Chapter 2.

THE BREMSSTRAHLUNG SPECTRUM

Summary:

The energy spectrum of bremsstrahlung photons has been obtained for primary electrons of $6 \times 10^{10}$ eV and $5 \times 10^{11}$ eV. It has been shown that up to these energies, no influence of the density of the medium is observable on the cross section for the production of photons of energy $> 30$ MeV. The results are in agreement with Bethe - Heitler theory and do not give evidence on the validity of Landau & Pomeranchuk modifications. No conclusions beyond $5 \times 10^{11}$ eV can be drawn from this work.
INTRODUCTION

Apart from predicting the average number of shower particles present under certain thickness of the medium, the cascade theory foresees the energy distribution of the electrons. The energy of the electrons when at a certain depth measured with respect to the origin of the cascade, can be measured and the energy spectrum compared with the theory. For the present data, such a comparison has been made in Fig.8. The agreement of the theory and the experimental data increases confidence in the method of energy estimation and on the validity of the theoretical foundations.

During recent years a new aspect of the problem evolved from the theoretical predictions of the Russian physicists Landau and Pomeranchuk (LP.53). It has been shown that during bremsstrahlung by far relativistic electrons ($E \sim 10^{13}$ eV), each stage of radiation emission cannot be considered independent of the previous occurrences. This arises due to coincidence between the directions of the electron and the photon and due to the multiple scattering of the electron on this path. This effect decreases the cross section for the emission of low energy photons in condensed media and is a fact open to experimental confirmation. A further enhancement of the suppression of very soft quanta has been attributed by Ter-Minasyan (TM.54) to the polarization of the medium, which again is density dependent.

Mgdal (Mi.56) has derived the modified expressions for the cross sections for bremsstrahlung and pair production. According to him the intensity of the
radiation varies as \((\frac{x_0}{\lambda_0})^{1/2}\) instead of \(\frac{d(E)}{x_0}\) as it does on the Bethe - Heitler theory, (abbreviated hereafter as B-H theory). The atomic density of the medium is involved in the expression for \(\lambda_0\), the radiation length (for definition, see Eq.1, Appendix B). It has been shown that for lead as an example, a 30% deviation from the B-H theory can be observed for electrons of \(\sim 10^{13}\) eV. At lower energies \(\lesssim 10^{11}\) eV, the relations derived by \(\delta_4,\delta_6\) transform into the B-H formulae, so that the effect is observable only for the cascades initiated by extreme relativistic electrons. After Ter-Avalezian (Tu.64) account has been taken also of the polarization of the atoms of the medium, in which case the dependence is as \((E_{\gamma}^2/E_{\gamma}^N) d(E_\gamma)/x_0\), where \(N\) is the atomic density.

Curves suitable for comparison between the experiment and modified theory (abbreviated hereafter as L-P-T theory) have been given by Varfolomeev et al (VGGM.C.58; VGGM.C.60) who have also made Monte-Carlo calculations on the cascade growth, using both the B-H variant and the L-P-T modifications. The deviations become measurable for pairs of energy less than \(10^9\) eV observed in cascades of primary energy \(10^{12}\) eV, whereas for primary energy of \(10^{11}\) eV, it becomes measurable for secondary pair energies less than \(10^7\) eV.

Nuclear emulsions have a density of \(\sim 4\) g cm\(^{-3}\) and electromagnetic cascades initiated by isolated electrons or photons and by the photons from the decaying \(\nu^\circ\)-mesons created in extremely high energy interactions are readily available. A number of attempts have therefore been made
to check the theoretical predictions. The present work as well as that of the other workers shall be discussed presently. Before that is done it appears essential to consider the limitations of the experimental method as applied to this problem.

2. LIMITATIONS IN THE EXPERIMENTAL TECHNIQUE

The experiment consists of determining the energies of the primary and the secondary pairs. It is essential that all the pairs on which the results are based, should be obtained with reasonably good and uniform detection efficiency.

a) Energy Estimation

The energy of the primary pairs can be determined, preferably by methods independent of the cascade development. This can be done by finding the suppression of ionisation near pair origin or from the opening angle of the pair. The cascade development may also be employed to find the primary energy by making use of the results on the longitudinal growth according to the cascade theory or from the lateral spread of the shower. These methods have been discussed in Appendix (C). The latter methods, utilising cascade development, are subject to the uncertainty arising due to fluctuations in the individual cascades. The error arising on account of this can be overcome by collecting together cascades of about similar characteristics. The advantages of this procedure have already been discussed in the previous chapter.

The energy of the secondary pairs can be determined from multiple Coulomb scattering of the electrons or from the true opening angle of the pair. For the energy region
under question, both these methods are equally reliable.

b) Detection Efficiency

As mentioned before, the problem of maintaining reasonably good and uniform detection efficiency is very important. The results on the subject are based entirely on the presence or absence of a few low energy pairs. The theoretical calculations on the cascade theory are carried out under the so-called, Approximation A, i.e., the ionization loss of the electron is neglected in comparison with the radiation loss and no account is taken of the loss of photons by Compton scattering. (For an outline of the theory see Appendix B). The critical energy in emulsions (see page 44) is \( \sim 40 \) Mev. For energies small compared to this, Compton effect and collision processes affect the production and absorption of shower particles. To assume complete screening, use is made of the asymptotic values for the cross sections, restricting the energy to values \( \gg 137 \mu Z^{-1/3} \) (in here is the electron rest mass). For nuclear emulsions these two conditions restrict the comparison of the theory and the experiment to be made for secondary energies \( > 30 \text{ MeV} \). The average opening angle of the pairs of energies less than this introduces an experimental bias against their detection in comparison to pairs of high energies for which the track in the initial stage is twice thick as compared to that of a single electron, as it would appear if the electron were alone. The situation on the detection efficiency worsens in the case of the high disparity pairs, for which only one of the electron tracks is straight.
and so easily detectable. Apart from all these factors, the detection efficiency is dependent upon the experimental conditions of observation such as the steepness of the event, and the clarity of the emulsion. In view of these factors it is considered advisable to restrict the comparison of experiment with theory for energies \( \geq 30 \text{ MeV} \).

c) Distinction between pairs of different generations.

There is another factor that influences the conclusions on the subject, as follows: The lack of low energy pairs predicted on the L-P-T theory is strongly dependent on the primary energy, so that one would like to take account of only the first generation pairs due to bremsstrahlung from the primary electron and not those created from the secondary electrons. This distinction between the pairs of the various generations is not straightforward and is highly subjective. This classification of the observed pairs has been attempted by some workers \( \text{(BC, } 59; \text{ FFTPSV, } 59) \). In such a procedure there is a possibility of introducing a bias towards the removal of more low energy pairs than the high energy one's.

In the light of the considerations given above, data on the subject were collected from the cascades available and is presented in the next section.

3. EXPERIMENTAL DATA.

17 cascades were selected out of our experimental material. The criterion for selection were good conditions of experimental observation (such as steepness of the event, clarity of the emulsion and straightforward track
tracing). For these cascades detailed measurements were made on pairs of energy less than 1.6 GeV. The energies of most of these pairs were determined both by multiple coulomb scattering measurements and by utilising the observed opening angle of the pair. The two measurements are shown to have good agreement (see Fig.13, Appendix C), the results been used to check also the energy partition between the two electrons of each pair (for details, see Fig.6 in Appendix A). The distribution of the cascades was as follows:

- 9 originating from a single pair,
- 5 initiated by a single electron entering the stack,
- 3 associated with a nuclear disintegration produced by a singly charged particle of $\sim 10^{13}$ eV.

In every case the development was normalised to a single electron and the cascades grouped into two bunches as: High Energy (650, 625, 550, 500, 600, 475, 350, 325) and Low Energy (250, 225, 200, 125, 50, 50, 40, 40, 40) groups. The figures in the brackets give for each cascade the energy per electron in GeV. In the case of cascades initiated by a pair, the energy was assumed to have been equipartitioned between the two electrons. These energies were in most of the cases determined by the application of different procedures and the most probable value estimated. The individual errors in the energy estimation are expected to have been smoothed out to some extent, as the cascades were collected into two groups. The data may be subjected to criticism on account of some of the cascades having been initiated each by a single electron.
It having been found that the energy obtained from cascade development is in agreement with the estimates made by the use of other methods, the error arising from the use of these cascades is small.

In order to ensure uniformity of the detection efficiency over the entire energy region, the electron pairs of energy less than 30 MeV were excluded. It was found that for energies > 30 MeV, the detection efficiency in the present experiment was ~ 98 %. (see page 40). The resulting energy spectrum up to a distance of 1.5 r.l, has been plotted in Fig. 3, (a) & (b) for the two energy intervals. The expected curves for the Bethe-Heitler and Migdal calculations have been included for comparison. No attempt to separate the pairs of different generation was made. In order to decrease the influence of further generations, the results were compiled only for the first 1.5 length.

From the figure, it may be seen that up to primary electron energy of $5 \times 10^{11}$ eV, and subject to the experimental errors, a measurable departure from the B-H theory is not observable. Since the energies of this work were not higher than $5 \times 10^{11}$ eV per electron, no indication on behaviour at higher energies could be obtained.

4. DISCUSSION.

In view of the limited statistics available to the individual workers, it appears useful to discuss all the results known on the subject. Varfolomeev et al (VGGMESC 58, VGGMRC.59) have studied the spectra for primary energies from $10^{11}$ eV to $10^{13}$ eV, and secondary pair
Fig. 3. The Bremsstrahlung Spectrum:

Energy spectrum of the electron pairs observed over the first 1.5 radiation length from pair origin. The lower limit for acceptable pair energy was set at 30 MeV.

Curve (a) for 9 cascades of median energy 500 GeV/electron
Curve (b) for 8 cascades of median energy 50 GeV/electron
energies up to 1.6 MeV. They have found a significant departure from the B-H theory and agreement with the L-P-T considerations. It is worth mentioning that their lower limit of ~1 MeV for the secondary energies is too low to guarantee a uniform detection efficiency over the entire range. In view of this it is not fair to consider their measurements as having established the existence of the effect.

The second investigation is that of the Polish group (BCW.59) who have studied four photon-initiated cascades out of which three are associated with a high energy disintegration and the fourth is that of MSW.54. The mean energy per electron is ~500 GeV, and they have attempted at the separation of the pairs of the first generation from the rest. The lack of low energy pairs may well be attributed to be due to the bias introduced against detecting the low energy pairs. Their energy region is the same as of the present investigation and since the present statistics was relatively larger, with no significant discrepancy, it may be concluded that the effect if present is not at least of the order suggested by the L-P-T theory.

There is yet another work of the Czeck-Hungary group (FPT/MV.SV.60) in which they have studied the energy spectrum up to 1.5 radiation length. The primary cascade energy is $10^{12}$ eV per electron. Though this energy is fairly high, in fact higher than the energies of BCW.59 and of the present work, no departure has been noted. The authors attempted at the separation of the pairs
of various generation, still no divergence from the conventional theory was observed.

Fowler et al (FPP, 59) have tackled the problem with a different approach. The method is based upon measuring the average distance of materialisation of the first pair for two groups of cascades of different energies. From the distribution of the distance and the mean value for the two groups of energy $10^{11} \text{ eV}$ and $10^{12} \text{ eV}$, they found for the higher energy a departure from the B-H theory and agreement with the L-P-T results. Their energy of $10^{12} \text{ eV}$ is much higher than most of the other investigators and in view of the large statistics gives evidence on the existence of the effect.

5. CONCLUSIONS.

In view of the present investigation and of the other workers, it may be concluded that the decrease of cross section for the low energy bremsstrahlung is not appreciable for primary energies up to $5 \times 10^{11} \text{ eV}$, whereas it would be expected to be present according to the L-P-T theory. There is an indication that the departure is measurable at primary electron energy of $\geq 10^{12} \text{ eV}$. It is only with further work that this may be confirmed.