POSSIBLE METHOD OF DETECTING HIGH-ENERGY CHARGED PARTICLES

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Submitted to JETP editor July 25, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) 41, 2002-2010 (December, 1961)

The characteristics of the radiation produced by fast charged particles moving in a layered medium are investigated. The possibility of detecting this radiation is discussed and experimental methods for observing it are proposed; methods of using this radiation for the detection of charged particles and the measurement of particle energies are considered.

1. CHARACTERISTIC FEATURES OF RADIATION PRODUCED BY THE PASSAGE OF FAST PARTICLES THROUGH A LAYERED MEDIUM. CHOICE OF PARAMETERS.

It has already been pointed out by one of the authors[1-3] that the radiation produced by the passage of fast particles through an arbitrary periodic medium can be of use in high-energy particle physics. As an example we discuss here the theoretical and experimental aspects of the problem of using this radiation (which, for brevity, will be called resonance radiation) for the detection of charged particles and the measurement of particle energy. From the experimental point of view the most convenient periodic medium is one made up of layers. Hence, in what follows we use the example of a one-dimensional layered medium consisting of alternating slabs of two different materials. The thickness of the first slab is denoted by l_1 and the second by l_2. The period of the medium is then

$$l = l_1 + l_2. \tag{1.1}$$

The number of electrons per cubic centimeter in the two materials is denoted by N_1 and N_2 respectively. To be specific we assume that $N_1 > N_2$. The ratio of the thickness of the second slab (less dense) to that of the first is denoted by α:

$$\alpha = l_2/l_1. \tag{1.2}$$

The number of photons radiated in the frequency interval $d\omega$ due to the traversal of one centimeter of the layered medium (transverse to the slabs) is given by the expression

$$dm = \frac{4p^2(1+\alpha)}{137\,\pi l_1}\sum_{r=1}^{r_{max}}\frac{d\omega}{r^3\omega^3}\,\frac{\left[1-\frac{1}{4}(E_{1t}/E)^2\,\omega/r-\omega^{-2}\right]}{(1-p/\omega r)^2\,(1+p\alpha/\omega r)^2}$$
$$\times\sin^2\left[\left(\frac{\alpha}{1+\alpha}\right)\pi r-\frac{\pi}{\omega}\left(\frac{\alpha p}{1+\alpha}\right)\right]. \tag{1.3}$$

The radiated frequency ω is measured in units of

$$\omega_{1min} = l_1 r_e c\,(N_1 + \alpha N_2), \tag{1.4}$$

where r_e is the classical electron radius and c is the velocity of light. The properties of the media appear in this expression through the quantity p, defined by

$$p = (N_1 - N_2)/(N_1 + \alpha N_2). \tag{1.5}$$

The quantity E_{1t} is given by

$$E_{1t} = mc^2 l_1\,[\pi^{-1} r_e\,(1+\alpha)\,(N_1+\alpha N_2)]^{1/2}. \tag{1.6}$$

We note first that the number of radiated photons is made up of radiation corresponding to different orders (or different harmonics); these are enumerated by the letter r. The quantity r can vary from r_e to r_{max}:

$$r_{max} \approx l_1\,[\pi^{-1} r_e\,(1+\alpha)\,(N_1+\alpha N_2)]^{1/2}. \tag{1.7}$$

The basic contribution in the processes considered below is due to harmonics characterized by harmonic numbers appreciably smaller than r_{max}. For these values of r to obtain, the period of the layered medium must be greater than 10^{-5} cm. We now deduce the basic properties of the resonance radiation. Since the expression in the numerator of Eq. (1.3) must be positive, it follows that for each harmonic the radiated frequency interval must lie between ω_{min} and ω_{max}:

$$\omega^{(r)}_{\substack{min\\max}} = \left(r \mp \sqrt{r^2-(E_{1t}/E)^2}\right)/(E_{1t}^2/2E^2). \tag{1.8}$$

This interval can be achieved if the expression under the radical in (1.8) is real, i.e., if $r < E_{1t}/E$

$$\frac{E}{mc^2} \geqslant \frac{E_t}{mc^2} = \frac{l_1}{r}\,[\pi^{-1} r_e\,(1+\alpha)\,(N_1+\alpha N_2)]^{1/2}. \tag{1.9}$$

Consequently there is a definite energy threshold for radiation of a given harmonic. The threshold energy decreases with increasing harmonic number. If the particle energy is appreciably greater than the threshold energy, so that (1.8) can be expanded in the parameter $E_{1t}/2E$, then the interval of radiated frequencies for each harmonic is given by the simple inequality:

$$1/r \approx \omega_{rmin} \leqslant \omega \leqslant \omega_{rmax} \approx 4rE^2/E_t^2. \qquad (1.10)$$

The physical meaning of the frequency introduced above ω_{1min} follows from (1.10); it is evident that $r = 1$ gives the lowest possible radiated frequency at the first harmonic $\omega_{1min} = 1$. In what follows the particle energy will be measured in units of $E_{1t}(\alpha = 1)$ — the threshold energy for the first harmonic for $\alpha = 1$.

Radiation with the properties described above can be generated only by relativistic particles [(1.7) and (1.9)]. At lower (still relativistic) energies, a particle can only radiate harmonics with high values of r. As the energy of the radiating particle increases radiation will gradually appear at new harmonics. If the particle energy is greater than the threshold energy for the first harmonic, denoted below by $(E/mc^2)_{1t}$ [Eq. (1.9) with $r = 1$], no new harmonics can be produced and the radiation intensity reaches a saturation point. Under these conditions the energy loss due to resonance radiation is approximately 10^4 ev per g/cm^2 for a periodic medium consisting of solid slabs in a gas. It should be noted that the loss given above is a weak function of slab thickness and slab material, and that it falls off slowly with increasing α; at large values of α ($\alpha > 10$) the loss goes as $1/\alpha$. This result can be understood qualitatively if one considers the fact that "harder" photons will be radiated from thicker slabs (1.4).

The differential photon spectrum for a given harmonic is given by a curve that exhibits a maximum at approximately $\omega = 1.5\,\omega_{min}$ and intersects the abscissa axis at ω_{min} and ω_{max}. The number of photons falls off sharply beyond the maximum. For this reason the high-frequency contribution to the radiation intensity can be neglected. The onset frequency ω_{min} does not change as the energy increases, but ω_{max} increases as E^2 [(1.10)].

However, because of the nature of the spectrum indicated above we can neglect the energy dependence of the radiation intensity at each harmonic if the particle energy exceeds the threshold value at a given harmonic. For illustration, in Fig. 1 we show the differential spectrum of resonance radiation for a particular case ($E = 2.2\,E_{1t}$, $\alpha = 1$). The resonance radiation at several harmonics is shown in the figure; the upper curve shows the total differential spectrum for all harmonics with $E = 5\,E_{1t}$ and $\alpha = 1$. The radiation frequency ω (in units of ω_{1min}) is plotted along the abscissa axis while the quantity $l_1 f(\omega)$ is plotted along the ordinate axis. We shall not give the corresponding curves for other values of the parameters here (cf. [3]).

Several parameters characterizing the differential spectrum of the resonance radiation appear in (1.3). It is assumed that $\alpha_2 N_2 \ll N_1$. This condition is satisfied in a periodic medium consisting of solid slabs in a gas. It should be noted that a layered medium consisting of two different kinds of solid slabs would be much easier to use than the one described here; however, to achieve the condition $p \approx 1$ it would be necessary to use solid slabs with markedly different atomic weights (a light material and a dense material). On the other hand, photo-absorption of resonance photons in dense materials could reduce the radiation output

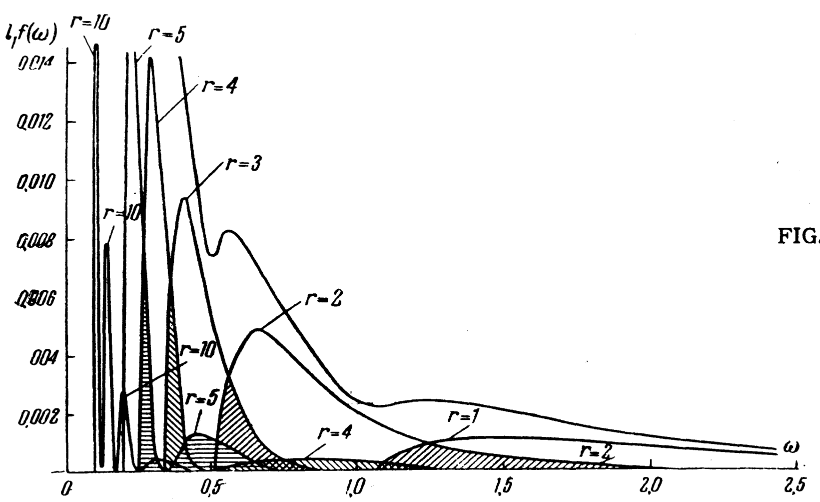

FIG. 1. Differential resonance radiation spectrum ($\alpha = 1$).

severely. With two materials with small atomic weights, however, p is of the order of 0.3 — 0.7 and the radiation intensity (which is proportional to p^2 for small values of p) is smaller than that obtained with slabs in a gas. Inasmuch as intense beams of charged particles are available from accelerators, from the purely experimental point of view it would be preferable to use a layered medium consisting of two different kinds of solid slabs. When cosmic rays are studied, however, it would be necessary to use a medium consisting of slabs located in a gas in order to obtain adequate radiation intensity (we have taken p = 0.99 in these calculations). It follows from Eq. (1.4) that the quantity ω_{1min} depends only on slab thickness and electron density when $p \approx 1$.

The values of $\hbar\omega_{1min}$ for several materials are shown in Table I. We emphasize that slab thickness and slab material determine completely the frequency region in which resonance radiation can be detected. Values of the threshold energy are given in the same table (for r = 1 and $\alpha = 1$). We also emphasize that in addition to depending on l_1 and N_1 the threshold energy is also a function of the interslab distance, varying as $(1 + \alpha)^{1/2}$ [(1.9)]. Using (1.4) we can compute $\hbar\omega_{1min}$ for a given material and thickness. Particles with energies greater than $(E/mc^2)_{1t}$ produce photons with energies greater than $\hbar\omega_{1min}$, but particles with smaller energies produce softer protons. Thus, an experimental device that detects photons at frequencies (energies) greater than some frequency related to ω_{1min} can be used to separate out particles with energies greater than E_{1t}. It will be evident that particles with smaller energies can be detected in precisely the same way if the first harmonic is used instead of the second and so on.

As an example we consider several typical curves (Fig. 2) illustrating the dependence of the number of radiated photons on particle energy. The energy of the initial particle is plotted along the abscissa axis in units of the threshold energy (E/E_{1t}). The ordinates represent the number of radiated photons per centimeter characterized by $\omega > 0.1$, $\omega > 1$, and $\omega > 3$ multiplied by the slab

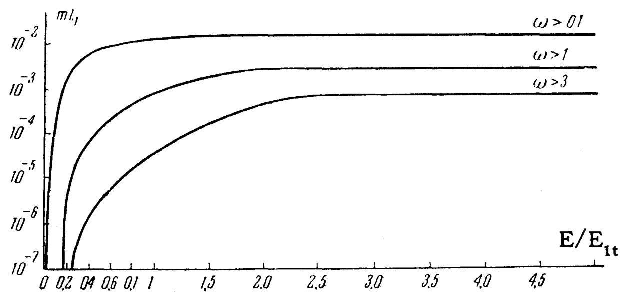

FIG. 2. The total number of photons (ml_1) as a function of particle energy for different ω with $\alpha = 1$.

thickness l_1. These curves show that the number of resonance photons per centimeter of path of layered material is a very sensitive function of particle energy. We do not give corresponding curves here for other values of α or for other values of the minimum frequency. The number of photons radiated per centimeter of path of a layered material increases with α (up to $\alpha \sim 3$) and then falls off approximately as $2/(1 + \alpha)$.

All these results can be easily obtained from (1.3). It is evident that a given experimental device is sensitive to photons in a given energy range. Hence, we start with some initial energy for the photons produced in the layered medium and detected by the device. For instance, the frequency region $\omega \geq 1$ corresponds to photons with energies greater than $\hbar\omega_{1min}$. We could have chosen the region $\omega \geq 0.1$ or $\omega \geq 10$; however, analysis shows that it is most desirable to operate in the region $\omega = 1.2 - 1.6$. In this region one obtains the maximum number of photons per centimeter with an adequately sensitive dependence of photon number on particle energy. For example, the slab thickness must be reduced by 50 % if the value $\omega = 2$ is taken and the observations are carried out with photons of the same energy. The threshold energies are correspondingly reduced by 50 %. With ω smaller than unity, for example $\omega = 0.1$, we find on comparing with the $\omega = 1$ case that the slab thickness and threshold energies are increased by a factor of ten while the number of photons per centimeter of path is one half as large. Let us assume operation in the region $\omega = 1$, i.e., that the detected photons have energies greater than

Table I

Material	$10^{-23}N_1$, cm^{-3}	$E_\gamma = \hbar\omega_{1min} = 5{,}55 \cdot 10^{-24}\, N_1 l_1$, Mev	$\frac{10^{-5}}{l_1}\left(\frac{E}{mc^2}\right)_{1t}$, $\alpha = 1$
Paper	2—3	$(1.1—1.7)l_1$	1.6--2.4
Polyethylene	2.8	$1.53l_1$	2.21
Be	4.9	$2.72l_1$	2.95
Al	7.8	$4.33l_1$	3.72

$\hbar\omega_{1min}$. This choice will be used in most of the further analysis.

When absorption in the medium is taken into account the number of photons emitted from the layered material is

$$n = (M/\mu)(1 - e^{-\mu L}), \qquad (1.11)$$

where M is the number of photons produced per centimeter of length of the layered material, μ is the radiation absorption coefficient, and L is the total length of the layered material. When $L \gg 1/\mu$, $n = M/\mu$. The layered material should have the lowest possible value of Z.

The radiation can be detected by several different methods, each of which will be considered individually.

2. METHOD OF ENERGY GENERATION

The particle and the radiation it produces pass through a detector, which registers the amount of generated energy. The detector must be such that the radiation it absorbs can be used to establish the initial radiation from the energy generated by the particle and the initial radiation. It is convenient to use a high-Z absorber. Useful data can be obtained with a proportional gas counter in which a heavy gas is used.

In Fig. 3 we show the quantity I (the ratio of energy generated by the γ photons of the resonance radiation to the energy generated by the particle) as a function of particle energy in Be for different parameters of the layered material. In Table II we give the conversion factor k for other materials. The optimum frequency region for this method is E_γ = 8 — 15 kev. It is evident from Figs. 2 and 3 that a layered material characterized by high values of α should be used. Making α too large, however, does not increase the value of I appreciably but can make the experimental apparatus, which consists of the layered material and

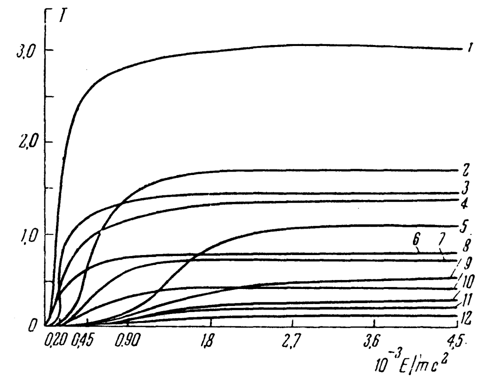

FIG. 3. The ratio of energies generated by resonance radiation and by the particle as a function of energy.

a proportional counter located under it, much more complicated. This method is suitable for the measurement of particle energies in the range $E/mc^2 = 2 \times 10^2 - 2 \times 10^3$ and for the detection of particles with energies greater than this value.

3. CHARACTERISTIC-RADIATION METHOD

The particle and the radiation it produces in the layered material pass through a gas absorber. Gamma photons with energies equal to or greater than the energy of the K level of the given gas produce a photo effect in the K level. The gas then emits characteristic radiation with energy E_K. The absorption coefficient for the characteristic radiation at the K edge is 5 — 7 times smaller than the usual absorption coefficient at the K edge; furthermore, the radiation distribution is isotropic. For these reasons the radiation can be detected in directions other than the direction of motion of the particle. As in the first method the layered material must be one with small Z. In Fig. 4 we show the number of photons emitted from a layered polyethylene material and absorbed in Xe as a function of particle energy for different values of α. The conversion coefficient k for other materials is also given.

Table II

No.	$E_{min}\cdot 10^{-6}$, ev	α	Gas	Slab thickness L, cm	kn_e	k_{Al}	No. of layers
1	1	60	Xe	122	0.3		650
2	1	10	Xe	22		$2.5\cdot 10^{-2}$	
3	1	60	Ar	122			
4	1.5	60	Xe	235	0.44		840
5	1.5	10	Xe	42		$41\cdot 10^{-2}$	
6	1.5	60	Ar	235			
7	1	10	Ar	22			
8	1	1	Xe	4			
9	1.5	10	Ar	42			
10	1.5	1	Xe	7.7			
11	1	1	Ar	4			
12	1.5	1	Ar	7.7			

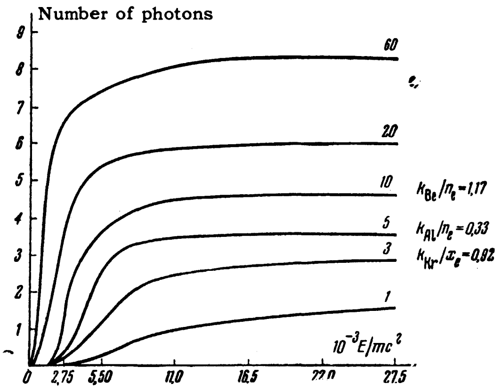

FIG. 4. The number of characteristic-radiation photons as a function of particle energy for various values of α.

The characteristic γ photons with energies E_K = 35 kev (E_K = 14.3 kev for Kr) can be detected transversely by means of scintillators. High-pressure proportional gas counters can be used. The counter walls can be very thin if the pressure in the counters is compensated by a light gas kept at the same pressure as the gas absorber.

Thus, the experimental device consists of the layered material under which there is a gas absorber. The scintillators are located at the sides of the gas absorber. It is desirable to use the scintillator NaI (Tl), in which the detection efficiency for γ photons is almost 100 % in the region 2 — 30 kev. A detection device of the following design can also be used. The γ photons from the gas absorber (Xe) enter another region which is also filled with xenon, but at a pressure such that all the radiation is absorbed. The xenon itself scintillates (the light yield is $^{32}/_{72}$ of the yield from NaI (Tl) [4]). This technique can be used to increase the light yield in a device when it is used for detecting high-energy cosmic-ray particles. We note that the transverse dimensions of the gas absorber must be equal to or less than the longitudinal dimension.

The layered material can also be located directly inside the gas absorber. In this case the characteristic radiation can be detected at the sides of the layered medium. This technique is suitable for measuring particle energies in the range $E/mc^2 = 5 \times 10^2 - 5 \times 10^3$ and for detecting particles with higher energies.

4. COMPTON-SCATTERING METHOD

We assume that the length of the layered material is such that the radiation produced by the particle experiences multiple Compton scattering in the material. The transmission factor T can then be written approximately in the form [5]

$$T = B \exp(-\mu_0 x), \tag{4.1}$$

where x is the thickness of traversed material and μ_0 is the minimum radiation absorption coefficient while the factor B lies between unity and $(\mu_0 x)^2$.

The remainder of the radiation (1 — T) escapes from the sides of the layered material. This situation holds for "good" geometry. To determine exactly the number and angle-energy distribution of the γ photons escaping from the sides of the layered material in a given geometry would require extremely complicated calculations (for example, a Monte Carlo calculation). We shall use the approximation formula (4.1), which indicates that most of the radiation escapes from the sides of the layered material. These γ photons can be detected most conveniently by means of large liquid scintillators such as those used by Cowan and Reines [6]. In this method the energy of the γ photons must be such that the photoeffect is negligible compared with the Compton effect.

For example, with a layered medium made from Al (l_1 = 0.1 cm, α = 1) we obtain 3×10^{-2} photons with energies greater than 0.5 Mev per centimeter of layered material. For Be, with $l_1 = 3.24 \times 10^{-2}$ and $\alpha = 1$ we find 9.23×10^{-2} photons with energies greater than 0.1 Mev. This method can be used to detect particles over a wide energy range since the detection of the resonance γ photons does not depend on absorption along the particle path.

5. EXPERIMENTAL BACKGROUND

The particle that produces the resonance radiation also produces a background radiation; this background must be taken into account, particularly in cosmic-ray work.

The particle will produce δ electrons in the layered medium and these electrons produce bremsstrahlung in coming to rest in the medium. The number of γ photons produced by the δ electrons per g/cm^2 of the layered medium is

$$N_{\delta\gamma} = \iint_{\varepsilon E_\gamma} R(\varepsilon)\, N_\delta(E_0, \varepsilon)\, d\varepsilon \cdot N_\gamma(\varepsilon, E_\gamma)\, dE_\gamma;$$

$$N_\delta(E_0, \varepsilon)\, d\varepsilon = 2\pi \frac{N}{A} Z r_e^2 m_e c^2 \frac{1}{\beta^2} \frac{d\varepsilon}{\varepsilon^2},$$

$$N_\gamma(\varepsilon, E_\gamma)\, dE_\gamma = \frac{4}{137} \frac{N}{A} Z^2 r_e^2 \ln(183 Z^{-1/3}) \left(\frac{m_e c^2 + \varepsilon}{\varepsilon}\right) \frac{dE_\gamma}{E_\gamma}. \tag{5.1}$$

The quantity N_δ is the number of δ electrons with energy ϵ that produce particles with energy E_0 in 1 g/cm^2 of material; $N_\gamma dE_\gamma$ is the number of γ photons with energies E_γ radiated by an electron with energy ϵ per g/cm^2 of material;

$R(\epsilon)$ is the range of an electron with energy ϵ, as given by empirical formulas[7].

In Table III we show the quantity $N_{\delta\gamma} \times 10^2$ for different materials for the case where the energy of the bremsstrahlung γ rays is greater than a given E_γ. The bremsstrahlung produced by the particle itself (not the electron) is negligibly small. Table III can be used to estimate the energy generation in a proportional counter (the first method in Sec. 3) due to bremsstrahlung of the particle and the δ electrons. This background is 0.5 % of the resonance radiation.

The number of background photons in the characteristic-radiation method (Sec. 4) is approximately 4×10^{-2}.

The background radiation is more noticeable in the Compton scattering method. Optimum conditions obtain when $\alpha = 3 - 5$, in which case the number of resonance radiation photons per centimeter of layered material is a maximum. Under these conditions the background radiation is 10 % for Be but as high as 150 % for Al.

The δ electrons produced in the layered medium by the particle can escape and be recorded by the detectors intended for recording the γ radiation. The number of δ electrons escaping from the layered material can be computed from the expression:

$$n_\delta = \int_\varepsilon R(\varepsilon)\, N_\delta(E_0, \varepsilon)\, d\varepsilon. \tag{5.2}$$

The number of δ electrons with energies greater than ϵ escaping from a layered material with a thickness of 10 g/cm^2 is given below:

E_γ, Mev:	0.01	0.05	0.1	0.25	0.5	0.7	1	2	6	10	20
n_δ:	0.216	0.212	0.200	0.192	0.180	0.170	0.160	0.130	0.094	0.075	0.037

The δ electrons can strike the detectors that are used for recording the γ photons. The geometry of the instrument can be selected to avoid this background. A better way of avoiding effects due to δ electrons is to locate the layered medium in a magnetic field that "ejects" δ electrons.

The energy generated by δ electrons in a proportional counter (Sec. 3) is

$$E_\delta = \int_\varepsilon \left(\frac{d\varepsilon}{dx}\right) [R(\varepsilon)]^2 N_\delta(E_0, \varepsilon)\, d\varepsilon, \tag{5.3}$$

where $(d\epsilon/dx)$ is the ionization loss of δ electrons with energy ϵ per g/cm^2 of material. The quantity E_γ is 15 — 20 % of the energy generated by the particle in a proportional counter filled with Xe (1.39×10^{-2} g/cm^2).

A particle passing through a gas absorber (characteristic-radiation method) can generate characteristic radiation directly. The number of such characteristic-radiation background photons per g/cm^2 of the gas absorber is

$$n_n = \frac{N}{A} \int_{E_K}^{E_0} \sigma_K(E_\gamma)\, N(E_\gamma)\, dE_\gamma, \text{ where } N(E_\gamma)\, dE_\gamma$$

$$= \frac{2}{137\,\pi} \ln(E_0/E_\gamma)\, dE_\gamma/E_\gamma \tag{5.4}$$

is the number of pseudophotons with energies E_γ for a particle with energy E_0 (Weizsäcker-Williams method) and $\sigma_K(E_\gamma)$ is the photo-effect cross section in the K-shell.[5] The quantity $n_n = 5 \times 10^{-2}$ if the amount of gas absorber (Xe) used in the experiment is 5.4×10^{-2} g/cm^2.

Table III

E_γ, Mev	Be	Polyethylene	Al
0.01	3.00	1.66	15.5
0.05	2.24	1.20	11.3
0.10	1.54	0.83	7.7
0.20	1.31	0.71	6.6
0.40	1.06	0.57	5.3
0.70	0.9	0.48	4.5
1.0	0.7	0.42	3.9
2.0	0.6	0.31	1.5

δ electrons with energies of 0.1 Mev or greater also produce background characteristic radiation. The number of such photons is less than 10^{-2}.

6. DETECTION OF COSMIC-RAY PARTICLES

The use of resonance radiation for the detection of charged cosmic-ray particles is made difficult only by the fact that it is necessary to distinguish high-energy particles against a strong background of low-energy particles.

Muons with energies of 10^{11} ev and higher in cosmic rays can be detected by the energy-generation method if two units are connected in coincidence (taking account of ionization fluctuations). When the characteristic radiation method is used it is necessary to detect 3 — 4 characteristic photons simultaneously; thus this technique can be used to detect μ mesons with energies of approximately 5×10^{11} and higher.

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