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DETECTION OF THE ISOTOPES OF HEAVY COSMIC RAY NUCLEI

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We are preparing for flight in September 1975 a counter telescope designed to detect and resolve the isotopic composition of cosmic ray nuclei heavier than neon. The telescope consists of a rather conventional charge measuring array using two scintillator elements and two solid Cerenkov radiators of differing refractive index. The mas s measurement is then obtained by combining the velocity information from one or both of the Cerenkov radiators operating near their threshold with residual range measured in a block of nuclear emulsion. Path length corrections and particle location in the emulsions is provided by a spark chamber fired in coincidence with potentially suitable particles. The telescope has a geometry factor of ≈530 cm^2 sr. It should be able to resolve the isotopes of iron over the energy range of 300 to 720 MeV/n and those of neon over 300 to 400 MeV/n. The expected response and characteristics of the telescope will be described in detail and the sensitivity to rare isotopes discussed. It is hoped that prior to flight the electronic portions of the telescope will have been calibrated with the heavy ion beam from the Bevalac.

1. Introduction. A cosmic ray telescope designed to resolve the more abundant isotopes of the elements between neon and nickel must be capable of resolving both charges and masses, and its ability to resolve depends on the measurement precision in the various detectors. In designing this telescope we have used the results given in Figure 1 to set our criteria. Here the standard deviation, σ, in charge or mass units, is plotted as a function of the observed peak to valley ratio that would be obtained for various values of the actual peak to peak ratio prevailing between two neighboring peaks that we are trying to resolve. Thus, if we are to have any hope of resolving an isotope having 10% of the abundance of its neighbor we must have a σ of less than 0.3 mass units - or a FWHM of less than 0.71 mass units. Hence, if we are considering nuclei in the mass range of $A \simeq 50$ we require a standard deviation of just over 0.5%. In addition, for the relatively rare nuclei in the charge range $Z \geq 10$, the telescope must have sufficient collecting power to collect statistically significant numbers.

2. The Basic Telescope. The telescope adopted depends for charge measurements on a scintillator-Cerenkov combination and for mass measurement on a Cerenkov-residual range combination. A schematic diagram is shown in Figure 2. An incident particle passes in turn through each of the detectors shown.

1) S1 is a scintillation detector consisting of a 0.95 cm thick square of NE 102 plastic scintillator 58.42 cms on a side, mounted in a light diffusion

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box and looked at by four 2-inch PMT's, EMI 9656R, mounted so as to be out of the acceptance angle of the telescope. The thickness of this radiator is chosen so that the Landau fluctuations are small and has been made uniform to within 1% over the entire surface.

2) C1 is a Cerenkov detector consisting of a 1.27 cm thick square of Pilot 425 plastic 41.5 cms on a side, mounted in a light diffusion box and looked at by eight 5-inch PMT's, RCA 4525. This radiator has a measured refractive index of 1.44, N. Lund (private communication).

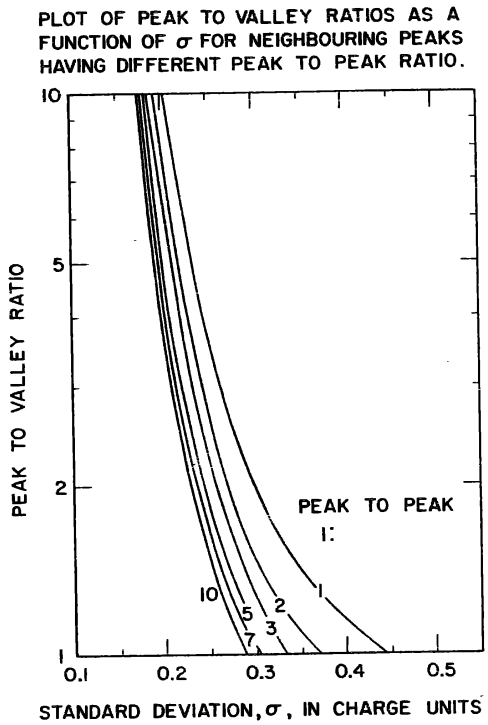
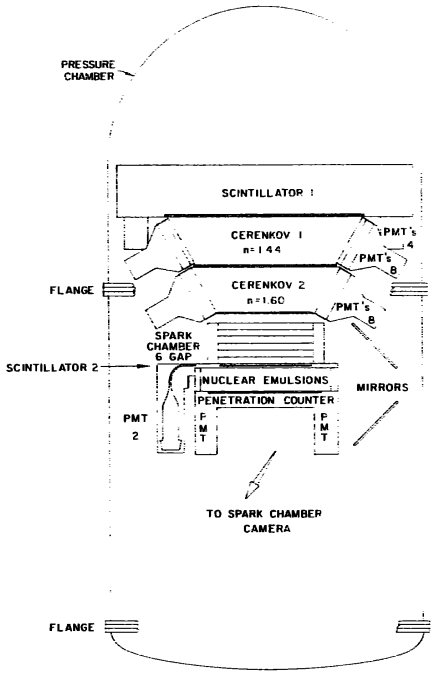


Fig 1



Cosmic Ray Isotope Instrument System (CRISIS)

Fig 2

3) C2 is a Cerenkov detector consisting of a 0.75 cm thick square of Schott lead glass 27.9 cms in a side, mounted in a light diffusion box and looked at by eight 5-inch PMT's. This radiator has a refractive index of about 1.6. While F2 is known to have bad scintillation properties, nothing appears to be known about SF2 or 5 and we will use one of these unless they also turn out to have the same problems.

4) The spark chamber is a six gap, thin plate, 1 mil aluminum foil, optical chamber that is fired by those particles that satisfy the coincidence criteria. The active area of the chamber is 28.0 by 28.0 cms.

5) S2 is a scintillation detector consisting of a 0.64 cm thick square of NE 110 plastic scintillator 27.9 cms on a side and looked at by two 2-inch PMT's coupled to adjacent edges by adiabatic light pipes. This radiator, like C1 and C2, has a thickness that is uniform to better than 0.5% and has had the variations in thickness mapped to better than 0.1%.

6) The block of nuclear emulsions is made up of 600μ thick pellicules

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6.35 cms deep. The position of this block is located with respect to the spark chamber by fiducial lights that are photographed with each spark chamber event. Thus particles can be traced from the spark chamber into the emulsion, using techniques successfully employed previously for the tracks of electrons.

7) The final detector is a scintillation counter that acts as a penetration detector.

This entire array, together with the folded optical bench and automated camera for the spark chamber is enclosed in a pressure chamber, which will be very heavily insulated in order to maintain a uniform temperature. This is particularly important for the PMT's since their spectral response appears to be temperature dependent, which makes compensations for temperature changes very difficult.

3. Mode of Operation.

3.1) Coincidence Requirements

The only particles whose mass we will be able to measure are those that are brought to rest and stop in the block of nuclear emulsions. Our coincidence requirement is therefore S1, C2, S2, $\overline{P}$. Placing the penetration counter in anti-coincidence serves to eliminate all those particles that are not brought to rest in the emulsion but either pass through or interact and produce fragments that pass through. This limitation of the event rate is important in order to reduce the use of spark chamber film and to allow for the considerable dead time, ~150 msec, of the array.

3.2) Charge Resolution

The first requirement for a cosmic ray telescope capable of studying isotopes is that is should be able to give clear charge resolution. Here this information will come from the comparison of the scintillation signal in S1 and S2 and the Cerenkov signals in C1 and/or C2. These detectors are being designed to have high intrinsic uniformity and an accurately mapped residual non-uniformity. Corrections for these non-uniformities and for path length variations will then be applied by using the trajectory information provided by the spark chambers. It is hoped, but not yet certain, that the non-uniformities can be kept small enough that preliminary charge resolution will be attained after path lengths corrections alone, since this will simplify the data analysis problem. In each detector the limitations due to photo-electron statistics should not be serious except for the lowest energy particles in the Cerenkov detectors.

The Cerenkov radiator of highest refractive index, and thus lowest energy threshold is C2. In that detector we estimate that the number of photo-electrons produced will be $\approx 30Z^2$ for a particle of high energy. This implies a standard deviation on the charge measurement of 0.09 charge units, which is quite adequate. In fact, even for a particle that only produces 10% of the maximum light, $\sigma = 0.29$ of a charge unit, which is just adequate and therefore represents the operational threshold of the detector.

The other Cerenkov detector will produce approximately as many photo-

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electrons and should therefore have a similar resolution, although the threshold is at a higher energy due to the lower refractive index. There is one complication, due to probability that one or both the radiators may also emit light due to scintillation. It can be shown that if the ratio of residual light emission at the Cerenkov threshold to that emitted for a $\beta = 1$ particle is ε, then the effect is to make the radiator behave as if it had an apparent refractive index n_{app} that is greater than the true index and is related to it by:

$$n_{app} = n\{1 - \varepsilon(\frac{n^2-1}{n^2})\}^{-1/2}$$

Thus for $\varepsilon = 0.10$ and $n = 1.44$, $n_{app} = 1.48$.

The resolution of the scintillator S1 depends not on the photo-electron statistics, but on the Landau fluctuations. For high Z particles these fluctuations are nearly Gaussian and for the thickness of radiator employed here result in a standard deviation of 0.15 to 0.09 charge units for energies of 700 to 300 MeV/n respectively. The second scintillation detector, S2 will not have as uniform a response as S1 and will also have larger, $\sim\sqrt{1.5}$, Landau fluctuations. Its prime purpose is to provide a consistency check that there have been no large charge changes due to nuclear interactions. However, combining its data with the results from S1 would permit us to sharpen the charge resolution if that should be necessary.

3.3) Mass Measurement

In this telescope the mass of each particle will be determined by comparing the signal from a Cerenkov counter with the residual range in the nuclear emulsions. The Cerenkov signal for a particle of known charge is given by $C = k(1-(\beta n)^{-2})$ where k is a constant. Hence:

$$\frac{dC}{C} = \frac{2}{\gamma^2\beta^2(\beta^2n^2-1)} \frac{dE}{E}$$ where E is the energy of the particle and

$\gamma = (1-\beta^2)^{-1/2}$. The residual range of a particle is related to the energy, for moderate energies, by the empirical relation $E = k'R^{0.581}$ so that $\frac{dE}{E} = 0.581 \frac{dR}{R}$. Furthermore, the range is related to the mass by $R = (\frac{10.78E^{1.724}}{Z^2}) M^{0.724}$ so that $\frac{dR}{R} = 0.724 \frac{dM}{M}$ for a given Z. Hence: $\frac{dC}{C} = \frac{0.842}{\gamma^2\beta^2(\beta^2n^2-1)} \frac{dM}{M}$

Thus the fractional change in the mass is related to that in the Cerenkov signal by a function of the velocity and refractive index. This function is shown in Figure 3 for two radiators of different refractive index plotted against the energy per nucleon for a particle having $2Z = A$. It can be seen that $(dC/C)/(dM/M)$ increases steeply as the energy falls, showing that at low energies a small fractional change in the mass results in a large fractional change in the Cerenkov signal. Also shown in this figure is the Cerenkov yield expected at any energy expressed as a fraction of the yield expected for

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a $\beta = 1$ particle. This ratio falls rapidly and becomes zero at the Cerenkov threshold. There is thus a rather narrow energy band over which the sensitivity for mass measurement is high and the Cerenkov signal is large enough to be statistically significant. Clearly by combining two Cerenkov radiators of different refractive index into one telescope the useful range of energies is extended.

Figure 4 shows the residual energy in MeV/n as a function of range in nuclear emulsion for a number of those elements of interest. Also shown are the Cerenkov thresholds for two radiators of different refractive index, together with the energies at which the yield falls to 10% of the maximum, the operational limit. Thus in principle particles will have their masses measured if they have energies greater than the 10% limit for the radiator of highest refractive index, but ranges less than that of the emulsion block used (6.3 cms). Clearly the intrinsic mass resolution is not uniform over these charge dependent energy bands, but the standard deviation expected does not appear to exceed 0.3 of a mass unit anywhere.

The range measurement can be rather easily made with the required precision of a fraction of a percent, i.e. several hundred microns on a five cm track, if attention is paid to obtaining uniform, or known, thicknesses for any intervening plates of material. Straggling is not serious for particles of high mass, being proportional to $1/\sqrt{M}$ and the order of 1% for protons between 100 and 1000 MeV.

This precision in the range measurement and the ability to detect almost all nuclear interactions represents the principle advantage of using nuclear emulsions rather than a total E detector.

Fig 3

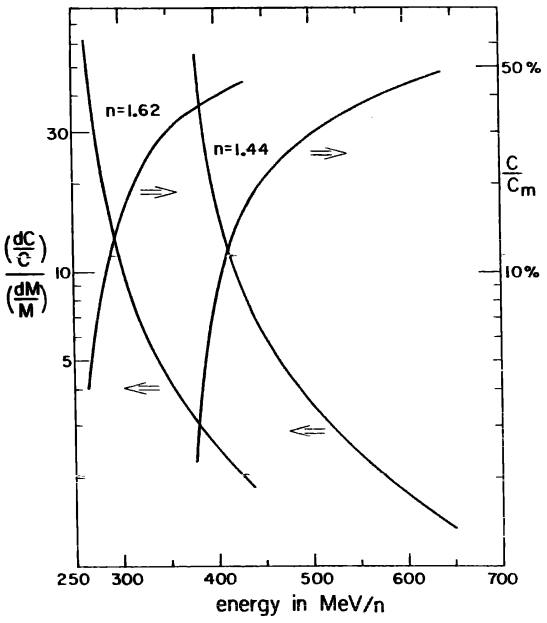
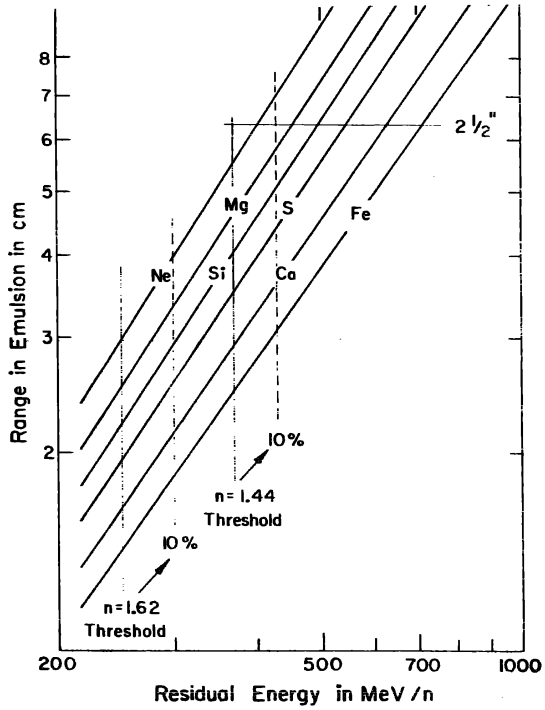


Fig 4



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3.4) Counting Rates

In order to calculate the counting rates we have first to extrapolate the useful energy interval in the emulsions to the top of the atmosphere, through the 6.7g/cm^2 of material in the telescope above the emulsions, and an assumed 2g/cm^2 of residual atmosphere. We have then calculated th e expected flux of particles, using published data on the energy spectrum and charge spectrum. The number of particles in the energy interval is then extrapolated down to the top of the emulsion block, making corrections for those removed by nuclear interactions. These particles then enter the emulsions and either interact there or are brought to rest. Only these later particles are of interest. Some of the relevant quantities are shown in Table I. Of particular interest are the numbers in the last two columns. N_{top} is the number of particles of each element that arrive at the top of the emulsion and could stop within it. Some of these will make interactions and may therefore trigger the penetration counter, but most will satisfy the coincidence requirements and result in spark chamber events. Allowing for those elements not listed in the table we come up with 100 events per hour or under 2 per min, a rate which is easily acceptable by the instrumentation. It is clear that in order to get results of reasonable statistical weight we need an exposure of 40 or more hours. Such an exposure would produce some 350 Fe-nuclei or some 100 Ca or S-nuclei. These numbers are large enough to permit the identification of isotopes having 10% of the element abundances, but not too large to make the data analysis problem intractable. It should be noted that emulsion analysis need only be undertaken on particles of those elements that appear particularly interesting. Thus, for example, it would be unnecessary to measure all of the Si-nuclei detected if the first 100 show no indication of more than one isotope. It is probably not very significant to look for isotopes whose abundance is much less than 10%, since the effects of nuclear interactions in the overlying matter cannot be allowed for with sufficient precision to permit an assesment of the significance of isotopes that are less abundant.

Element	ΔE_{obs} MeV/n	$\Delta E_{top\ of\ atmosphere}$ MeV/n	$\Delta j/\Delta E$ particles/m^2 sr sec	$N^*_{top\ of\ emul}$ particles/hr	$N_{stopping}$ particles/hr
Ne	300-400	420-510	0.08	12.8	8.2
Mg	300-455	445-575	0.13	20.2	12.8
Si	300-495	470-615	0.11	15.8	9.9
S	300-550	490-710	0.033	4.6	2.9
Ca	300-630	530-820	0.027	3.4	2.0
Fe	300-720	570-960	0.148	15.3	8.9

*assuming $A\Omega$ = 530 cm^2 sr.

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