transition curves that bursts exhibit a maximum frequency at a thickness of shielding material equivalent to about 7 radiation units. These experiments are in progress with a 12-cm iron shield (about 7 radiation units).

[1] M. Schein and P. S. Gill, Rev. Mod. Phys. 11, 267 (1939).
[2] R. F. Christy and S. Kusaka, Phys. Rev. 59, 414 (1941).
[3] R. E. Lapp, Phys. Rev. 64, 129 (1943).

On the Spin of the Mesotron from Burst Measurements

R. E. Lapp
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
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In an accompanying Letter,[1] it has been pointed out that the large bursts observed under thick (i.e., 20 radiation units) shields of heavy material are chiefly produced by mesotrons. The contribution of *A* showers to these bursts is of the order of 4 to 7 percent of the total burst frequency and for the purposes of this discussion, can be neglected. Through the generous cooperation of Dr. Jno. A. Fleming of the Carnegie Institution, the extensive burst data obtained at the Cheltenham Cosmic-Ray Station (72 meters elevation) were made available to the writer. These data were obtained with a Carnegie model C ionization chamber shielded with a uniform layer of lead shot equivalent to a solid 10.7-cm lead shield. From an analysis of the data, an integral size-frequency distribution curve was constructed as shown by the experimental points in Fig. 1. The large amount of data available at Cheltenham allows for a small statistical error for bursts containing even 1000 or more particles; the accuracy of the experimental points is illustrated by the small statistical error drawn for each point. Here the absolute burst frequency N (number of bursts greater than size S per square cm per sec.) is plotted against the product βS where β is the critical shower energy characteristic of the shielding material, and S is the size of the burst in number of particles. On the same graph, three additional curves have been plotted; these are the theoretical curves for burst production by spin 0, $\frac{1}{2}$, and 1 mesotrons, respectively, as calculated by Christy and Kusaka.[2] It is seen that the experimental data are apparently in excellent agreement with the theoretical spin 0 curve. However, certain factors[3] which enter into the theory possibly introduce an uncertainty into the theoretical results so that it is not certain at present whether spin $\frac{1}{2}$ can be eliminated from consideration. For example, the present agreement between theory and experiment is obtained on the basis of an assumed mesotron mass of 177 m_e (m_e=mass of the electron); however, calculation shows that the mesotron mass of 230 m_e would yield a theoretical curve for spin $\frac{1}{2}$ which would be in fair agreement with the burst data.

While it does not seem possible to distinguish between spin 0 or $\frac{1}{2}$ on the basis of the present data, it is possible to state that the existence of a spin 1 mesotron at sea level is definitely ruled out by the experimental evidence. The marked increase in frequency of large bursts as a function

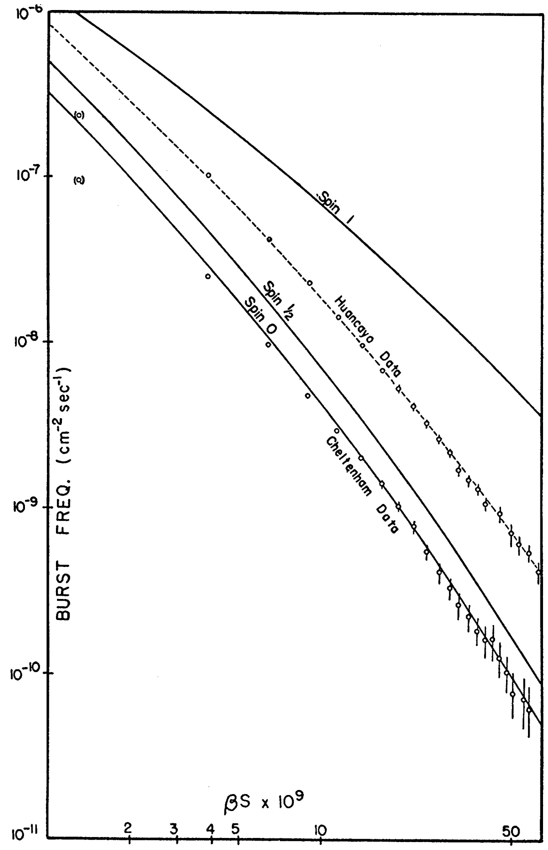

FIG. 1. Integral size frequency distribution curves. The burst frequency per square cm per second is plotted against the product of S where β is the critical shower energy of the shielding material, and S is the number of particles in the burst. The curves labeled spin 0, $\frac{1}{2}$, and 1 are the theoretical curves for burst production by mesotrons as given by Christy and Kusaka.

of altitude has been pointed out by Schein and Gill.[4] An analysis similar to that obtained from the Cheltenham burst data has been carried out for the burst data obtained at the Carnegie station at Huancayo, Peru (3350 meters). From the analysis a size-frequency distribution curve was plotted as shown in Fig. 1. Since the mesotrons giving rise to the bursts under thick shields at Huancayo were due to mesotrons of the same kind as are present at sea level, there should be no increase in the burst frequency with increasing altitude, for the high energy mesotrons are absorbed very little in traversing the atmosphere between Huancayo and sea level and are therefore just as numerous at sea level as at high altitude. There are two explanations possible for this observed increase with altitude. The first and more probable explanation is that at high altitude the cores of *A* showers (extensive atmospheric showers) penetrate 12 cm of lead and produce the majority of these bursts. This explanation is given additional credence by the evidence presented in the accompanying letter. Furthermore, the marked increase of *A* showers with altitude as found by Auger and Hilberry indicates that the increase in burst frequency could be due to this phenomenon. The other explanation[5] is that spin 1 mesotrons are present at higher altitudes in addition to spin $0-\frac{1}{2}$ mesotrons, and these give rise to the observed bursts. One assumes that the spin 1 mesotrons are of the fast decaying type, and only the highest energy ones reach sea level.

[1] Phys. Rev. **64**, 254 (1943).
[2] R. F. Christy and S. Kusaka, Phys. Rev. **59**, 414 (1941).
[3] This point is discussed in an accompanying Letter to the Editor by S. Kusaka, Phys. Rev. **64**, 256 (1943).
[4] M. Schein and P. S. Gill, Rev. Mod. Phys. **11**, 267 (1939).
[5] H. Snyder, Phys. Rev. **59**, 1043 (1941). R. F. Christy and J. R. Oppenheimer, Phys. Rev. **60**, 159 (1941).

The Effect of Radiation Damping on Burst Production

SHUICHI KUSAKA
Department of Physics, Smith College, Northampton, Massachusetts
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IN a recent paper Chakrabarty[1] has repeated the calculation of Christy and the present author[2] on the frequency of burst production by mesons and concludes that the comparison with the experimental data shows that the meson has spin 1, in contradiction to our result that the spin is 0 or 1/2. He states that the reasons for the different conclusion obtained are (1) the difference in the form of the fluctuation assumed, (2) the rough values used for the average number of particles produced in a cascade shower by an energetic electron or photon, and (3) the consideration of the effect of radiation damping on the cross section for bremsstrahlung of spin 1 mesons.

Chakrabarty used the Poisson distribution in preference to the fluctuation formula obtained on the Furry model which we used, and the recent work of Scott and Uhlenbeck[3] indicates that the former is nearer the truth. However, this point does not introduce any appreciable difference since we found that the effect of the fluctuation on the frequency of burst production on our model is to give just about twice as many bursts as calculations based on the assumption of no fluctuation. The Poisson distribution gives smaller fluctuations than the Furry model, and hence it would give results intermediate between the two. Moreover we recognized the fact that the Furry model gave too great a value for the fluctuation and corrected for this by reducing the burst production probability by a factor of $\sqrt{2}$. Thus the difference introduced by the use of the Poisson distribution should at most be a factor of about $\sqrt{2}$.

The second difference is due to the fact that we used Serber's[4] calculation on the cascade theory while Chakrabarty used the recent results obtained by Bhabha and himself.[5] The latter gives for the average number of particles a value smaller than the former by a factor ranging from 1.5 to 2.1 for initial energy between 10^{10} and 10^{12} ev.

Most of the deviation between the two calculations arises from the third difference. Chakrabarty based his calculation on the formula for bremsstrahlung cross section of spin 1 meson with radiation damping obtained by Wilson,[6] but it has now been found that this formula is in error, and hence his conclusions are invalid.

Formula (52) in Wilson's paper for the cross section for scattering of light quantum by a meson with spin 1 initially at rest is incorrect and should read instead[7]

$$\varphi_0=\frac{5\pi}{36}\left(\frac{e^2}{\mu}\right)^2\frac{k_0}{\mu}\ (k_0>>\mu),$$

where k_0 is the initial energy of the light quantum. When the calculation of the cross section for bremsstrahlung is carried out in the same way by using the method of the virtual quanta and Wilson's approximate way of taking into account the effect of radiation damping, the result is

$$\varphi(\epsilon)d\epsilon=\frac{5Z^2\alpha}{144}\left(\frac{e^2}{\mu}\right)^2(2-2\epsilon+7\epsilon^2)Gd\epsilon,$$

where $\alpha=1/137$ is the fine structure constant, ϵ is the fraction of the initial energy, E_0, of the meson emitted in the form of a light quantum, and

$$G=\int_1^{\mu R}\frac{dy}{y}\int_{y\mu/E_0}^{\infty}\frac{dx}{x+(5/288)\alpha^2},$$

R being $a_0Z^{-\frac{1}{3}}=(\alpha mZ^{\frac{1}{3}})^{-1}$ and where we are using units in which $\hbar=c=1$. The effect of the radiation damping appears in the term $(5/288)\alpha^2$ in the denominator. It is negligible for energies such that $(E_0/\mu)^2<<(288/5\alpha^2)$, and its effect becomes appreciable only for energies of the order $E_0/\mu\sim 10/\alpha=1370$. In the limit of very high energies, $E_0/\mu>>10\mu/\alpha^2mZ^{\frac{1}{3}}$, the cross section becomes

$$\varphi(\epsilon)d\epsilon=\frac{\pi}{12}\left(\frac{5}{2}\right)^{\frac{1}{2}}Z^2\left(\frac{e^2}{\mu}\right)^2(2-2\epsilon+7\epsilon^2)\log\left(\frac{137\mu}{Z^{\frac{1}{3}}m}\right)d\epsilon.$$

It must be noted here that there is an uncertainty in the numerical coefficient of the order unity due to the averaging over the angles which was necessary in order to compute the effect of the damping. The above result is essentially the same as that obtained by Gora,[8] and agrees with the general conclusions of Landau[9] and Oppenheimer[10] that the cross section obtained by the perturbation theory should be valid up to energies of the order 137μ. Hence our calculation in which we cut off the frequency integral at 137μ should at least give the lower limit of the burst production by spin 1 mesons.

The improvements in the treatment of the fluctuation and in the cascade theory mentioned above should change our results at most by a factor of 3, and our conclusion that the spin of the meson can be 0 or 1/2, but not 1 is still valid. Comparison of Chakrabarty's results for spin 0 and 1/2 with ours shows that his theoretical burst frequencies are smaller by a factor of about 5. We both used the same value for the meson mass, 177 m, but Chakrabarty fails to mention the value he used for β, the critical energy in the cascade theory, and the additional difference may be due to this.

It should be emphasized again that these calculations for the burst production give the *minimum* estimates in which only the electromagnetic interaction of the meson with the atomic nuclei is considered. Hence it is possible to rule out particles for which our calculations give burst production frequencies greater than the observed values,