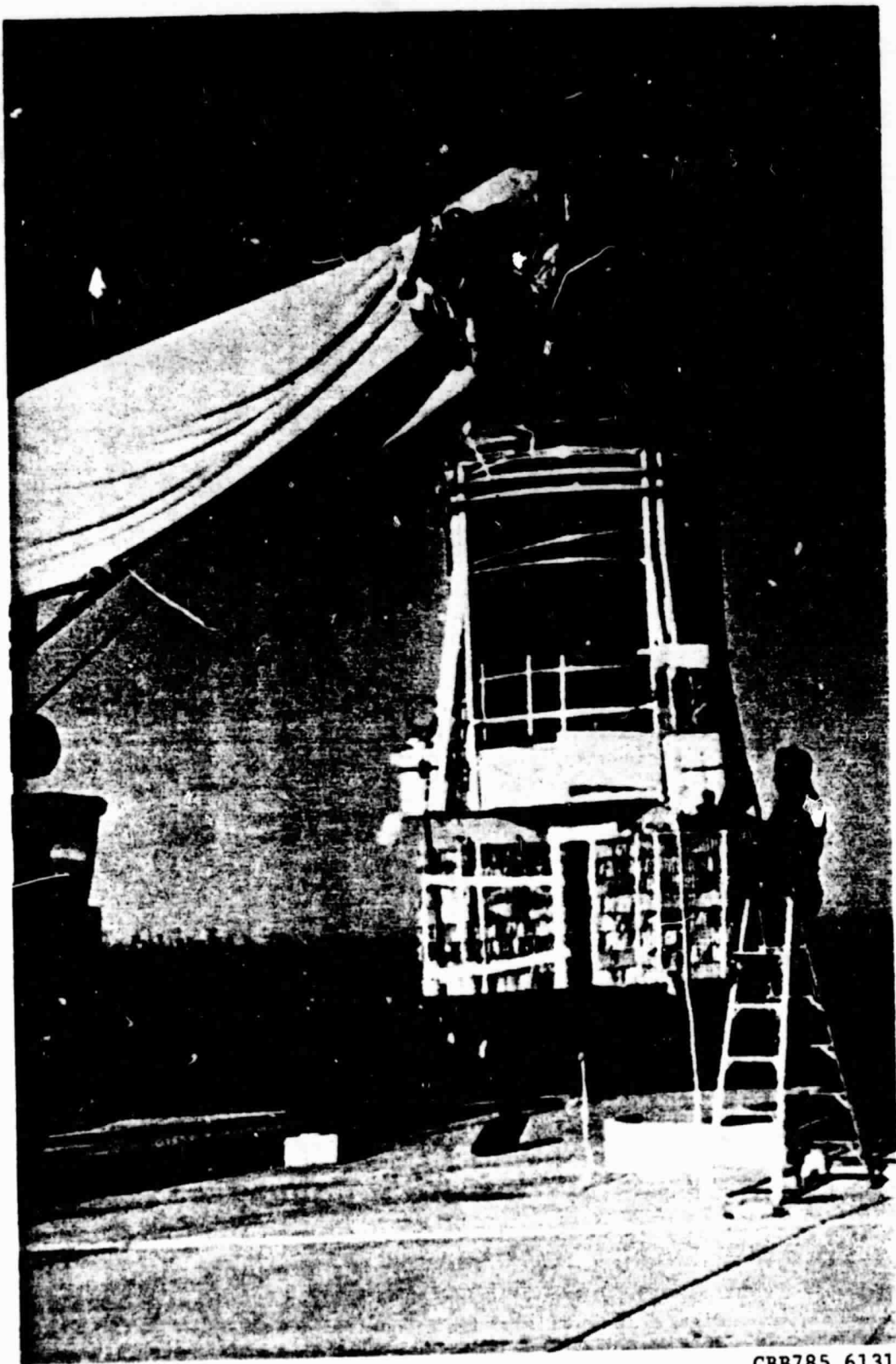


Figure 8. Photograph of the apparatus
of figure 7 (courtesy of J. Ormes).

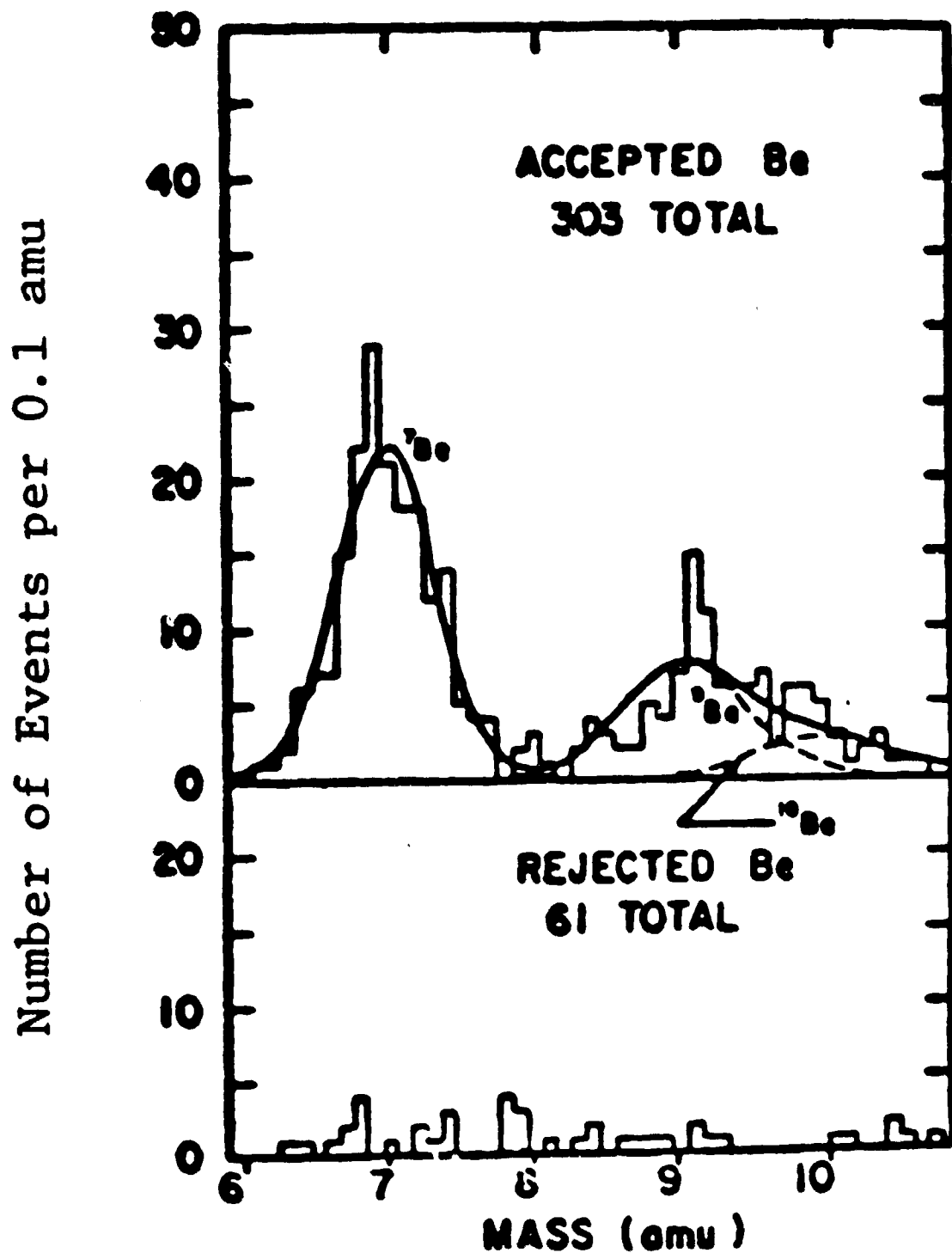
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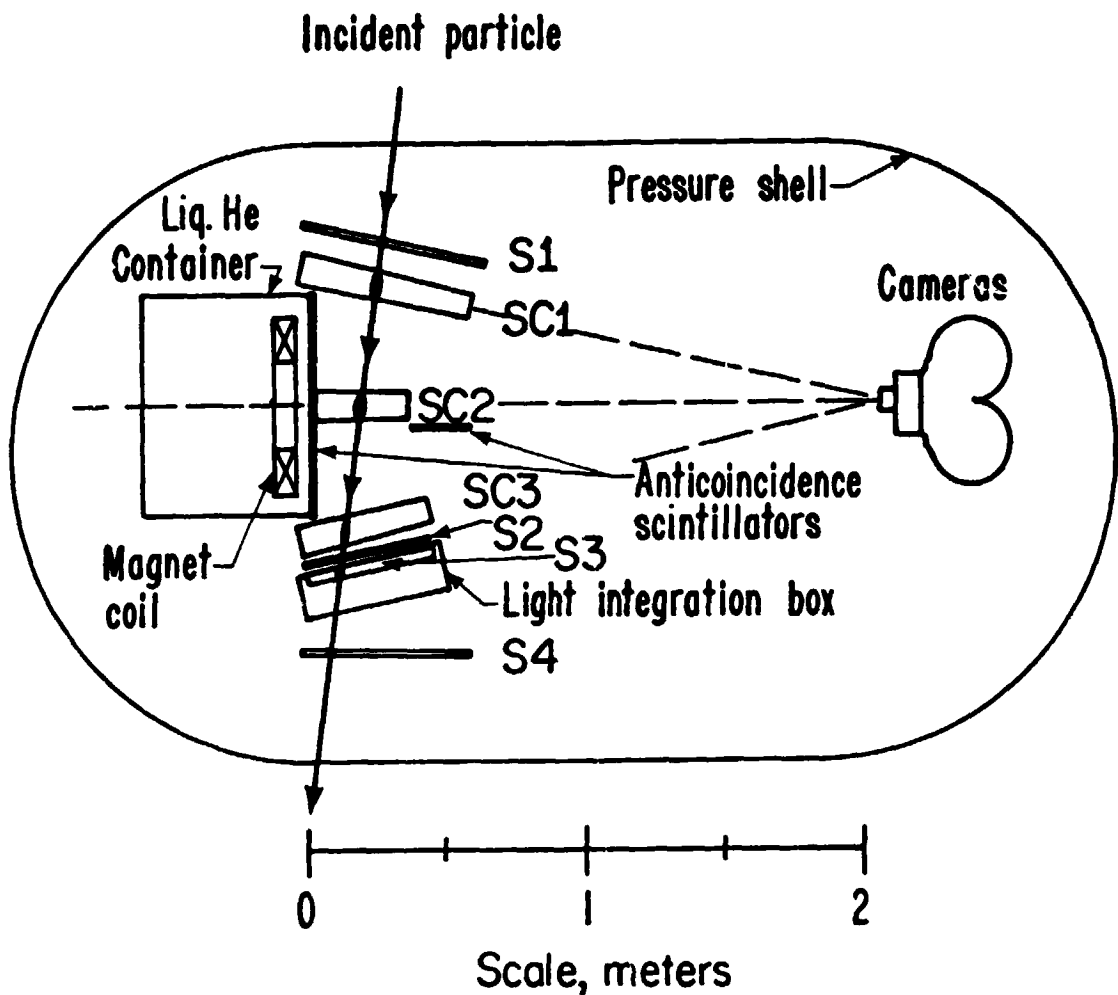
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Figure 9. Apparatus of figure 7 on
balloon launch crane (courtesy of J. Ormes).



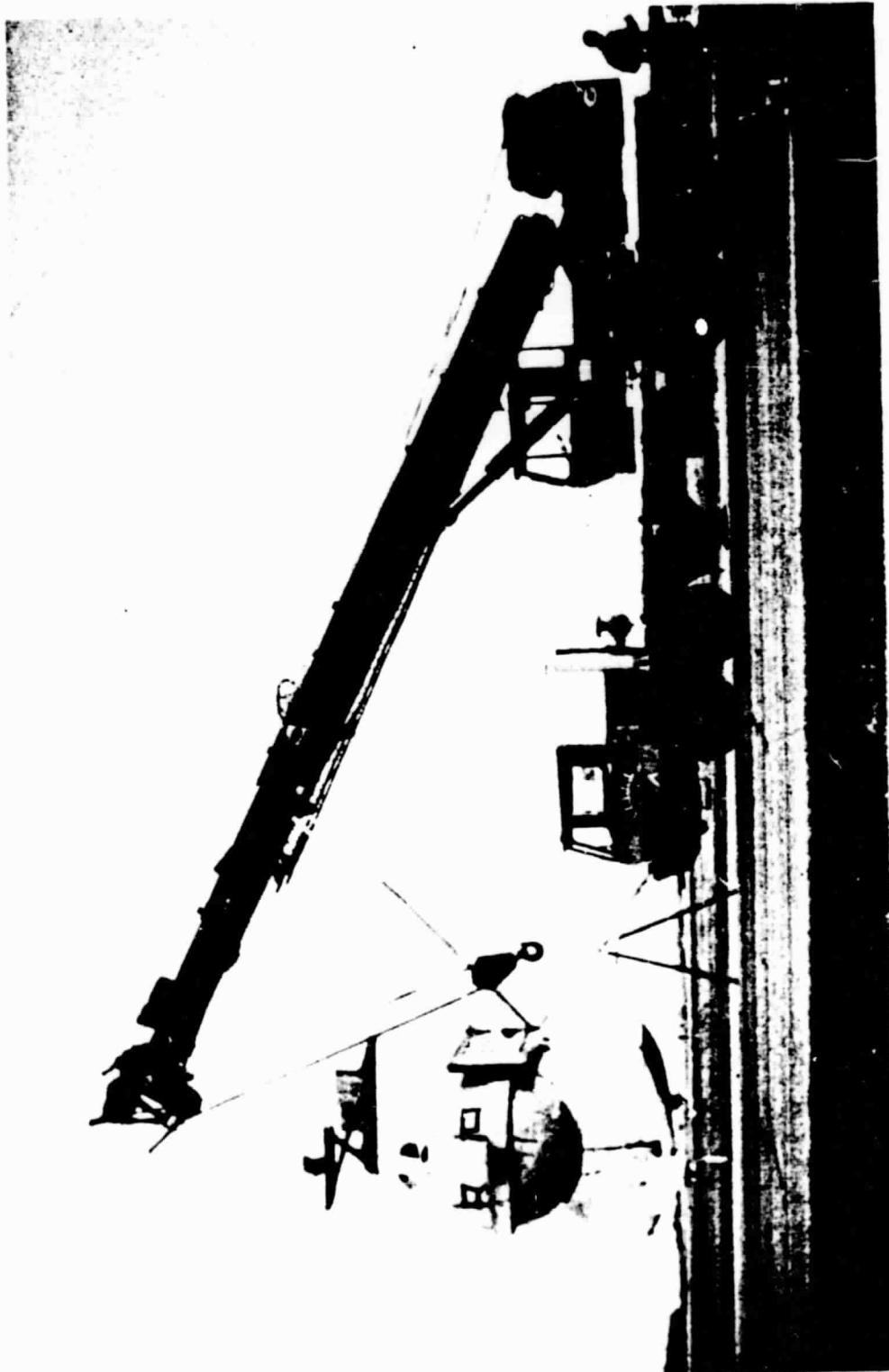
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Figure 10. Flight data from Goddard experiment. The lower histogram shows events which failed data analysis criteria (from reference 2).



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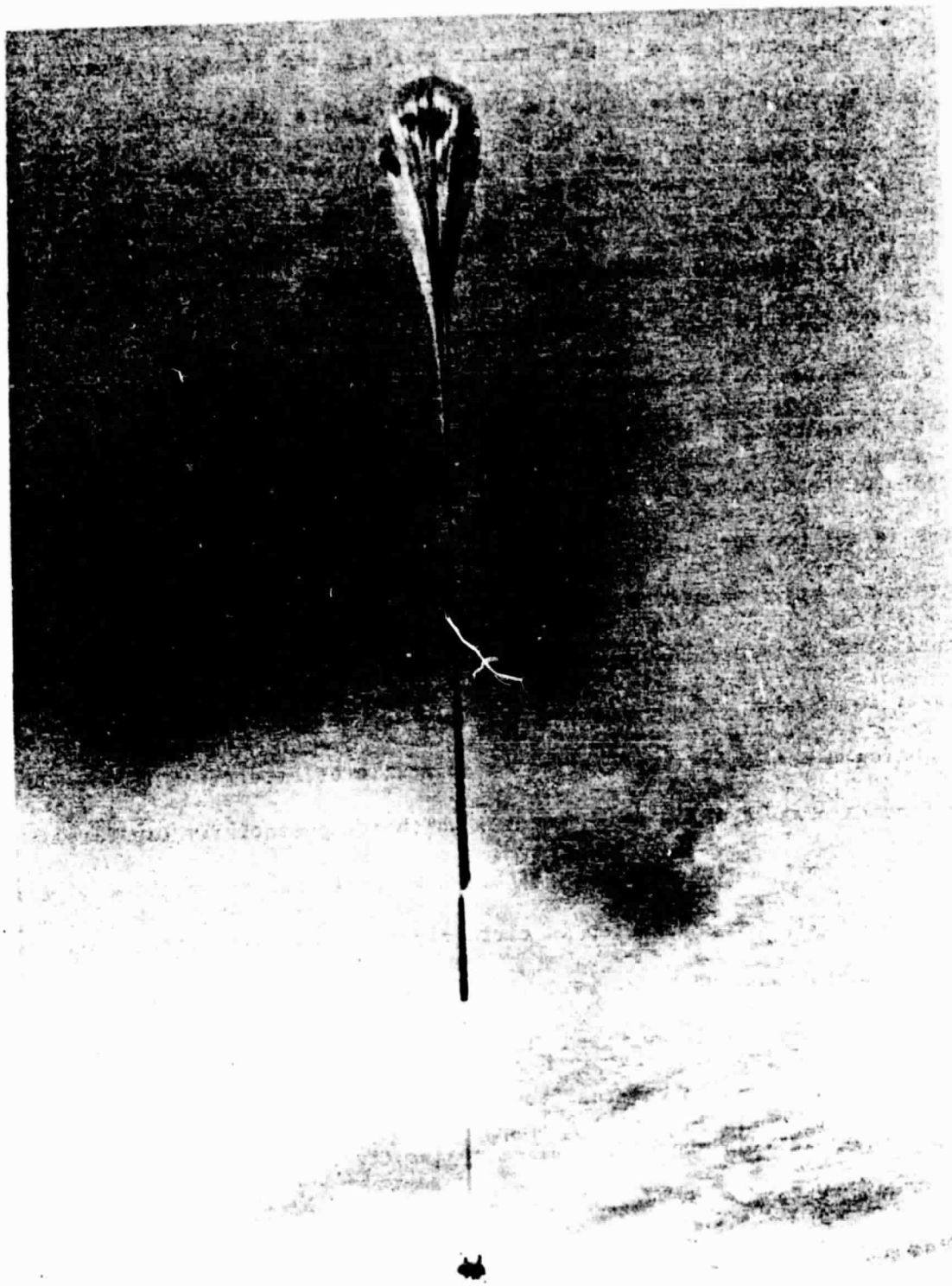
Figure 11. Schematic diagram of balloon-borne magnetic spectrometer of the Berkeley group (from Buffington, Orth, and Mast, to appear in Ap. J., 15 November 1978).



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Figure 12. Experiment of figure 11 mounted on launch crane.

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Figure 13. Magnetic spectrometer experiment at beginning of balloon ascent.

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a pretty balloon picture I can't resist showing, and figure 14 shows the results in rigidity bins. The low-rigidity results are like those of the other experiments. I'll come back to the controversial higher-rigidity results later.

I will now make some comments comparing these experiments. First, all of the experiments have comparable mass resolution of about 0.3 to 0.4 amu. This is not really what we would like for this work, since the isotopes are not well separated, and each experiment must depend on fitting resolution curves to the data to get the isotopic abundances. Although it appears there is not too much risk to this, it would be much more satisfying if the experiments had resolutions like 0.1 to 0.2 amu, so individual isotope identification is possible on an event-by-event basis, and one would be largely independent of knowing one's resolution shapes well. This poor resolution makes important the fits to scintillator saturation (since all experiments utilize dE/dx measurements) which are essentially empirical, at least up to the present time. Although we feel that the problem of the unknown scintillator saturation is certainly solveable by preflight or in-flight calibrations and fits, we would certainly feel more secure if the isotope peaks were well separated from each other, so such things would have little potential grip on the results to be reported. I have already pointed out how the satellite experiment makes up for its small size by long exposure times. One final and very important advantage of satellite experiments is lack of atmospheric background. Because the cosmic Be^{10} has mostly decayed, while atmospheric Be^{10} has not, the balloon experiments are at a real disadvantage for Be^{10} measurements. For example, about half of the Be^{10} events we observed in our flight came from the atmosphere and had to be subtracted away. Even if the atmospheric contribution could be calculated

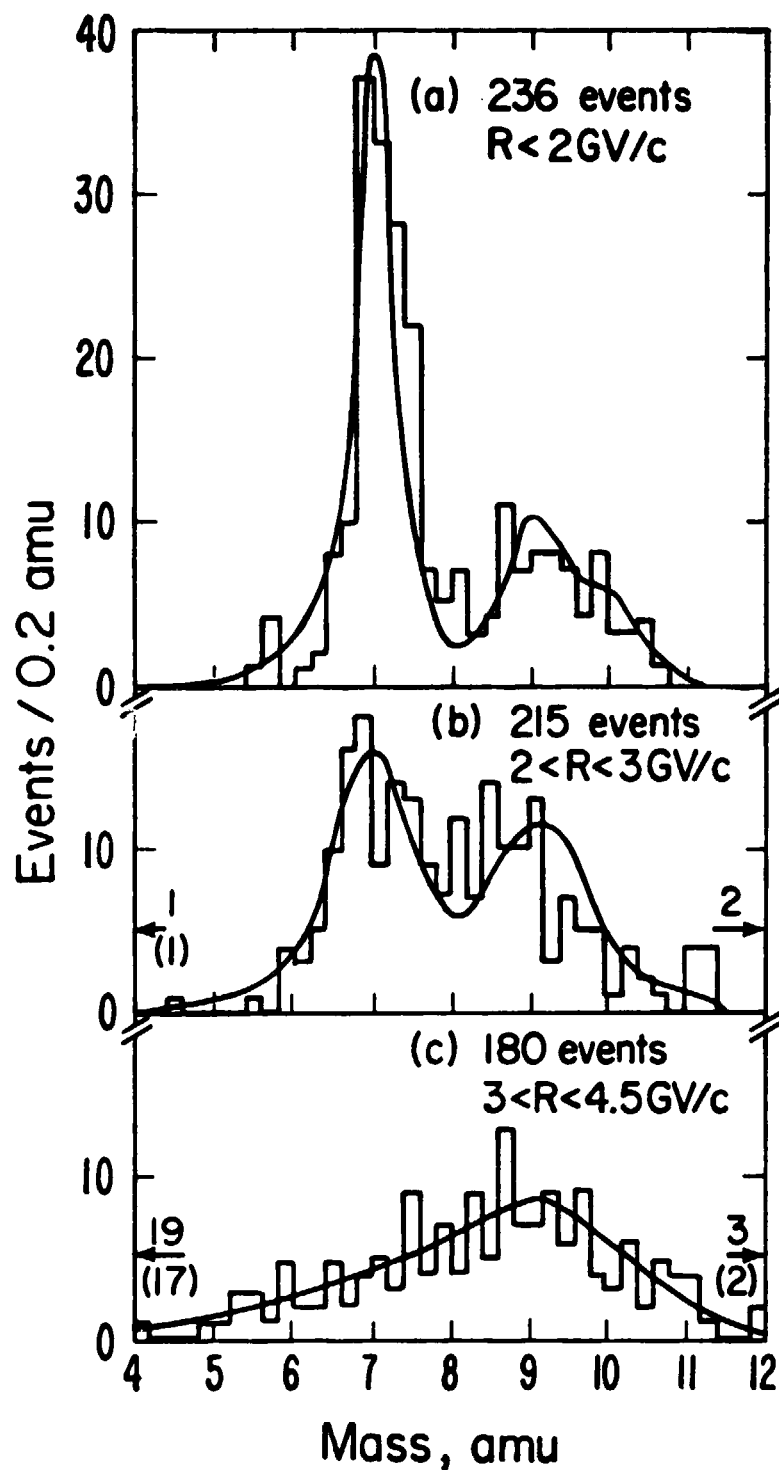


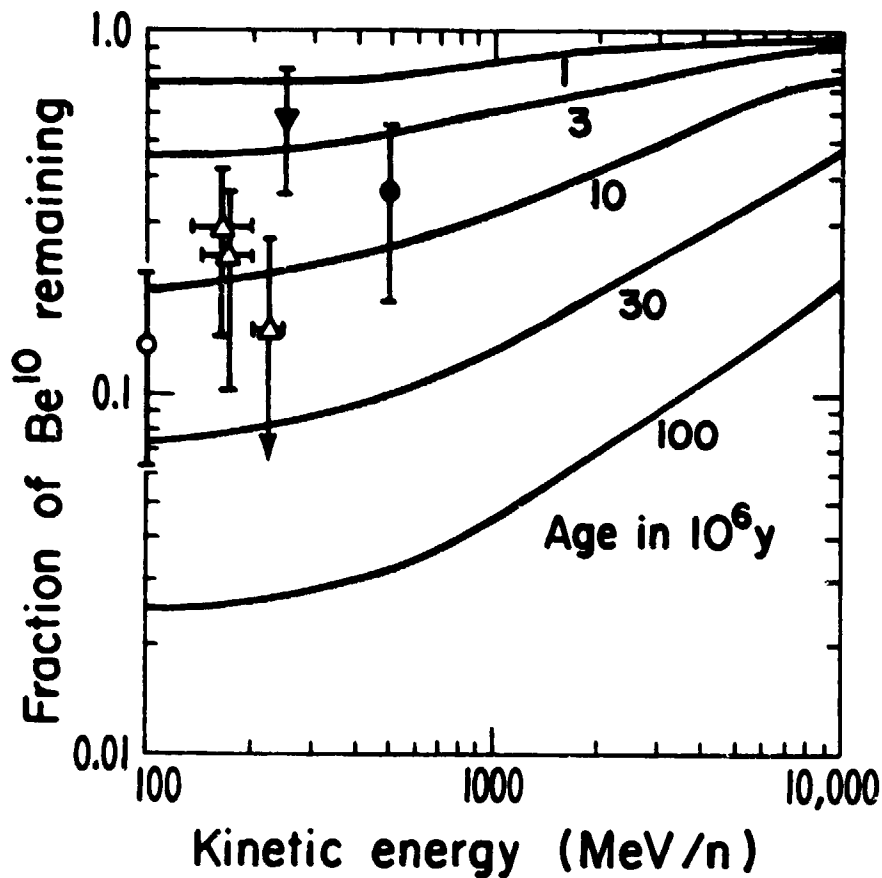
Figure 14. Beryllium isotope data from magnetic spectrometer experiment. The three histograms are the data divided into rigidity bins (GV/c). The smooth curves represent Monte Carlo fits to the data. (from Buffington, Orth, and Mast, to appear in Ap. J., 15 November 1978).

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exactly (and it cannot!) statistical fluctuations in the atmospheric contribution do a balloon experiment substantial harm. Satellite experiments will always have this advantage over balloon ones, when the isotope being measured is rare in the cosmic rays but common in the atmospheric contribution.

Now I would like to turn to the results. The Be^{10} clock is working out well. We will examine the data in the context of the "leaky box model", in which interaction and decay occur at random throughout a boundaryless homogeneous medium, and escape is included as an additional "disappearance" term. There are other models, but the error bars on present-day data aren't yet small enough for the differences to be worthy of concern. The leaky box gives the fraction of Be^{10} survival as $f = 1/(1 + \tau/\gamma\tau_d)$, where τ is the total lifetime to interaction or escape, $\gamma\tau_d$ is the time-dilated decay lifetime. Figure 15 shows the data. To get the escape lifetime you need to unfold the interaction losses. This gives a τ_{escape} which is a bit longer than the indicated τ and brings in the density ρ . The cosmic rays are about 10^7 years old, and no strong energy dependence of this is indicated by the data. To get the density ρ , take 4 gm/cm^2 spread out over a column $3\pi \times 10^{24} \text{ cm}$ long, which implies a density of about $1/4$ hydrogens/cc, which is four times less than the radio astronomy value. This shortfall is probably significant, and has been used as an indication that the cosmic rays may spend a significant fraction of their time in the galactic halo, or some other place of lower than average density.

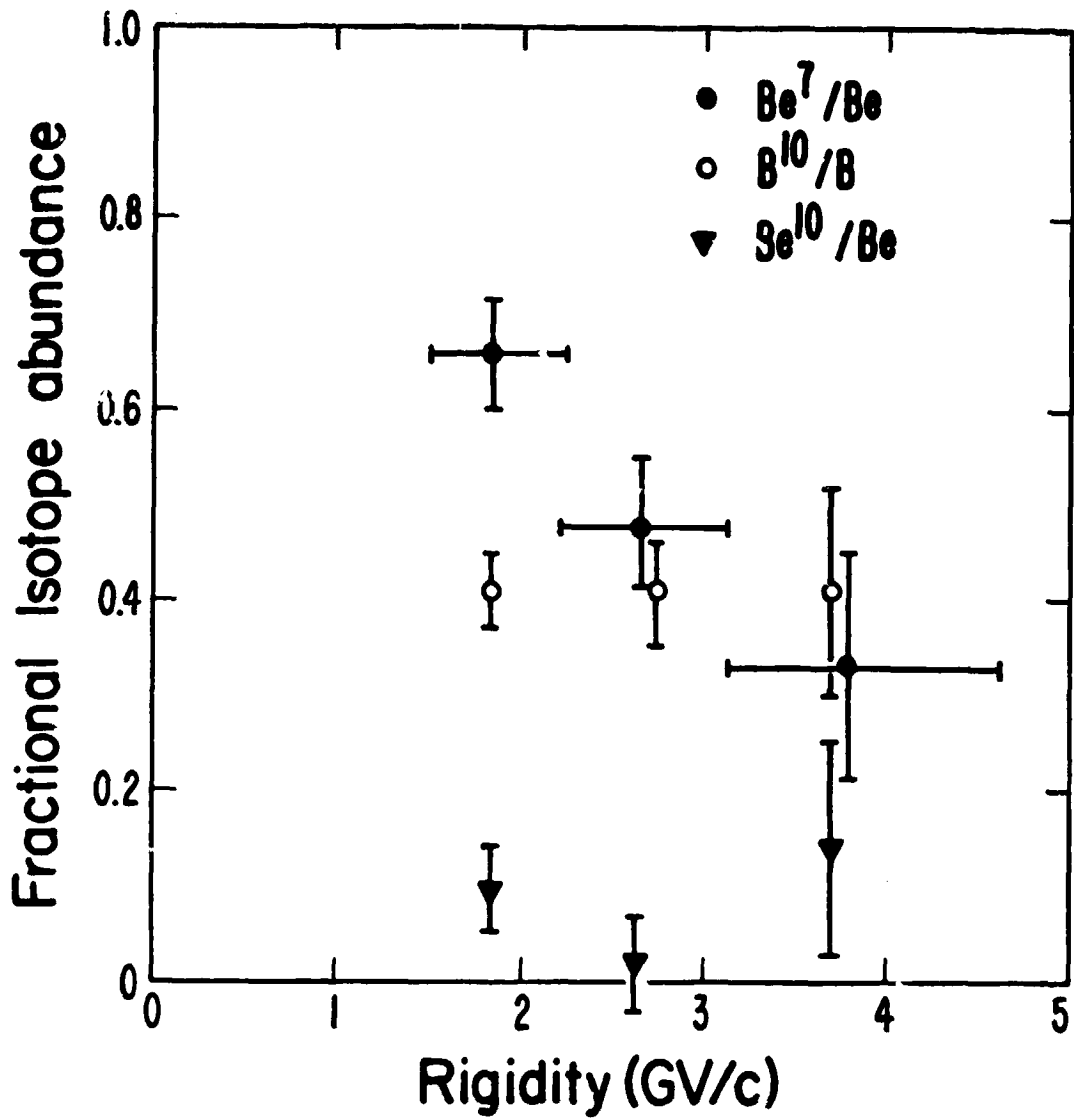
I would now like to move on to the Be^7 results. The relative composition of Be^7 is not expected to change with energy, since the Be^7 was presumably created in interstellar space stripped of its orbital electrons and stays that way except below about 20 MeV/nucleon as has been shown by



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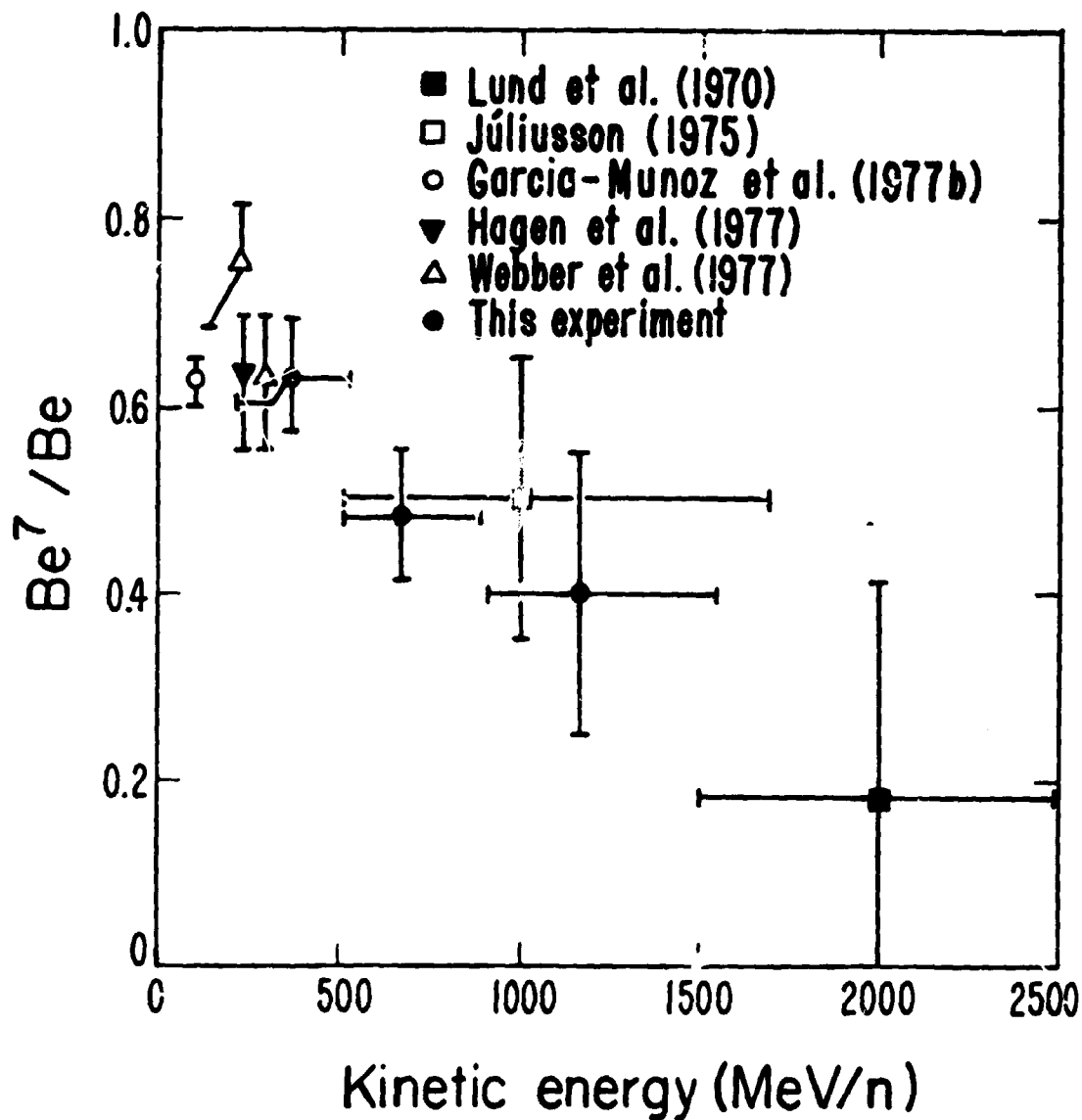
Figure 15. Measurements of Be¹⁰ survival under the assumption that Be¹⁰/Be⁹ = 0.6 in the absence of decay of Be¹⁰. IMP-7,8 measurement is the open circle; New Hampshire is open triangles; Goddard is the closed triangle; and Berkeley is the closed circle. See text for the significance of the curves. (from Buffington, Orth, and Mast, to appear in Ap. J., 15 November 1978)

Yiou and Raisbeck. But our data in figure 14 show a big change, with Be^7 dropping relative to Be^9 . The relative abundance of these changes by a factor between two and three as the rigidity goes from 2 to 4 GV/c. Viewing the data in figure 14 as the production of 4 to 5 gm/cm^2 of interstellar medium plus about 7 gm/cm^2 of atmosphere, we see that this large change almost certainly couldn't have resulted from energy dependences in the production cross-sections, since nothing this large has been seen in any individual production cross-section, and reactions accounting for about 80% of the Be^7 production have been directly measured at accelerators. To compare the data of figure 14 with other experiments, we must correct for slight bin-edge differences and for the atmosphere. Figure 16 shows the beryllium and boron results corrected for these. Note that the B^{10}/B ratio shows no hint of a rigidity dependence. When the data are converted to kinetic energy per nucleon, figure 17 shows the result. We don't know any reason to prefer a rigidity representation to an energy-per-nucleon one. It's true that energy per nucleon is what is preserved in spallation reactions, but many astrophysical processes involving magnetic fields are more "diagonal" in a rigidity representation. It may be that yet some other quantity than these two may prove to show the basic astrophysics most clearly in the future. In any case, in figure 17 we show previous Be^7 measurements along with our own. The kinematic conversion has somewhat narrowed the statistical significance of our results, but the effect is still clearly present. The two "mean mass" experiments using the method of Peters are also shown; they may have hinted at changing Be^7 , but since they measured only mean mass, changing Be^{10} might have caused the effect. We feel our relativistic Be measurements probably exclude further Be^7 drop beyond what we have observed. If you like the spectral index way of



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Figure 16. Beryllium and boron isotope measurements as a function of rigidity from the Berkeley experiment (from Buffington, Orth, and Mast, to appear in Ap. J. 15 November 1978).



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Figure 17. Be^7/Be ratio as a function of kinetic energy per nucleon for various experiments. The "mean mass" data of Lund and Júlíusson have been plotted assuming complete absence of Be^{10} . These points would both move up by about 0.05 if a ratio $\text{Be}^{10}/\text{Be} = 0.1$ were assumed.

describing results, we see a steepening in Be^7 's spectral index by about unity, but only, between 500 and 1500 MeV/nucleon, and our relativistic Be measurements (with, however, no mass information within the charge group) put an upper limit on further drop above this of about 0.2 in the spectral index. We think Be^7 is the isotope doing the changing, since its ratio to carbon changes much more in our data than does that of Be^9 . The low energy beryllium isotope ratios are as expected from the spallation reaction measurements, so we think something unexpected is happening above 500 MeV/nucleon, although we recognize that there are other possibilities. We attribute the Be^7 drop to an onset of K-capture decay above 500 MeV/nucleon. The K-capture decay yields Li^7 , so an energy dependence in the Li/C ratio should be observed in the same energy range. Unfortunately, we feel the Li/C measurements are inconclusive, since the spread in measured data points is outside statistical errors.

I would like to say here that we realize that this result is a very disruptive one to present-day views of cosmic rays, and I feel that any result this disruptive, no matter how good the experiment is, needs confirmation. There are two experiments coming up soon which may be able to do this. One is a balloon measurement to be tried by Steve Jordan from the University of Chicago which will utilize the geomagnetic cutoff method and will be flown at 15 GV/c near the equator in about a year. The other is the HEAO-C experiment of Koch and Peters which also will utilize the geomagnetic cutoff method.

The other thing I want to make clear is that we don't at present have an explanation for this measurement. We feel quite confident that the dropping Be^7 abundance could not have been caused by the instrument, the atmosphere, changing cross sections, kinematics, some geomagnetic effect, or the solar modulation. Electron pickup in the interstellar medium seems

impossible. There are, however, a number of ideas we've had which may be kept in mind while searching for an explanation:

(1) If K-capture is invoked for explaining the decay, as we feel it must, the "handbook value" of 53 days for the decay is not necessarily relevant, since this value assumes a full complement of orbital electrons around the nucleus. If a single S-electron is present, the decay lifetime will be in excess of 100 days.

(2) Carrying this idea further, we can imagine environments in which the electron density is much higher at the nucleus than with laboratory nuclei, and that will run the decay lifetime down, perhaps dramatically. We're used to radioactive decay lifetimes being immutable, but that's not true for K-capture decays. We must be careful, however, that this dense electron environment not be sufficiently hot as to destroy the Be.

(3) If our measurement is confirmed, it may constitute strong evidence against energy-changing mechanisms (such as the Fermi acceleration mechanism) having an important impact on cosmic rays, as has been suggested in other talks at this meeting, since such mechanisms would tend to blur out the rather sharply defined change we've seen.

(4) Since we couldn't find any explanation for changing Be^7 all the way back to the cosmic ray sources, we feel we must look there for the explanation, since that's where we know the least about the environment. We need either an environment which provides co-moving electrons for Be created above 500 MeV/nucleon, so they can capture the electrons and decay, or we need a very high density of electrons which force the onset of decay. A drift time after a shock wave might provide co-moving electrons.

(5) Finally, we note that Soutoul and others have recently invoked K-capture decay to explain why cosmic-ray iron is observed rather than

nickel at high energies. There may be a connection between our measurements and this, but it is not presently apparent.

We have made up an admittedly artificial scenario which would yield our Be^7 results. Since we see half of the Be^7 to decay, we put about half of the "grammage" within a source region which makes about half of the Be^7 total. The other half is made in the interstellar medium and never gets a chance to decay. Below 500 MeV/nucleon the nuclei escape directly into interstellar space, but those we observe above 500 MeV/nucleon pass through an additional acceleration and/or history phase which provides a decay mechanism such as those mentioned above. We recognize that this scenario doesn't represent a satisfactory explanation of this new effect, but it summarizes the measurement well, and represents the present status of our search for the true explanation.

In conclusion, I would like to say that I think the time of isotope measurements in the cosmic rays has really come, at least for the lower-Z elements, and we're having a very stimulating and enjoyable time. The new measurements are raising more questions than they're answering, and it seems likely that a more detailed and structured understanding of the cosmic rays is going to be the result.