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Satellite-Borne $dE/dx \cdot E$ Semiconductor Detector Telescope for Isotope Identification in Heavy Primary Cosmic Ray Particles of Mass Number $7 \leqq M \leqq 56$*

By

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Summary: Satellite-borne $dE/dx \cdot E$ semiconductor detector telescopes are proposed for isotope identification in heavy primary cosmic ray particles of mass number $7 \leqq z \leqq 56$. Some disadvantages in the use of scintillation counter as E-detector are pointed out. Next, mass resolutions in $dE/dx \cdot E$ detector telescopes consisting only semiconductor (silicon) detectors are estimated for dE/dx-detectors of various thickness. As the result, it is shown that separation of the two adjacent isotopes near iron nucleus can be achieved by the detector telescopes. $dE/dx \cdot E$ detector telescopes, of which E detector is composed of three transmission type silicon detectors of 5 mm in thick stacked in series, are designed for carbon and manganese isotope identification in the energy region near 100 Mev/nucleon.

1. INTRODUCTION

Identification of charged particles by a $dE/dx \cdot E$ detector telescope has been widely used in low energy nuclear reaction experiments. Recently, a $dE/dx \cdot E$ detector telescope, composed of two silicon detectors, has been successfully applied to isotope identification in heavy particles of several MeV/nucleon produced by heavy ion reactions [*1*]. This method for isotope identification has been also applied to heavy primary cosmic ray particles. All of detector telescopes used in such cases were composed of silicon detectors as dE/dx-detectors and scintillation counters as E-detectors [*2, 3, 4, 5*]. The reason why silicon detectors were not used as E-detectors is because it is difficult to fabricate silicon detectors which are thick enough to be used as E-detectors for heavy primary cosmic rays. In a detector telescope consisting of only silicon detectors, the mass resolution for heavy charged particles is mainly determined by the statistical fluctuation of the energy loss in the dE/dx-detector and can be estimated theoretically. In a detector telescope having a scintillation counter as E-detector, on the other hand, the mass resolution depends not only on the statistical fluctuation of the energy loss

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in the dE/dx-detector, but also on the intrinsic fluctuation of the light out-put from the scintillator and on the statistical fluctuation of the number of photo-electrons emitted from the photocathode of the photomultiplier. Since there are few informations about the pulse height distribution of output pulses from the scintillation counter for high energy heavy charged particles, the accurate estimation of the contribution from scintillation counter to mass resolution is difficult. With the present techniques, it is sure that fabrication of thick silicon detector as needed in the cosmic ray experiments is impossible. However, if two or three transmission type silicon detectors of 4 or 5 mm in thickness, which can be easily fabricated, are stacked in series and electrically connected in parallel, its detector system can be used as an E-detector having the effective thickness of 10–15 mm. A $dE/dx \cdot E$ detector telescope, consisting of such an E-detector system and a dE/dx-silicon detector, will be useful as a tool for isotope identification of heavy charged particles in the energy region near 100 MeV/nucleon.

In this paper, we will first point out some disadvantages in the use of scintillation counter as E-detector and next estimate the mass resolution of $dE/dx \cdot E$ semiconductor detector telescope for heavy nuclei such as ^{7}Be, ^{12}C and ^{53}Mn in the energy region near 100 MeV/nucleon. Finally, we will give semiconductor detector telescopes designed for isotope identification in heavy primary cosmic particles.

2. Scintillation Counter as E-detector

In general, the fractional half-width of the pulse height distribution of output pulses produced from a scintillation counter by monoenergetic particles of energy E_0 can be given as a following formula [6];

$$\eta^2 = \left(\frac{\Delta E}{E_0} \right)^2 = \eta_0^2(E_0) + \frac{5.56 W(keV)}{E_0(MeV)} \times 10^{-3} \qquad (1)$$

where, ΔE denotes full width at half maximum ($fwhm$), $\eta_0(E_0)$ the contribution to the half width due to intrinsic effects in the phosphor for monoenergetic particle of energy E_0, W the average energy spent in scintillator per an effective photoelectron produced from the photocathode in photomultiplier or per electron-hole pair produced in photodiode. In this formula, the second term represents the contribution from the statistical fluctuation of the number of photoelectrons or electron-hole pairs. When the energy of incident particles is low, the energy resolution of scintillation counter is mainly determined by the second term. Although the second term decreases with increase of particle energy, the first term remains almost independently of energy of incident particles. For high energy particles, therefore, the energy resolution of scintillation counter is determined by the first term in formula (1). At present, we have no detail information about $\eta_0(E_0)$ and W of scintillators for high energy heavy charged particles. Nevertheless, let us try to estimate the mass resolution of a $dE/dx \cdot E$ detector telescope consisting of a silicion detector and a scintillation counter, which has been often used in the cosmic ray experiments, using the observed values of energy resolution for high energy protons. Recently, Bateman obtained the energy resolution of 4.2% fwhm for 50 MeV protons in a CsI(Tl) scintillator-photodiode detector system [7]. Since this value includes the contribution from the electronic noise, the net energy resolution of the scintillation counter to be represented by formula (1) is estimated to be 3.3%. Since the value of W in this detector system is considered to be 0.1–0.2 keV, the contribution of the second term in formula (1) to the fractional half width for 50 MeV protons is negligibly small. Therefore, the so-called intrinsic resolution $\eta_0(E_0)$ is estimated to about 3.3%. According to the experimental results for gamma rays, $\eta_0(E_0)$ is very nearly inversely proportional to the fourth root of the energy of incident particles [8]. Assuming this relation, we can estimate $\eta_0(E_0)$ for heavy charged particles having the energy of 50 MeV/nucleon. $\eta_0(E_0)$ for particles having mass number larger than 30, obtained thus, will exceed $1/2M$ which is the fractional mass difference between two adjacent isotopes having mass number M and $M+1$. In such cases, it will be impossible to identify the adjacent isotopes by the $dE/dx{\cdot}E$ detector telescope, even when the statistical fluctuation of the energy loss in the dE/dx-detector can be neglected. Recently, Ahrens et al. found that $\eta_0(E_0)$ was almost constant for a large size NaI(Tl) scintillator using high energy gamma rays [9]. If $\eta_0(E_0)=3.3\%$ is independent of the energy of incident particles, the upper limit of mass number of incident particles that two adjacent isotopes can be identified is estimated to be less than $M=16$. It is considered that the upper limit of mass resolution obtained thus gives optimistic one, because it is estimated on the basis of the assumption that the light yield and $\eta_0(E_0)$ of scintillation counter for heavy charged particles are the same as those for protons having the same velocity. In semiconductor detectors, on the other hand, the spread of line spectrum due to electronic noise and ionization straggling produced as the result of total energy absorption of incident particles is negligibly small, and so, in the estimation of mass resolution, these contribution can be neglected. Therefore, we can achieve the estimate of mass resolution by considering mainly the statistical fluctuation of the energy loss in dE/dx-detector without any ambiguity.

3. Mass Resolution of $dE/dx{\cdot}E$ Semiconductor Detector Telescope

Fig. 1 shows a schematic diagram of $dE/dx{\cdot}E$ semiconductor detector telescope. Output from dE/dx-detector and the sum of both outputs from dE/dx and E-

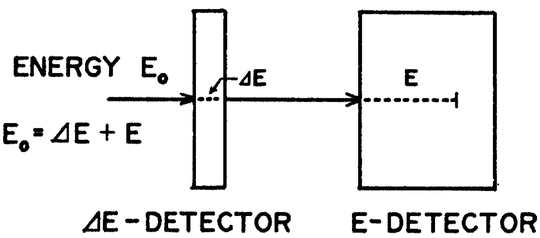


Fig. 1. Schematic diagram of $dE/dx{\cdot}E$ semiconductor detector telescope.

detectors are plotted on ΔE versus E_0 coordinates, respectively. Thus, the two dimensional curves, which are characterized by nuclear charge and mass of incident particles, are drawn. Of course, these curves have the width determined by the fluctuation of energy loss in the dE/dx-detector. In addition to the energy loss fluctuation, in practice, the width is broadened by the variation of energy losses of oblique incident particles in dE/dx-detector and by the nonuniformity of thickness of dE/dx-detector. Therefore, the actual *fwhm* is given as follows;

$$(fwhm_{total})^2=(fwhm_{sf})^2+(fwhm_{ob})^2+(fwhm_t)^2 \qquad (2)$$

where $fwhm_{sf}$ is a statistical spread of energy loss, $fwhm_{ob}$ a spread due to oblique incident particles and $fwhm_t$ due to nonuniformity of detector thickness.

i) *Energy Loss Fluctuation*

The statistical fluctuation of the energy loss of a charged particle traversing a thin material is characterized by a following dimensionless parameter [*10*].

$$\kappa=\xi/E_{max} \qquad (\xi=2\pi e^4 z^2 NZx/mc^2\beta^2\rho) \qquad (3)$$

where

e, m = charge and mass of electron;
z = nuclear charge number of incident particle;
β = particle velocity/light velocity;
Z = atomic number of the marerial;
N = number of atoms per cc of the material;
x = thickness of the material (g/cm^2);
ρ = density of the material (g/cm^3); and
E_{max} = maximum energy transfer in a heavy particle-electron collision.

If $\kappa \gg 1$, the fluctuation of the energy loss shows the Gaussian distribution, while if $\kappa \ll 1$, the fluctuation shows the Landau distribution. In the transition between both cases, the fluctuation is given by the Vavilov distribution. As shown later, if a silicon detector thicker than 1 mm is used as a dE/dx-detector, the statistical fluctuation of the energy loss of particles having mass number larger than 10 shows the Gaussian distribution over an energy range from 20 MeV/nucleon to 300 MeV/nucleon. In this paper, we will treat the energy loss distribution to be Gaussian, because the energy and mass ranges of heavy particles shown above are wide enough to cover the useful range as $dE/dx \cdot E$ semiconductor detector telescope for the heavy primary cosmic ray particles as shown later.

The most probable energy loss of a heavy particle passing through a detector x g/cm^2 thick is given by [*11*]

$$\Delta E=\xi\left\{ln\frac{mv^2\xi}{I^2(1-\beta^2)}-\beta^2+0.37-U-\delta\right\} \qquad (4)$$

where

I = average excitation potential for the detector material;
v = velocity of incident particles;
δ = density effect correction; and
U = inner shell effect correction,

and $fwhm_{sf}$ is given follows [12];

$$fwhm_{sf} = 2.35\left\{\xi\cdot E_{max}\left(1-\frac{\beta^2}{2}\right)\right\}^{1/2}$$
$$= 2.35\left\{\frac{0.30Z}{\beta^2 A}z^2mc^2xE_{max}\left(1-\frac{\beta^2}{2}\right)\right\}^{1/2} \qquad (\kappa \gg 1). \tag{5}$$

Now, let us consider about the separation of a heavy particle from adjacent isotopes. The following quantity should serve as a good measure in isotope identification,

$$S(M, z, E_0) = fwhm_{sf}(M, z, E_0)/\{\varDelta E(M+1, z, E_0) - \varDelta E(M, z, E_0)\}. \tag{6}$$

In the non-relativistic approximation, S is given by a simple formula

$$S(Mz, E_0) \propto \frac{1}{g(\beta)}\frac{E_0}{\sqrt{xz}} \tag{7}$$

where $g(\beta)$ ig given by

$$\varDelta E(M, z, E_0) = \frac{\pi e^4 NZ}{m} g(\beta)\frac{M}{E_0}z^2x.$$

Since z is proportional to M and $g(\beta)$ depends only on the velocity of incident particle, the above formula shows that $dE/dx{\cdot}E$ detector telescope has the same resolution for particle having the same energy per nucleon. In other words, if the energy per nucleon of incident particle is constant, the ability of the telescope for particle identification between two adjacent isotopes does not depend on the particle mass, as long as pulse height distribution of output pulses from the dE/dx-detector is determined only by the energy loss fluctuation. Accordingly, if the identification for adjacent isotopes with small mass number such as hydrogen, helium or beryllium isotopes can be achieved, it may be done as well for those with large mass number.

To investigate the relation between $fwhm_{sf}$ and $\varDelta E(M+1, z, E_0) - \varDelta E(M, z, E_0)$ for heavy particles in the high energy region, we calculated the fractional resolution defined as follows;

$$R = \frac{fwhm_{sf}(M, z, E_0)}{\varDelta E(M, z, E_0)} \tag{8}$$

over a wide energy range from 20 MeV/nucleon to 800 MeV/nucleon for three

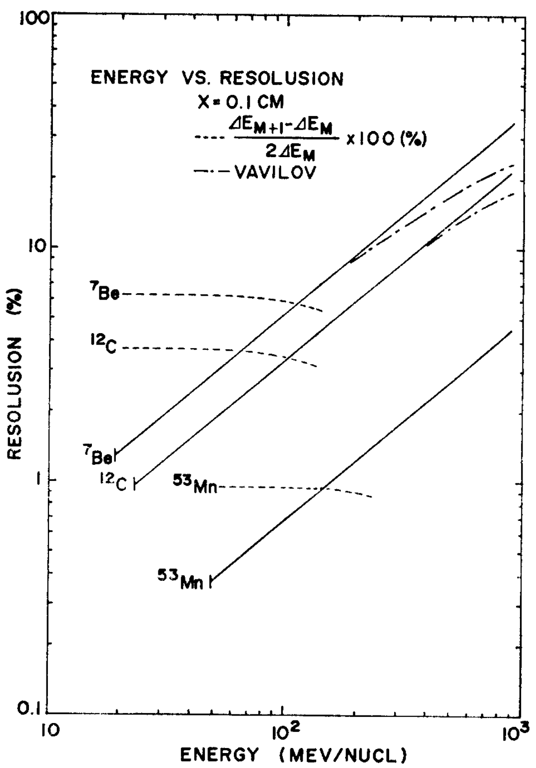


FIG. 2(a)

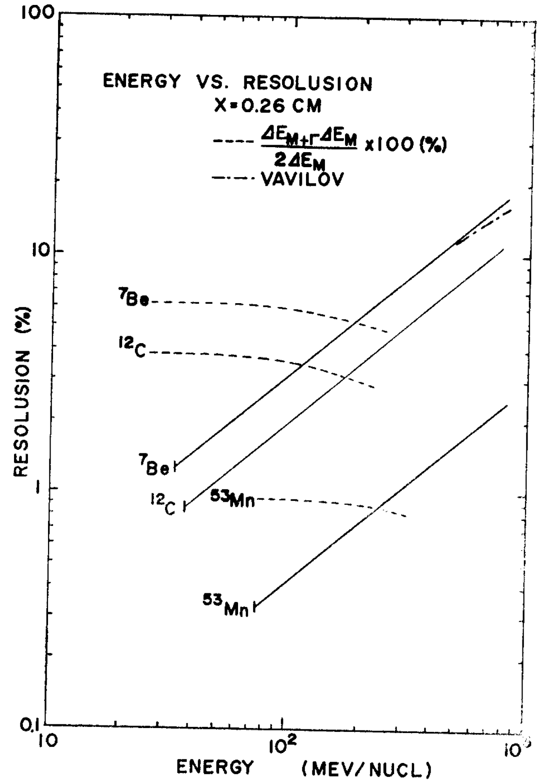


FIG. 2(b)

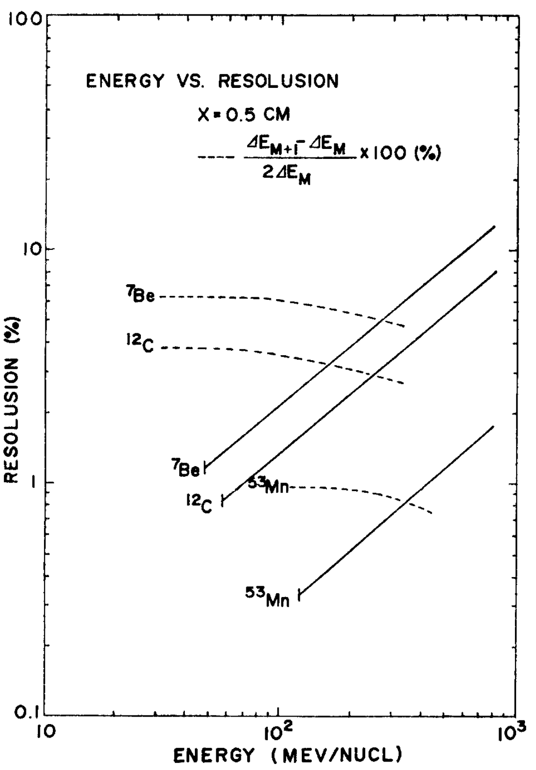


FIG. 2(c)

FIG. 2. Variation of R versus energy/nucleon of incident particle for ^{7}Be, ^{12}C and ^{53}Mn for thickness of dE/dx-detector 1 mm thick (a), 2.6 mm thick (b) and 5 mm thick (c). The dotted curves show the half fractional separation defined as $(\Delta E_{M+1}-\Delta E_M)/2\cdot\Delta E_M$, which is a measure for identification between two adjacent isotopes. Chain curves show fractional resolution given by Vavilov distribution.

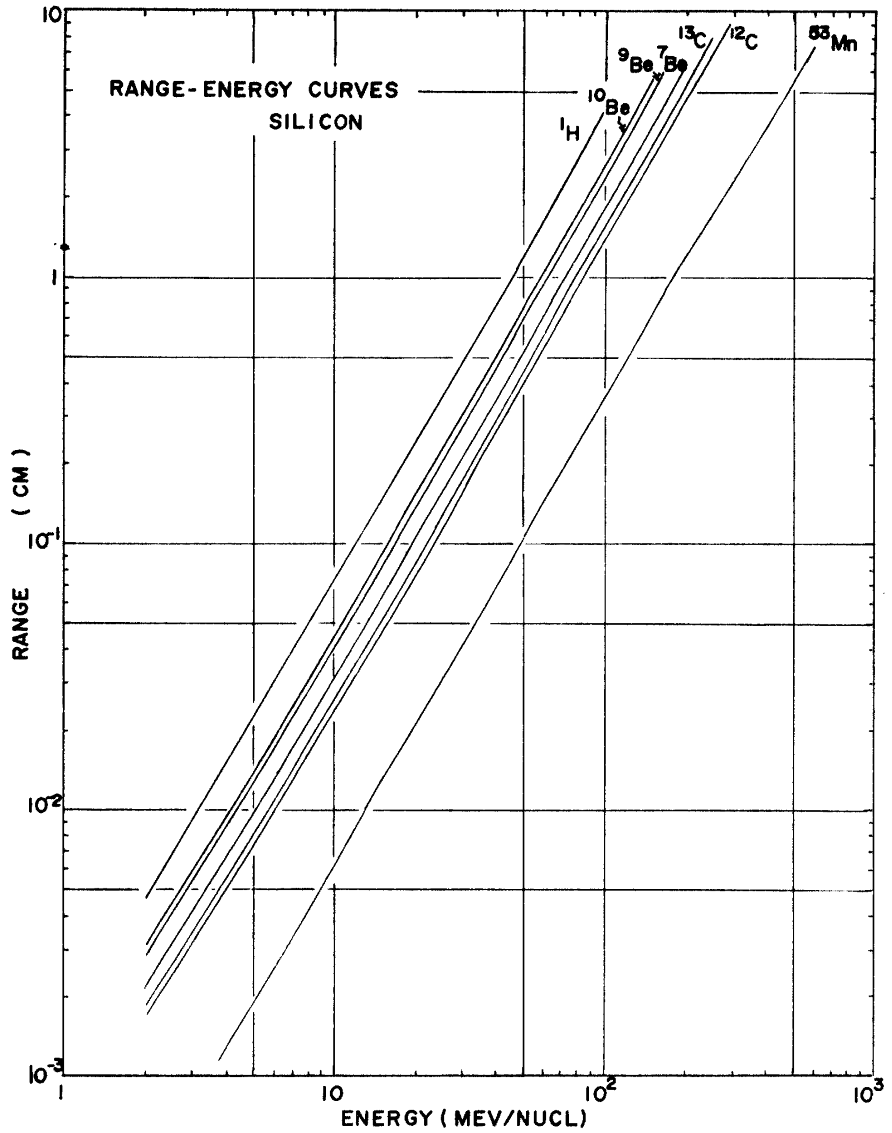
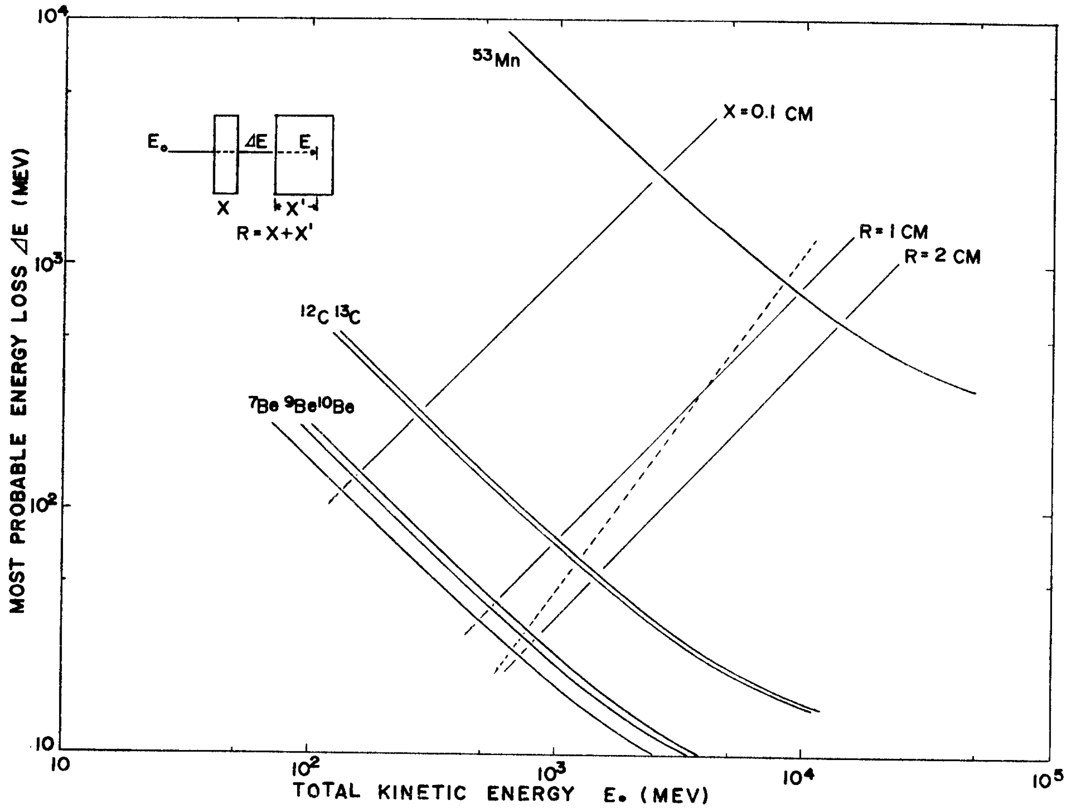


FIG. 3. Range-energy relation in silicon for proton, beryllium, carbon and manganese isotopes.

dE/dx-silicon detectors with different thickness. Fig. 2(a), (b) and (c) show the variation of R with the energy of incident particle, expressed by MeV/nucleon, for ^{7}Be, ^{12}C and ^{53}Mn. The dotted curves in the figures show the variatoin of

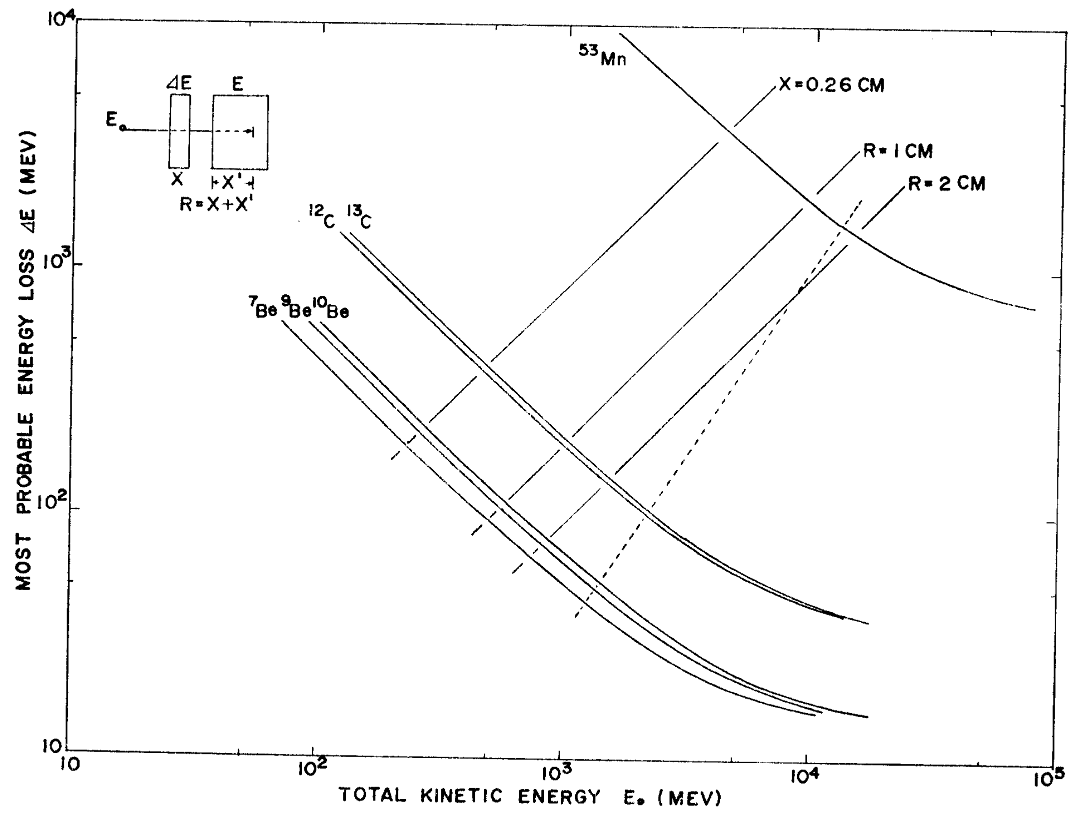
$$\frac{\Delta E(M+1, z, E_0) - \Delta E(M, z, E_0)}{2 \cdot \Delta E(M, z, E_0)}$$

which is a measure of separation between two adjacent isotopes, calculated from equation (4). If the fractional resolution R is lower than the value shown by the dotted curve, it means that the telescope has the ability enough to separate two adjacent isotopes. Thus, the crossing-point of the solid line and the dotted curve gives a measure of upper limit of particle energy for mass resolution of telescope, and it depends on the particle mass apart from the similarity low of



^{53}Mn
X=0.1 CM
R=1 CM
R=2 CM
^{12}C ^{13}C
^{7}Be ^{9}Be ^{10}Be
E₀
ΔE
E₁
X
X'
R=X+X'
MOST PROBABLE ENERGY LOSS ΔE (MEV)
TOTAL KINETIC ENERGY E₀ (MEV)
10
10²
10³
10⁴
10⁵

FIG. 4(a)



^{53}Mn
X=0.26 CM
R=1 CM
R=2 CM
^{12}C ^{13}C
^{7}Be ^{9}Be ^{10}Be
ΔE
E
E₀
X
X'
R=X+X'
MOST PROBABLE ENERGY LOSS ΔE (MEV)
TOTAL KINETIC ENERGY E₀ (MEV)
10
10²
10³
10⁴
10⁵

FIG. 4(b)

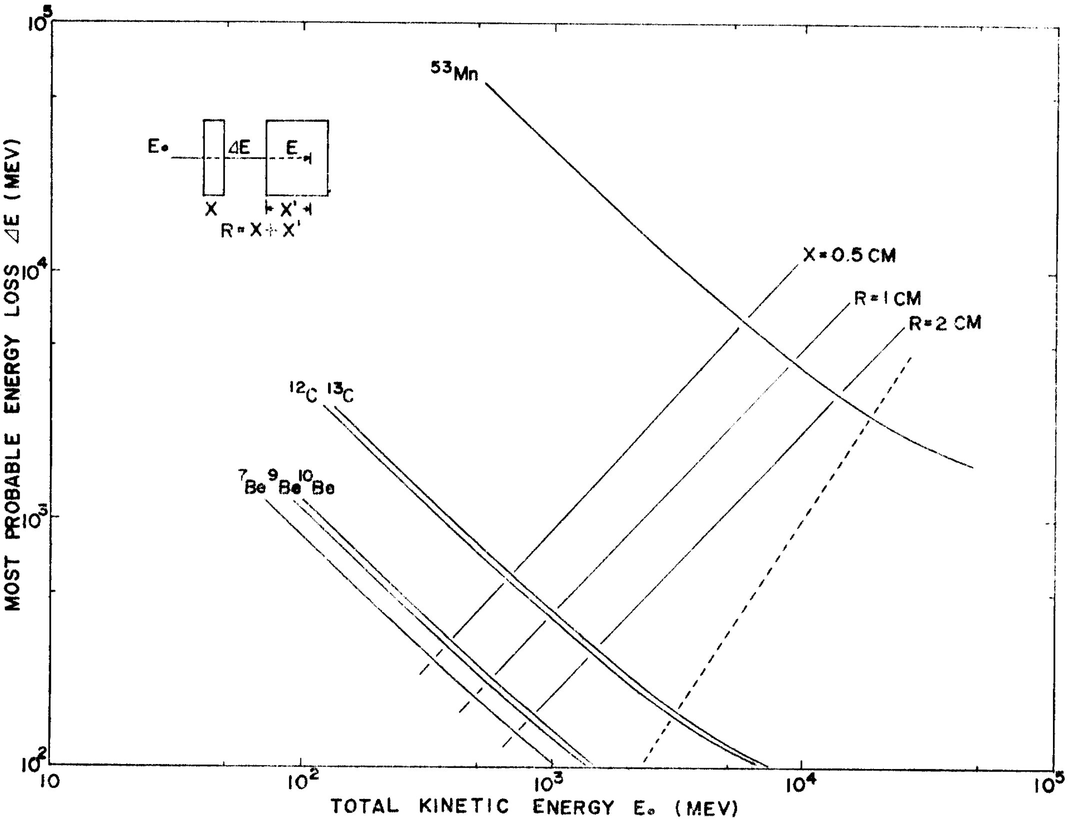


FIG. 4(c)

FIG. 4. Variation of ΔE as the function of E_0 for ^{7}Be' ^{12}C and ^{53}Mn for thickness of dE/dx-detector 1 mm thick (a), 2.6 mm thick (b) and 5 mm thick (c). Dotted line shows upper limit of energy of incident particle that adjacent isotopes can be identified. Solid line given by the thickness X of dE/dx-detector shows lower limit of energy of incident particles which can pass through dE/dx-detector and others express lines limited by total detector thickness R.

mass resolution shown in equation (7). The lower limit of particle energy for separation of two adjacent isotopes is determined by the thickness of dE/dx-detector. As seen in Fig. 2, the over-all range of particle energy, determined by the both limits, is almost the same for each particle mass, and shifts toward the high energy side with increase of the detector thickness. If the thickness of E-detector in a telescope is limited to be about 15 mm by reason of difficulty of the detector fabrication, the use of dE/dx-detector 5 mm thick is infavorable because of reduction of the useful energy range, as be understood from the range-energy relations in silicon for various charged particles (see Fig. 3). In Fig. 4 (a), (b) and (c), the variation of ΔE as the function of E_0 is plotted for Be, C and Mn isotopes, respectively, and also the limits of mass resolution and the range-energy relations are shown easily to understand various conditions.

ii) *Variation of Energy Loss due to Oblique Incident Particles*

In the previous paper, the energy loss distribution due to oblique incident particles was calculated on the basis of the assumption that the direction of the incident particle is isotropic [*13*]. The energy loss distribution obtained thus can be expressed as a function of the ratio of the diameter D to the length L of the telescope. From the function, the $fwhm_{ob}$ are estimated to be 5%, 2%, 1% and 0.5% for $D/L=1$, 1/2, 1/3 and 1/5, respectively. The geometry of the detector telescope should be designed so that the spread may be negligibly small compared to statistical spread. For example, let us consider about identification between ^{12}C and ^{13}C. The separation of ΔE between these isotopes is about 8% and so, the $fwhm_{ob}$ must be kept less than 2%. Accordingly, the maximum solid angle of the telescope is limited less than 0.66 steradian, corresponding to $D/L=1/2$. For ^{53}Mn, the separation between adjacent isotopes is only 1.7 or 1.8%. Therefore, the $fwhm_{ob}$ must be kept at least less than 0.5%. This means the reduction of the solid angle to 0.122 steradian. In this case, it is necessary to increase the effective area of the telescope so that the telescope has the same geometrical factor as that for carbon isotopes.

iii) *Effect of Nonuniformity of Detector Thickness*

From our experience, it is easy to fabrcaite transmission type silicon detectors of mean thickness 2.6 mm within the error of $\pm 50\mu$ (peak to peak) [*14*]. Furthermore, the uniformity of thickness in each detector is estimated to be of the order of $\pm 10\mu$. Such transmission type detectors can be satisfactory used as dE/dx-detectors for identification in carbon isotopes. In order to identify two adjacent isotopes near iron, however, the uniformity of detector thickness is required to be less than 0.5% as $fwhm_t$. This means that the uniformity of thickness of a dE/dx-detector 1 mm must be within at least $\pm 5\mu$ (peak to peak), which gives a $fwhm_t$ of about 5μ, if the distribution of detector thickness is Gaussian. With the present fabrication technique, it seems that the fabrication of transmission type silicon detector whose thickness uniformity is less than $\pm 10\mu$ is not so easy. For isotope identification near iron, therefore, it is desirable to use a dE/dx-detector thicker than at least 2 mm.

4. Design of Semiconductor Detector Telescope for Isotope Identification in Heavy Primary Cosmic Rays

On the basis of the above consideration for the mass resolution of the $dE/dx \cdot E$ semiconductor detector telescope, we have designed two silicon detector telescopes for identification of carbon isotopes and manganese isotopes. Now let us consider on the detector telescope for carbon isotopes, consisting a dE/dx-silicon detector and an E-detector system consisting of three transmission type silicon detectors of 5 mm thick stacked in series, as described before. In this cases, the maximum energy of incident particles which are stopped in the E-detector system is 100 MeV/nucleon. As seen from Fig. 2, the upper limit of particle energy in which adjacent carbon isotopes can be identified is 100 MeV/nucleon, 170 MeV/nucleon and 240 MeV/nucleon for dE/dx-detector of 1 mm, 2.6 mm and 5 mm thick,

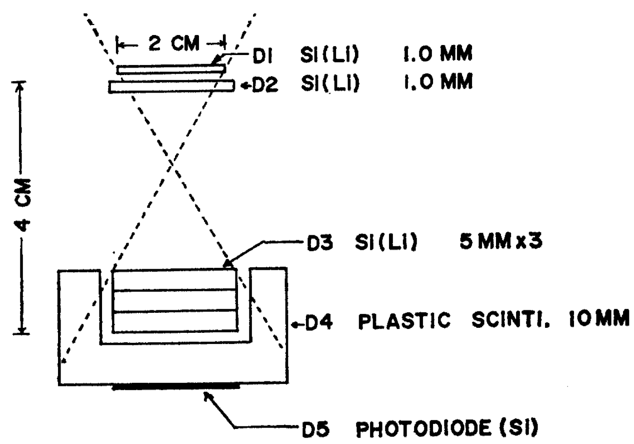


FIG. 5(a)

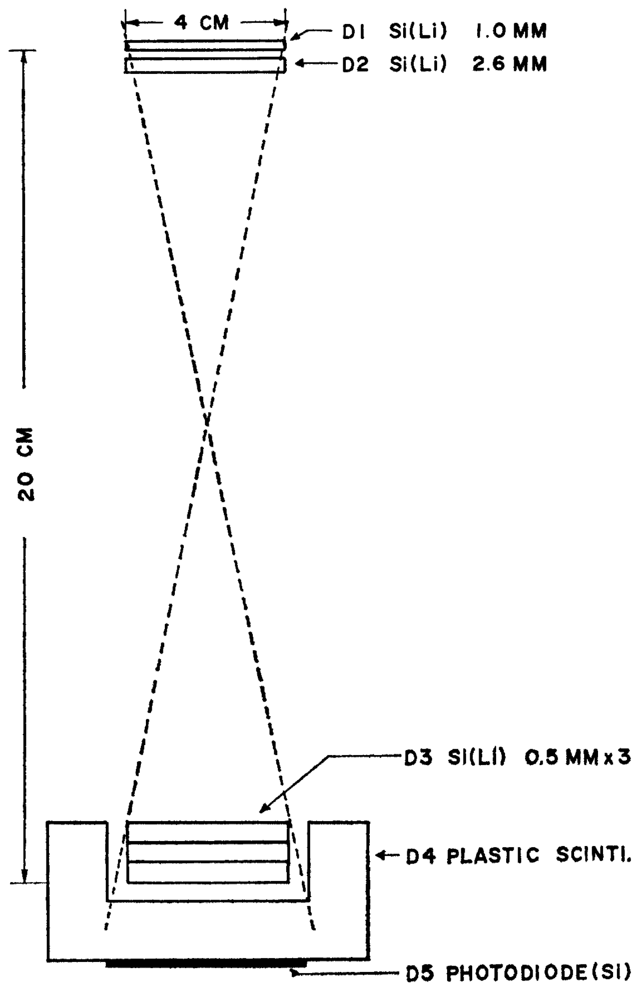


FIG. 5(b)

FIG. 5. Cross sectional views of semiconductor detector telescope for isotope identification in the heavy primary cosmic rays. (a) $dE/dx \cdot E$ detector telescope for carbon isotopes, (b) $dE/dx \cdot E$ detector telescope for manganese isotopes. D1: coincidence detector, D2: dE/dx-Si(Li) detector, D3: E-Si(Li) detector, D4: anticoincidence scintillator, D5: photodiode.

respectively. Accordingly, a dE/dx-detector thicker than 1 mm is not necessary as long as the E-detector system with effective thickness equal to/less than 15 mm is used. As shown in the previous section, the ratio of the diameter to the length of the detector telescope D/L must be kept less than 1/2. Fig. 5 (a) shows a typical silicon detector telescope designed for identification of carbon isotopes. The geometrical factor of this telescope is 0.59 cm^2•steradian, whihc is almost the same as that of the satellite-borne telescope used for identification of helium and beryllium isotopes in heavy primary cosmic rays by the Chicago University Group [*3, 4, 5*].

For identification of manganese isotopes, taking account of the restriction on nonuniformity of thickness of dE/dx-detector and on effectvie solid angle of the detector telescope, a detector telescope of D/L-1/5, consisting of a dE/dx-detector 2.6 mm thick and an E-detector system having an effective thickness of 15 mm were designed. Fig. 5(b) shows a cross sectional view of the detector telescope. In order to keep the geometrical factor of the detector telescope to be almost the same as that for carbon isotopes, the diameter of the detector telescope must be larger than twofold of that for carbon isotopes. It seems that fabrication of transmission type silicon detector with such a wide area is not so much difficult.

Both detector telescope have a transmission type silicon detector 1 mm thick to define the solid angle of the detector telescope and a well type scintillation counter system for anticoincidence mode in order to remove transversing particles through the E-detector, respectively. The over all thickness of silicon in the detector telescope system for carbon isotopes is 12 mm (2.76 g/cm^2) and for manganese isotopes 18.6 mm (4.28 g/cm^2). Here, let us consider the contribution of background counts produced by nuclear reactions into the two dimensional plotting on the $\Delta E-E_0$ coordinates. The mean free path of charged particles such as carbon, nitrogen and oxygen, in silicon, determined by nuclear reactions, is estimated to be 35~38 g/cm^2 and it of iron particles 20 g/cm^2*. From these mean free paths, it is estimated that the probability that nuclear reaction is produced in the silicon detectors is 7.6% for an incident particle of carbon, nitrogen and oxygen, respectively, while the probability for an iron partcile 21.4%. Since the events produced by the nuclear reactions due to carbon, nitrogen and oxygen are widely spread near each $\Delta E-E_0$ curve, the probability that the spurious counts will fall on the $\Delta E-E_0$ curve of ^{13}C is considered to be less than 10%. The effect of the spurious events produced by iron particles on the $\Delta E-E_0$ curve of ^{53}Mn is estimated to be almost the same as that for ^{13}C. These show that the detection of adjacent isotope having an intensity of at least one-tenth of the main isotope such as carbon, nitrogen and oxygen or iron is possible. At present, the fabrication of transmission type silicon detectors 5 mm in thick and 20 mm in diameter is in progress in our laboratory.

* These values are calculated from the formula given by Peters [*15*].

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