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Interaction of high energy muons in association with EAS, with rock and lead

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Abstract. An investigation on the interaction of high energy muons, associated with EAS and having energies greater than several hundred GeV, has been carried out at Kolar Gold Fields. A visual detector consisting of neon flash tube hodoscope has been used together with a scintillator detector to observe the muons and accompanying showers at the underground level.

It has been found that nearly 90% of the showers observed at the underground level are generated in course of pure electromagnetic interactions of the muons with the matter traversed by them. The observed number of the showers is found to be consistent with the expected number calculated using the cross-sections for knock-on, bremsstrahlung and direct pair production processes.

Rest of the observed showers do not appear to fit in the pure electromagnetic interaction scheme. Various possible production processes for these events have been discussed. Considering these events to be due to photonuclear interaction of muons in the rock, the observed number leads to a production cross-section σ_{μ} ($\gtrsim$ 25 GeV) $\simeq (1\cdot 6 \pm 0\cdot 75)\, 10^{-29}$ cm^2/nucl.

1. Introduction

In recent years, a number of investigations have been carried out to study the interaction of muons with matter. However, only a very few experiments have so far been carried out to investigate the detailed characteristics of such interactions for muons with energy greater than several hundred GeV. It is important to get more information about the interactions of muons occurring at such ultra high energies. Such a study may reveal whether these high energy muons undergo any anomalous interaction other than the known interactions, *e.g.*, pure electromagnetic interactions or photo-nuclear interaction through virtual photon beam of fast muons, as suggested by Williams (1933) and Weizsacker (1934).

In the present experiment, at the vertical depth of 580 m.w.e., we have investigated various interactions of muons associated with ground level Extensive Air Showers (EAS) of size in the range 5×10^3 to 5×10^5 particles. This experiment was carried out at KGF (15° N, 920 gm/cm^2) in collaboration with the Tata Institute of Fundamental Research (TIFR), Bombay.

2. Experimental set-up

The apparatus at the vertical depth of 580 m.w.e. consisted of a scintillator of area $1\cdot 5$ m $\times$ $1\cdot 5$ m and a neon flash tube hodoscope placed under the scintillator covering an area $1\cdot 2$ m $\times$ $1\cdot 2$ m. Neon flash tubes (n.f.t.) were in two trays,

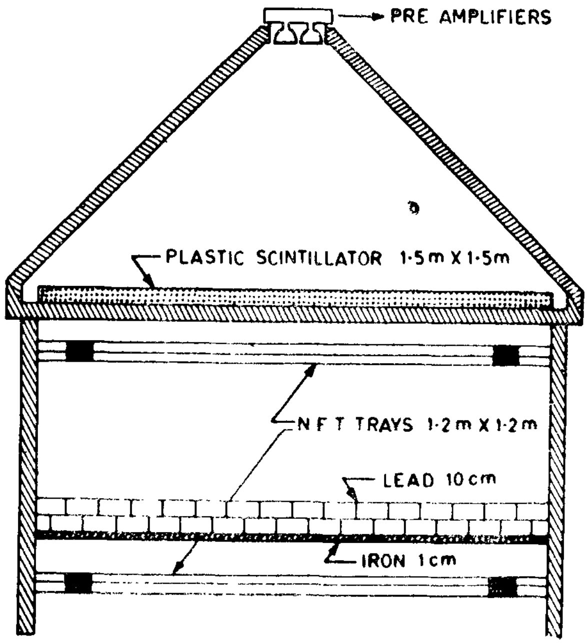

Figure 1. Underground muon detector.

vertically separated by 38 cm air, 10 cm lead and 1 cm iron. Each tray consisted of four horizontal layers of the flash tubes (0·98 cm dia), placed lengthwise in East-West direction. The lead absorber extended 15 cm on both sides and 30 cm at the back of the lower flash tube tray (figure 1). The triggering of flash tubes was initiated by the coincidences between the underground (U.G.) scintillator detector and the EAS pulses from the ground level array.

The air shower array at the ground level is part of TIFR air shower project at KGF. The centre of the EAS array is $\simeq$ 70 meter South-West of the vertical projection of the underground detector. Because of such a geometrical alignment with respect to the centre of the EAS array, the U.G. detector was mostly triggered by the particles at 20°–30° to the vertical. Thus the effective depth of investigation in the present case is 650 m.w.e. instead of the vertical depth of 580 m.w.e.

3. Analysis of experimental data and discussion

In an earlier paper (Chowdhuri and Saxena 1973) we have shown that except for a few events, most of the U.G. showers were generated in course of pure electromagnetic interactions of muons with the surrounding matter. In the present report, therefore, we classify all the observed events broadly into two groups: Group A showers, which are produced by electromagnetic interactions of muons either in the rock or in the lead absorber, and Group B showers, the events which do not appear to fit in the pure electromagnetic interaction scheme. Group A consists of three different types of showers. Type I showers were initiated in the rock, but the secondaries were absorbed in the lead absorber. Type II showers consist mostly of very dense and tight bursts which were also initiated in the rock but which spread out in traversing the lead absorber after further development and multiple scattering. Type III showers were produced and developed in the lead absorber by the single penetrating particles incident on it.

Group B includes very large showers, which were generated and reached nearly the stage of maximum development in the rock but which still continued their path through 18 radiation length of the lead absorber. In most of the cases more than 3 particles were detected under the lead absorber.

Relevant data for the Group A and Group B showers are given in tables 1, 2 and 3. Total effective running time of the experiment is $5\cdot 38 \times 10^6$ sec., stretching over a duration of $1\frac{1}{2}$ years.

3.1. *Group A showers*

Table 1 shows all showers classified under types I and II. In type I there are 23 showers with spread $\leqslant$ 60 cm at the upper n.f.t. tray and number of particles $\leqslant$ 10. They were produced by fast penetrating particles in the surrounding rock, the secondaries of which must be low energy electrons which could not penetrate 10 cm lead absorber. The spread of the showers under the rock and the number of particles in the showers suggest that the showers were at the maximum stage of the cascade development. We have estimated the expected number of showers

Table 1. *Group A—Showers. Showers initiated in the rock*

TYPE I—EVENTS

No. of events	Linear spread under rock	Description
23 ..	$d \leqslant 60$ cm $\langle d \rangle = 31\cdot 13$ cm	Number of single tracks, excepting 2, less than 10; $\langle N \rangle = 8$; accompanied by small dense bursts in some cases; spread 6–9 cm
2 ..	$d > 90$ cm $\langle d \rangle = 103$ cm	$>$ 10 single tracks $\langle N \rangle = 16$
Total number of events		25
Number of single muons		1400

TYPE II—EVENTS

No. of events	Linear spread: rock	Linear spread: lead	Description
1 ..	8 cm	20 cm	Under rock dense burst, individual tracks cannot be identified. Under lead—4 to 7 single tracks, accompanied by small dense bursts of spread 5 to 8 cm in some case.
1 ..	6 cm	17 cm	
1 ..	3 cm	17 cm	
Total number of events 3			

with $\leqslant$ 10 particles to be of the order of 15, taking account of knock-on, bremsstrahlung and direct pair production by the muons associated with ground level EAS, transferring 1 GeV energy in the course of interaction. During the same interval of time, 1400 single penetrating particles were observed. The expected value has been calculated using the cross-section for knock-on, bremsstrahlung and direct pair production given by Rossi (1952) and folding the energy spectrum of the muons, associated with EAS, with the cross-section. The differential energy spectrum used for this purpose is given by

$$n_\mu (E_\mu)\, dE_\mu = A E_\mu^{-\gamma-1} dE_\mu \tag{1}$$

The value of γ as given by Greisen (1960), Sivaprasad (1970) (also Sreekantan 1971), Saxena (1972) and Erlykin *et al* (1973) are $1{\cdot}37$, $1{\cdot}35 \pm 0{\cdot}15$, $1{\cdot}3 \pm 0{\cdot}16$ and $1{\cdot}48 \pm 0{\cdot}19$ respectively. We have used $\gamma = 1{\cdot}37$ as this is nearly the mean of different observed values.

The expected probability for an electromagnetic interaction with cross-section $\phi\,(E_\mu, \epsilon)$ and energy transferred $E_{\min}$, can thus be written as

$$\int_{E_{\min}}^{E_{\max}} E_\mu^{-\gamma-1} \int_{E_{\min}}^{E_\mu} \phi\,(E_\mu, \epsilon)\, d\epsilon\, dE_\mu \Big/ \int_{E_{\min}}^{E_{\max}} E_\mu^{-\gamma-1}\, dE_\mu \tag{2}$$

for interaction per particle per unit radiation length. The value of $E_{\max}$ is taken as 10^4 GeV, determined from the energy of the accompanying EAS.

Type II showers were in the form of very dense and small bursts, initiated in the surrounding rock, which were found to spread out 3 to 4 times after traversing 18 radiation length of the lead absorber; the tracks due to dispersed single particles can also be idêntified under the lead absorber. This behaviour of the showers can be explained by considering them as young electron-photon cascades, which were generated by muons in the surrounding rock within a few radiation length above the U.G. detector. The showers after further development and multiple scattering in nearly 18 radiation length of the lead absorber, were found to emerge with larger width. The expected probability of such events is estimated to be $\sim 10^{-3}$ per muon for the muons associated with EAS, transferring about 30 GeV energy in the course of electromagnetic interaction in the rock within 3 radiation length above the detector. From table 1, we find the occurrence of such showers to be $(2{\cdot}23 \pm 1{\cdot}2) \times 10^{-3}$ per muon. The estimated value is therefore within the experimental error of our observed result.

On the other hand, the third type of events (type III) were found to be produced in the lead absorber by the single penetrating particles emerging from the rock above the detector. Table 2 shows details of the detected events. These events, excepting 9 cases, are all very dense and tight bursts in which tracks due to single particles could not be identified. These bursts (more than 75% of the total number) were most probably generated by the single muons in the last few radiation lengths after traversing a greater part of the lead absorber. Another noticeable feature is that in 22% of the events track due to single muons above the lead abosorber was not visible. Probably, in these cases the shower producing single particles were incident on the lead absorber either from the sides or from the back of the detector in such area and inclination that they were unable to strike the upper

Table 2. *Group A—Showers. Type III events due to interaction in the lead absorber*

No. of events	Linear spread under lead	Description
27 ..	$\leqslant 25$ cm	Dense bursts under lead; average projected angle of incident track $\langle \theta \rangle = 12°$; in 5 cases single track is not visible above the lead absorber
4 ..	> 30 cm	Dense bursts under lead; average angle of incident track $\langle \theta \rangle = 23°$
7 ..	$\leqslant 25$ cm	Showers with dispersed single particles. Number of tracks 6, average angle of incident track $\langle \theta \rangle = 10°$
2 ..	> 30 cm	Number of tracks 7–8
Total number of events		40
Number of single muons		1400

n.f.t. trays (only 3/5th of the total area was covered by the n.f.t. hodoscope). It seems most likely that most of these bursts are also electromagnetic cascades, generated somewhere inside the lead absorber and further multiplied before emerging from it.

We thus find that the showers which are included in Group A are mostly electromagnetic cascades at different stages of development, generated by fast muons either in the rock or in the lead absorber.

3.2. *Group B showers*

Table 3 shows 6 cases of the rock showers consisting of large number of particles, a few of which can be detected even under nearly 18 radiation length of the lead absorber. Actually under the lead absorber more than 3 particles were detected in all cases, excepting one in which only one small burst was observed (case V in table 3).

If these showers are electronic cascades produced in the rock by muons in pure electromagnetic interaction, then the particles detected under 18 radiation length of lead absorber must be at the tail end of the cascades after going through further development and absorption in it. However, the noticeable features of these showers are that the number of particles under the rock were generally >10 with linear spread > 70 cm at the upper n.f.t. tray; the spread even just under the rock cannot be less than 30–35 cm which is approximately of the order of Moliere length in the rock. The rock is about $1 \cdot 5$–$2 \cdot 0$ m above the upper n.f.t. tray. According to the electromagnetic cascade theory, all these features indicate that these showers were nearly at the maximum stage of cascade development when they emerge from the rock, and to initiate these showers then at least 20–25 GeV energy is necessary, which must have been transferred by the muons in the course of electromagnetic interaction.

We have estimated the expected value of this type of events per 1000 muons associated with EAS taking account of Bremsstrahlung, knock-on and direct pair

Table 3. *Group B—Showers*

Event	Description under rock: Total spread	Spread of accompanying bursts	Total No. of single tracks	Description under lead: Total spread	Spread of accompanying bursts	Total No. of single tracks	EAS Size*
	cm	cm		cm	cm		
I	119	22	30	38	6	6	$5 \cdot 15 \times 10^4$
II	93	nil	20	16	nil	4	$4 \cdot 05 \times 10^5$
III	85	6	15	7	nil	4	..
IV	70	6	15	25	nil	4	$9 \cdot 6 \times 10^4$
V	70	4	9	8	8	nil	$1 \cdot 04 \times 10^4$
VI	105	nil	9	10	nil	3	..

Total number of single muons = 1400
Total number of events = 6
Number of events per 1000 single muon = 4·28

* Information available from TIFR air shower experiment.

production. Following the formula given in eq. (2) the values turn out to be about 1·50 and 0·70 for energy transferred of the order of 25 GeV and 50 GeV respectively. These numbers are about 2–3 times smaller than our observed value. Further, since the average energy of the particles incident on the lead absorber are expected to be of the order of 50 MeV (the critical energy of electrons in rock), the range of showers in the lead absorber according to Bhabha and Chakraverty's cascade theory cannot be greater than '4' radiation length in lead. Thus the mean number of particles at a distance of 18 radiation length is expected to be zero, whereas in all these cases more than 3 particles were detected. Furthermore, it is also noticeable that in two events (I and V of table 3) the showers under the lead absorber were accompanied by very dense bursts of particles, which shows that these secondaries were generated within the last few radiation lengths, after traversing greater part of the lead absorber. Such rejuvenation is not expected to happen at the tail end of pure electromagnetic cascades.

It is, therefore, not possible to interpret these events as pure electromagnetic cascades generated in the rock, which were able to penetrate 18 radiation lengths of the lead absorber.

On the other hand, table 1 shows that in group A showers there are two events with average number of particles $\sim$ 16 and width $\geqslant$ 90 cm in the upper n.f.t. tray without any particle detected under the lead absorber. This agrees very well with the expected value, calculated on the basis of electromagnetic interactions due to muons in the rock, transferring about 25 GeV energy.

The possibility that these are side showers produced in e.m. interactions in the rock by the muons at larger inclination to the vertical ($\geqslant 60°$) so that they can trigger the lower n.f.t. tray without traversing the lead absorber is negligible; as both sides and the back of the lower tray were shielded by the lead absorber against the particles at inclination $\geqslant 60°$. Further the location of the surface EAS array from the U.G. detector was such that the possibility of muons accompanied by EAS entering from the front of the detector at a greater inclination is also negligible.

The possibility that these showers were due to double e.m. interactions by fast muons—one in the rock and the other in the lead absorber with the transferred energy of the order of 25 GeV and 100 MeV respectively—is also too small as the expected probability is only $\sim 0{\cdot}1$ per 1000 muons. Furthermore, in the present investigation we have observed only 2 cases per 1000 muons of small double knock-on showers (number of particles 3–4). In these cases the energy transferred was only a few hundred MeV in both the interactions. The occurrence of so many large double electron bursts during the same interval of time is, therefore, rather unusual.

Another possible interpretation for these events may be that these are nuclear showers produced in the rock by muons in photo-nuclear collision, in which charged and neutral pions and other interacting particles are created. These showers are able to continue their path through large thickness of matter by nuclear cascade process. Higashi *et al* (1961) in their plate cloud chamber experiment at 50 m.w.e. found some very large showers which penetrate 15 lead plates each 1 cm thick. Later Chin *et al* (1969) at 40 m.w.e. in a large calorimeter with liquid scintillators and spark chambers separated by iron and lead absorbers found that the shower curves were stretched even after 14 radiation lengths from the point of origin. The frequency and energy of these showers did not appear to fit the e.m. cascade theory. These events have much similarity with our observations.

The electromagnetic field of a high energy muon is equivalent to a beam of virtual photons. These virtual photons interacting with nucleons of the medium are able to generate nuclear showers. The cross-section for such production is given by

$$\sigma_\mu (E_\mu > E_c) = \int_{E_c}^{E_{max}} E_\mu^{-\gamma-1} \int_{E_c}^{E_\mu} \sigma_{ph} n_\mu (E_\mu, \epsilon)\, d\epsilon\, dE_\mu \Big/ \int_{E_c}^{E_{max}} E_\mu^{-\gamma-1}\, dE_\mu \quad (3)$$

where σ_{ph} is the photo-nuclear cross-section for real photons, $n_\mu (E_\mu, \epsilon)$ is the number of virtual photons with energy between ϵ and $\epsilon + d\epsilon$, associated with muon of energy E_μ. E_c is the minimum energy that can produce such a shower and is taken to be 25 GeV from the considerations of the energy of the accompanying electron cascade. $E_{max} \sim 10^4$ GeV as determined from the energy of the associated ground level EAS, and the differential spectrum of muons used for the calculations is same as given by eq. (1). Bezrukov *et al* (1972) from their observations at 316 m.w.e. underground have obtained a value of $(1{\cdot}1 \pm 0{\cdot}2) \times 10^{-28}$ cm²/nucl. for σ_{ph}. The value of σ_{ph} was found to be constant over the photon energy ϵ, in the range 25 GeV–100 GeV. In this experiment they detected nuclear showers produced by muons which were accompanied by neutrons. From an analysis of the data of an investigation in search of solar neutrinos at various depths down to 1080 hg/cm^2, Wolfendale *et al* (1972) have estimated the photo-nuclear cross-section. They also conclude that the value $\sigma_{ph} \simeq 10^{-28}$ cm^2 nucl and there is no evidence of any marked change in the value at least up to 100 GeV. The value of photo-nuclear cross-section $\sigma_{ph} \simeq 10^{-28}$ cm^2/nucl was also found from accelerator experiments up to 20 GeV at Stanford (Guiragossian 1969).

The value of photo-nuclear cross-section for virtual photons is considered to be of the order of that for real photons, because the two interaction cross-sections tend to become equal, as q^2 the square of 4-momentum transfer approaches zero. The effective value of q^2 was found to vary from 0·1 to 0·2 (GeV/C)^2 over the energy range of $\epsilon = 25$ GeV to 1000 GeV (Bezrukov *et al* 1972).

The virtual photon spectrum of Williams and Weizsacker, as given by Heitler (1954), is

$$n(E, \epsilon)\, d\epsilon = \frac{2\alpha}{\pi}\left(\ln \frac{E}{\epsilon} - 0{\cdot}38\right)\frac{d\epsilon}{\epsilon} \tag{4}$$

(W–W spectrum).

Assuming this spectrum, the expected cross-section for photo-nuclear interaction of muons σ_μ (from eq. 3) is estimated to be $\simeq 1{\cdot}25 \times 10^{-30}$ cm^2/nucl, whereas the estimated photo-nuclear cross-section 'σ_μ' for muons, ignoring the event No. V of table 3 and taking account of the detection efficiency of the neon flash tubes, is found to be of the order of $(1{\cdot}6 \pm {\cdot}75) \times 10^{-29}$ cm^2/nucl. The structure of the shower No. V, especially under the lead absorber, where only one small electronic burst was detected, is different from the other events of table 3. So, finally we decide not to include it with other events which may possibly be explained as nuclear cascades. Further in this calculations, as the showers are produced inside the rock, the ranges of secondaries cannot be determined unambiguously. This ambiguity in the range introduces a certain amount of uncertainty in the cross-section besides the statistical error. The cross-section σ_μ has been calculated following the method given by Barrett *et al* (1952). The mean range of the secondaries was taken as 300 gm/cm^2 of rock for the calculation. Thus the value of σ_μ based on the observation is found to be incompatible with the expected value obtained on the basis of the W–W spectrum, as given by Heitler (1954).

On the other hand using the modified virtual photon spectrum of Kessler and Kessler as given by Hayakawa (1969)

$$n(E, \epsilon)\, d\epsilon = \frac{2\alpha}{\pi}\left(\ln \frac{E}{m_\mu c^2} - 1\right)\frac{d\epsilon}{\epsilon} \tag{5}$$

(K–K spectrum)

the expected cross-section turns out to be $\simeq 1{\cdot}30 \times 10^{-29}$ cm^2/nucl. We have also used another spectrum for virtual photons given by Kessler and Maze (1957), taking account of the spin of muons. The expected value of σ_μ, in this case, also turns out to be $\sim 10^{-29}$ cm^2/nucl. Thus between W.W. spectrum given by Heitler and K–K spectrum our observations agree better with the latter.

Later two more rigorous expressions for virtual photon spectrum were given; one the so called DKMN spectrum by Daiyasu *et al* (1962) and the other by Hand (1963). To take account of the finite nuclear charge distribution they introduced some suitable form factor in the expression for the point charge nucleon. Higashi *et al* (1965, 1972) working at 50 m.w.e., Bezrukov *et al* (1972) for their experiment at 315 m.w.e. with underground cosmic ray muons, and McNulty and Jain (1969) with accelerator muons of energy 5 GeV, studied the behaviour of the nuclear showers by muons comparing all these various theories. The results obtained from the analysis of all these observations are rather contradictory. It is therefore still not very clear which expression will be most suitable to represent the virtual photon spectrum. However, both our observation and the Russian results (Bezrukov *et al* 1972) show that the expected values obtained using Heitler's formula are underestimated. The more rigorous treatments given by DKMN and Hand may be regarded as intermediate cases between the expressions by Heitler and Kessler. No attempt has been made to analyse the present experimental results using these two rigorous treatments, since the statistical accuracy of our data is not sufficient to yield any further definite information regarding the virtual photon spectrum by such analysis. To decide finally about the most suitable spectrum to represent the virtual photon field, better statistics is necessary.

The photo-nuclear cross-section obtained from the present investigation may be regarded as an upper limit, as it is possible that some of these events might arise out of fluctuation at the tail end of the showers in pure e.m. interaction, which may, in effect, increase the value of the cross-section. In this experiment with only a single block of lead absorber we could not get much information about the nature of the showers. So it is not possible to differentiate between the pure e.m. showers arising from the fluctuations and the nuclear cascades. The contribution due to these fluctuations has not been considered in the present analysis. However, in a private communication, G T. Zatsepin has expressed the view that the fluctuations in pure e.m. interaction could not account for these events.

For a short duration ($9 \cdot 7 \times 10^5$ sec), the triggering of the flash tube hodoscope was done with underground muons only, without the requirement of associated ground level EAS. In this investigation, we observed two similar types of showers with more than 12 particles under rock having a spread $\geqslant 10$ cm, and 3–6 particles under lead with spread $\geqslant 20$ cm. In the same duration a total number of 5000 single muons were recorded.

The average energy of muons recorded at 580 m.w.e. without the requirement of association with the ground level EAS is $\langle E_\mu \rangle \sim 88$ GeV, calculated on the basis of the integral energy spectrum $n_\mu (\geqslant E_\mu) \propto E_\mu^{-\gamma}$, with $\gamma \sim 2 \cdot 6$, while the average energy of muons associated with the ground level EAS $\langle E_\mu \rangle \sim 370$ GeV with exponent of integral spectrum $\sim 1 \cdot 37$. The values of nuclear interactions cross-section, taking the same threshold energy for the detection ($E_\mu \simeq 25$ GeV), in the two cases are found to be $(2 \cdot 0 \pm 0 \cdot 8) \times 10^{-30}$ cm^2/nucl and $(1 \cdot 6 \pm \cdot 75) \times 10^{-29}$ cm^2/nucl respectively. In these two experiments, one with muons associated with EAS and the other with U.G. muons alone, the systematic errors are of the same order. These results indicate a tendency of an increase in photo-nuclear interaction cross-section with the energy of the incident muons.

We give below in table 4 the photo-nuclear cross-section of muons obtained in various investigations with cosmic rays at different underground levels and also with the accelerator. Table 4 shows that much discrepancies exist among the results of different experiments and the quoted statistical errors are also very high. It is to be noted that these experiments were not performed under the same experimental conditions, especially the minimum energies were quite different from each other. However, there is a tendency for the cross-section to increase with energy of the muon in those investigations which were performed with the same experimental arrangement.

4. Conclusions

Present observations indicate that the common type of showers generated by high energy muons associated with EAS, at the vertical depth of 580 m.w.e. may be interpreted as due to pure electromagnetic interactions of the muons in the rock and in the lead.

Besides these showers another type of events has been detected which cannot be accounted for by the electromagnetic interactions of muons. Various considerations outlined above show that these events are probably produced by muons through photo-nuclear interactions in the rock. The photo-nuclear interaction cross-section σ_{μ} ($>$ 25 GeV), calculated from these events, is found to be $(1 \cdot 6 \pm 0 \cdot 75) 10^{-29}$ cm^2/nucl. This cross-section is found to be in better agreement with the value expected on the basis of virtual photon spectrum given by Kessler and Kessler than by Heitler. However, there may be some contribution due to fluctuation in pure e.m. interaction which have not been considered here.

In order to get more definite information regarding these events, it is necessary to determine more accurately their point of origin as well as the minimum energy required for such interactions. The estimates of these are very rough in the present set-up. An experiment with several layers of absorber of small thickness ($\simeq$ 1 cm lead) with alternate layers of flash tubes arranged in between, instead of one single block of lead absorber, will be more useful to give the whole history of the development of the showers. It is also necessary to determine the deflected angle of muons.

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Table 4. Photo-nuclear cross-section of muons obtained from various experiments

Author	Source cosmic rays	Producing material	Underground detector	Average energy of muon GeV	Minimum energy transferred GeV	Cross-section cm^2/nucl	Nature of trigger for underground apparatus
Argan *et al* (1954)	(i) 190 m.w.e. (ii) 50 m.w.e. $\rho = 2\cdot49$ gm/cm^3	(i) lead (ii) lead	G M counter	$\langle E \rangle = 40$ $\langle E \rangle = 10$	2	(i) $(7\cdot5 \pm 1) \times 10^{-30}$ (ii) $(2\cdot4 \pm \cdot4) \times 10^{-30}$	underground muon only
Krishnaswamy *et al* (1969, 1971)	(i) 816 m.w.e. (ii) 3630 m.w.e. $\rho = 3\cdot02$ gm/cm^3	rock	scintillator (i) neon f. tube (ii)	$\langle E \rangle = 105$ $\langle E \rangle = 250$	2–5	(i) $(3 \pm \cdot7) \times 10^{-30}$ (ii) $(8 \pm 4) \times 10^{-30}$	do.
Present experiment	650 m.w.e. $\rho = 3\cdot02$ gm/cm^3	rock	scintillator (i) and neon f. tubes (ii)	$\langle E \rangle = 88$ $\langle E \rangle = 370$	25	(i) $(2 \pm 0\cdot8) \times 10^{-30}$ (ii) $(1\cdot6 \pm 0\cdot75)\, 10^{-29}$	(i) underground muon only (ii) underground muon accompanied by EAS
Barret *et al* (1952)	1600 m.w.e. $\rho = 2\cdot65$ gm/cm^3	rock	G M counter	$\langle E \rangle = 300$	5	$(4 \pm 2) \times 10^{-29}$	underground muon only
George and Evans (1955)	60 m.w.e.	emulsion	emulsion		1	$(4\cdot6 \pm 0\cdot05) \times 10^{-30}$	do.
Naranan *et al* (1957)	180 m.w.e. $\rho = 2\cdot9$ gm/cm^3	lead plate in cloud chamber	cloud chamber	$\langle E \rangle = 47$	1	$(5\cdot7 \pm 2\cdot8) \times 10^{-30}$	do.
Kessler and Maze (1957)	65 m.w.e.	lead plate in cloud chamber	cloud chamber	$\langle E \rangle = 47$	12	$(0\cdot43 \pm 0\cdot08) \times 10^{-30}$	do.
Higashi S *et al* (1965)	50 m.w.e.	(i) lead (ii) iron	cloud chamber	10–100	1	(i) $(2\cdot8 \pm 0\cdot36) + 10^{-31}$ (ii) $(3\cdot62 \pm 0\cdot76) \times 10^{-31}$	do.
McNulty and Jain (1969)	accelerator	nuclear emulsion	nuclear emulsion	5	1	$(3\cdot6 \pm 0\cdot30) \times 10^{-30}$	do.
Bezrukov *et al* (1969)	315 m.w.e. (gypsum mine)	liquid organic scintillator	scintillator	energy spectrum $N_\mu(> E_\mu)\, \alpha E_\mu^{-\gamma} \times$ $\gamma \sim 2\cdot65$	25	$(3\cdot4 \pm 0\cdot7) \times 10^{-31}$	do.

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