EmC 63/19
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PROPOSAL FOR AN EXPERIMENT TO STUDY NEUTRINO INTERACTIONS USING PHOTOGRAPHIC EMULSION

1. General Considerations

The nuclear emulsion method of studying interactions of fundamental particles possesses a great advantage over other visual methods with respect to the very high spatial resolution of which it is capable. Spatial separations of 0.5 μm can be resolved in individual events. This is about 1000 times better than can be obtained using a bubble chamber. Separations of 0.1 μm or better can be inferred statistically. This remarkable spatial resolution has made possible estimates of the life-time of the π^o meson of the order of 10^{-16} sec.

The tediousness of the analysis of large stacks of emulsion pellicles has so far prevented the fullest exploitation of this high resolution property. Further the difficulty of association in time of events seen in emulsion has made it very difficult to use it as a detector of rare events in the presence of much more common processes.

In recent years Takabaev and his associates in the Kazakhstan Academy of Sciences have successfully used nuclear emulsion to study selected types of cosmic ray interactions by exposing an emulsion stack close to a counter controlled Wilson chamber. The latter was used to detect secondary products of interactions produced in the emulsion. By following the tracks of these secondaries back from the place where they enter the chamber it has been possible to locate the interaction centre and study its details taking advantage of the high resolution available with emulsion. Such an arrangement is essentially a means of "triggering" of emulsion detectors for interactions of a desired type.

Recently the use of a technique in which a stack of emulsion is associated with a spark chamber has been proposed at Dubna$^{x)}$.

2. Use of an emulsion stack in association with a spark chamber for the study of neutrino interactions.

The present proposal conceives an experiment to use an emulsion stack-spark chamber combination to study neutrino interactions. The secondaries from the interactions would be picked up in spark chambers triggered by a set of scintillation counters which select neutrino-like interactions. Spark chambers in which the distance between the first and last gap is 20 cm are envisaged. With such chambers the position of the secondary when it enters the chamber should be located to an accuracy of 0.5 mm. The direction of the secondary should be located to within 5 milliradians. The emulsion stack would be accurately located relative to the first plate of the spark chamber. It should then be possible to associate tracks in the emulsion with the particles observed in the spark chamber. These tracks will be followed back to the origin of the neutrino interaction producing them. In this way it will be possible to study neutrino interactions using the high resolution of which the emulsion technique is capable.

It seems practicable in the first instance to expose an emulsion stack consisting of rather more than 800 pellicles each 50 x 20 cm in lateral dimensions and 0.6 mm thick, making up a solid block of emulsion of volume 50 litres with a mass of 200 kg, representing about 30 per cent of the mass available in the present heavy liquid bubble chamber experiment. If the extension of the method appears fruitful one can conceive of a later experiment in which the mass of the emulsion could be made equal to that contained in the heavy liquid bubble chamber. The emulsion stack would in that case be slightly larger than the largest stack so far flown in cosmic ray balloon experiments.

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x) Private communication from M. Danysz.

The set-up proposed for the present experiment is shown in the diagram

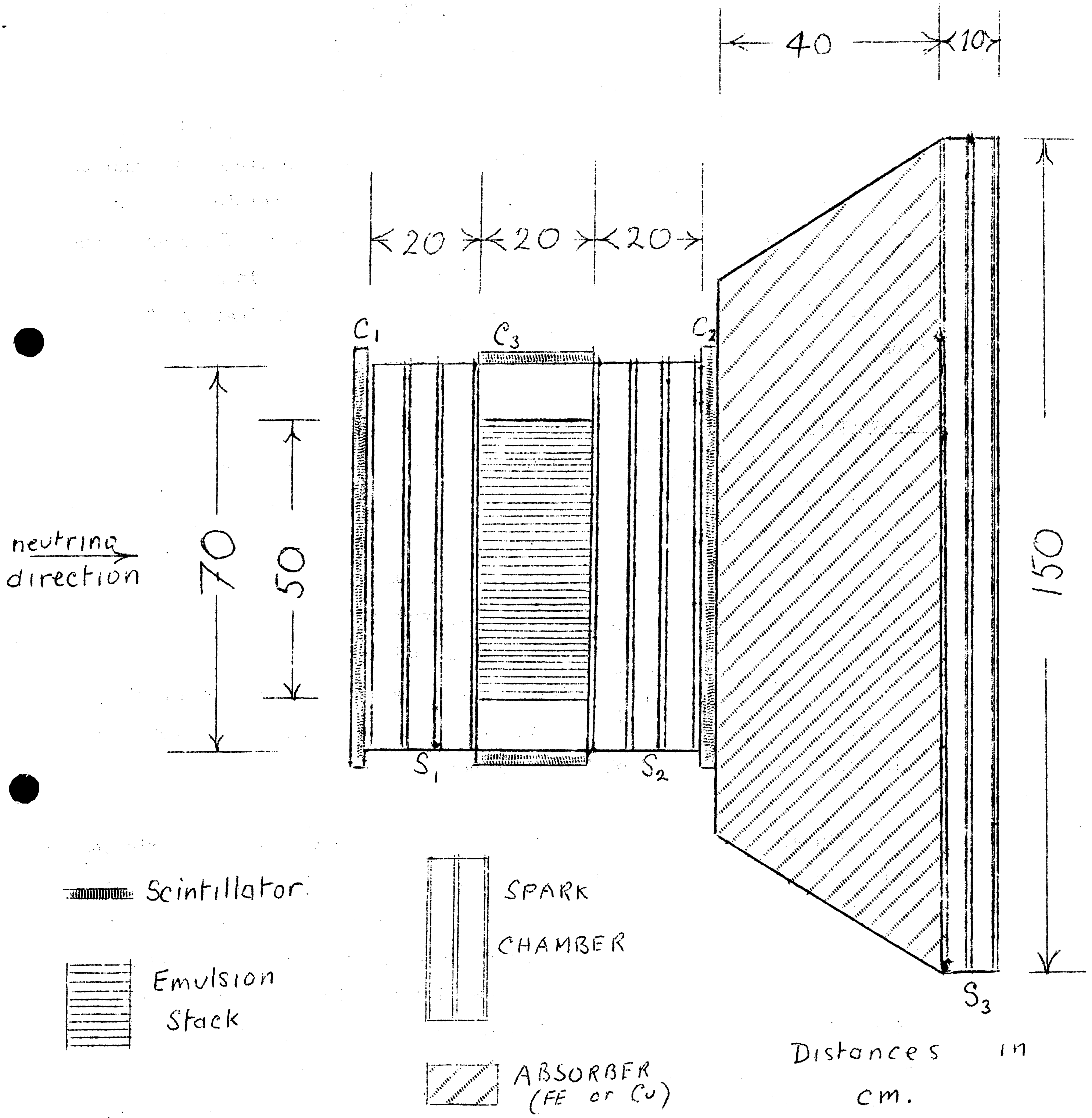

Figure 1

C_1 , C_2 , C_3 are scintillation counters. C_3 surrounds the emulsion stack. S_1 , S_2 and S_3 are spark chambers. An event $C_2 - C_1 - C_3$ triggers spark chambers S_2 and S_3 and enables one to detect a neutrino interaction in which a fast track is emitted in the forward direction. An event $C_1 - C_2 - C_3$ triggers spark chamber S_1 and enables the detection of a neutrino interaction in which a track is emitted backwards. Events in which a particle is observed in more than one scintillator are attributed to cosmic rays. The spark chambers S_1 and S_2 (and thence the emulsion stack itself) are placed in a region of magnetic field of about 10,000 gauss to enable a sign determination of the muon.

3. Event Rate

With the existing neutrino set-up the heavy liquid bubble chamber yields about 14 events per day. The event rate with the emulsion-spark chamber set-up should be about 30 per cent of this, i.e. about 4 events per day. Inevitably, however, some of these events will be missed. If for example the momentum, p_μ , of the μ meson is less than 0.2 GeV/c, such a particle emitted from an interaction at the centre of the stack will not emerge from the emulsion. Similarly if its angle of emission, θ_μ , relative to the incident neutrino direction is such that $|\cos \theta_\mu| < 0.4$ it will not leave the stack at a point contiguous to the first spark chamber plate.

By studying the distribution of p_μ and θ_μ for 47 events (elastic and inelastic) produced in the heavy liquid bubble chamber it is concluded that 75 per cent of all neutrino events should be detectable in the emulsion stack. With the geometry proposed in the figure and assuming a magnetic field of 10,000 gauss it would be possible to determine the sign of the fast track emitted in 90 per cent of these interactions and to identify it definitely as a μ meson in slightly less than 50 per cent of the events. (These last include the 10 per cent whose momenta are too high for sign determination.)

4. Background Flux of Cosmic Radiation

In order to accumulate a useful number of neutrino events it will be necessary to expose the emulsion stack for several months to the neutrino beam. During this time the stack will accumulate an unwanted background of cosmic ray tracks which may cause confusion with tracks of particles from neutrino interactions.

The flux of the hard component of the cosmic radiation at sea level is $0.83 \times 10^{-2} \cos^2 \theta \ \mathrm{cm}^{-2}.\mathrm{sr}^{-1}.\mathrm{sec}^{-1}$, where θ is the zenith angle.

The total flux per second across a vertical area Δs and within a solid angle $\Delta\Omega$ is $0.83 \times 10^{-2} \cos^2 \theta \ . \ \Delta s \sin \theta \ . \ \Delta\Omega$ which has a maximum value of $0.33 \times 10^{-2} \Delta s \ . \Delta\Omega$ at a zenith angle of $\theta = 35^{\circ}$. Putting $\Delta s = (0.1)^2$, $\Delta\Omega = (0.01)^2$ this gives a flux of $0.33 \times 10^{-8} \ \mathrm{sec}^{-1}$, i.e. 1 particle in 10 years that could be confused with a given track recorded in the spark chamber.

This figure is of course critically dependent on the assumed accuracy of location of the tracks in the spark chamber. If the accuracy of determination has been overestimated by a factor of 2, for example, the number of background tracks that are capable of being confused with the track being sought would be increased by a factor of 16. The above calculation, however, assumes no shielding of the incident cosmic ray flux. The existing Fe absorber will provide quite a lot of shielding. The provision of 10 metres water equivalent of absorber above the stack would restore the number of background tracks likely to be confused with secondaries from ν events to the value estimated above even if the accuracy of location of the spark chamber tracks has been overestimated by a factor of 2.

It may be desirable to build up the stack and to store it pending development in an underground room. A suitable room is available at the Holborn Tube Station in London.

We conclude that the confusion of tracks due to the cosmic ray background will not represent a serious problem in this experiment.

In addition to the above there will be a background of events due to cosmic rays which will trigger the counters during a pulse and simulate neutrino events. These are events which will pass through counters C_1 or C_2, enter one side of the emulsion stack but fail to emerge from the other side of the stack. The angle subtended by the two counters C_1 and C_2 together at the center of the stack is $\simeq \frac{\pi}{2}$ sterad and the mean zenith angle $> 60^o$. (A machine day of 24 hours gives 29 milliseconds sensitive time (assuming a sensitive time of 10^{-6} sec per pulse). The total number of cosmic ray tracks entering either face of the emulsion stack after passing through C_1 or C_2 in this time will be less than

$$2.9 \times 10^{-2} \times \frac{\pi}{2} \times \frac{1}{4} \times 0.83 \times 10^{-2} \times 2500 = 0.23$$

or less than ten per cent of the expected number of neutrino events in 24 hours.

In fact the situation is much better than this. Most of the cosmic ray background particles will pass right through the stack and counters and spark chambers C_1 , C_2 , S_1 , S_2 and so will not be confused with neutrino events. The Fe absorber already present in the neutrino set-up will harden the incident cosmic ray flux.

If an absorber thickness of 10 metres of water equivalent is disposed both fore and off of the emulsion spark chamber set-up the consequent hardening of the cosmic ray flux would be such as to make completely negligible the background of cosmic ray particles simulating neutrino events.

5. Relative Advantages of the Emulsion-Spark Chamber Method of Studying Neutrino Events.

(a) Detection of possible new short-lived particles

The chief advantage of this method of studying neutrino interactions arises from the high spatial resolution of the emulsion method, as a result of which it should be possible to study fine details of the neutrino interactions with nuclei. If any unknown unstable particles with life times in the range 10^{-12} - 10^{-15} sec are produced in such interactions these should appear in this method but would have been missed hitherto using the bubble chamber or spark chamber methods of detection. Some writers have speculated on the possible existence of a short-lived heavier μ-meson which might show up in such an arrangement. On the other hand the maximum expected life-time of the W particle is 10^{-17} sec and in view of the evidence for a lower limit of its mass so far obtained its life-time is probably considerably shorter than this so that the emulsion method is unlikely to provide an additional means for measuring its lifetime, if it exists. The details of neutrino interactions are subject to such uncertainty, however, that there is a strong case for using the greatly enhanced spatial (and therefore time) resolution made available by the emulsion technique, even though present theoretical ideas do not predict new phenomena of the time scale made accessible.

(b) Detection of the intermediate vector boson

From the point of view of detecting W production by the observation of two μ mesons this arrangement is in a similar position to the conventional spark chamber set-up. Both methods have a big advantage over the heavy liquid bubble chamber where neither μ meson can be followed over more than one interaction length so that it is never possible to distinguish them unequivocally from π mesons. The emulsion method possesses the additional advantage over the spark chamber, however, that it is easy to distinguish between μ mesons originating directly in the neutrino interaction and those originating in π-μ decay within a few centimetres of the interaction.

Further, having revealed a case of W production, the emulsion method would permit a study of the kinematics of the production process in a detail not possible with the spark chamber.

In the electron decay mode of W^+ the e^+ should be readily distinguishable in emulsion. Under some conditions in the bubble chamber it may be difficult to distinguish unambiguously a single electron from the production of a Dalitz pair. No such ambiguity appears conceivable in the case of electrons of this energy in emulsion.

In the spark chamber it is difficult to identify the e^+ decay mode of the W^+, although it may be possible statistically to distinguish showers produced by single electrons from those originating in π^0 decay. This is clearly only possible, however, provided the e^+ production is a reasonable fraction of the π^0 production in inelastic events. The results of the CERN run so far seem to indicate that this is not the case.

It is possible to estimate the fraction of all W^+ particles decaying by lepton modes that could be identified in the emulsion spark chamber experiment proposed above.

In the production reaction the μ^- can be identified with high probability if $p_{\mu^-} \gtrsim 1$ GeV/c and $\cos\theta_{\mu^-} \gtrsim 0.8$. From the sample of events from the heavy liquid bubble chamber experiment it appears reasonable that this might account for about half the cases of neutrino interaction.

In the μ^+ decay mode of the W^+ there are two regions in which the μ^+ can be identified, viz

(a) $p_{\mu^+} \lesssim 0.2$ GeV/c in which case the μ^+ e^+ decay will be seen

(b) $p_{\mu^+} \gtrsim 1$ GeV/c, $\cos\theta_{\mu^+} \gtrsim 0.8$, in which case the μ will be identified by its passage into spark chamber S_3 and its sign by magnetic de

A rough guess might suggest (a) + (b) would represent about 1/2 of the $W^+ \rightarrow \mu^+$ decays.

In the e^+ decay mode the e should almost always be identified. Remembering therefore that the μ^+ and e^+ decay modes are expected to have equal probabilities the fraction of leptonic decay modes of the W^+ that should be identifiable is

$$\frac{1}{2}\left(\frac{1}{2} \times \frac{1}{2} + \frac{1}{2}\right) = \frac{3}{8} .$$

(c) Detailed study of neutrino interactions

The emulsion method shares with the heavy liquid bubble chamber the advantage over the conventional spark chamber method that it is possible to examine in detail neutrino interactions with complex nuclei. Because of its improved spatial resolution the emulsion is able to extend much farther the detailed analysis of the charged particles emitted from such interactions. For example an alpha particle of range 1 mm in a heavy liquid bubble chamber lies on the limit of what can be observed. Such a particle carries with it an energy of 30 MeV and a momentum of nearly 500 MeV/c. With emulsion α particles of energy less than 1 MeV can be readily detected. In studies of the elastic neutrino interaction process it should therefore be possible in many cases to obtain a better energy and momentum balance than for the bubble chamber. This is especially the case for neutrino interactions with the light nuclei (C , N , O) of the emulsion, where in some cases it should be possible to identify the interaction completely (About one sixth of all the interactions in emulsion would be expected to occur on light nuclei.) On the other hand the emulsion method does not enable the direct identification of slow neutron emission.

The advantage is possibly even more marked in the case of the detailed analysis of processes involving pions. In the bubble chamber and spark chamber it is difficult to distinguish stopping μ^+ from stopping π^+ .

In the emulsion, however, the characteristic π-μ-e decay is readily observed. Decays of charged Σ hyperons are also in general more readily observed in emulsion than in the bubble chamber. In addition the energy of the hyperon can often be quite accurately measured, which is usually very difficult in the bubble chamber or spark chamber.

Although it is in general very difficult to associate showers due to π^0 decay, or the decays of Λ^0 hyperons with interactions in emulsion, the possibility of their detection in the spark chambers is not excluded in the present experiment. The stack is 7 radiation lengths thick from front to back, so that a reasonable proportion of π^0 should give rise to one or more easily recognisable electron tracks in the spark chambers. Λ^0 should also be recognisable from tracks leaving the emulsion (which can be followed back to the V) or from V events in the spark chambers.

6. Proposed Trial Experiment

Before proceeding with the design of an experiment involving a large emulsion stack in conjunction with a spark chamber it will be necessary to test the accuracy of track location in emulsion by means of spark chambers under experimental conditions that will simulate those to be expected in the neutrino experiment. An arrangement to do this is shown in the figure (2).

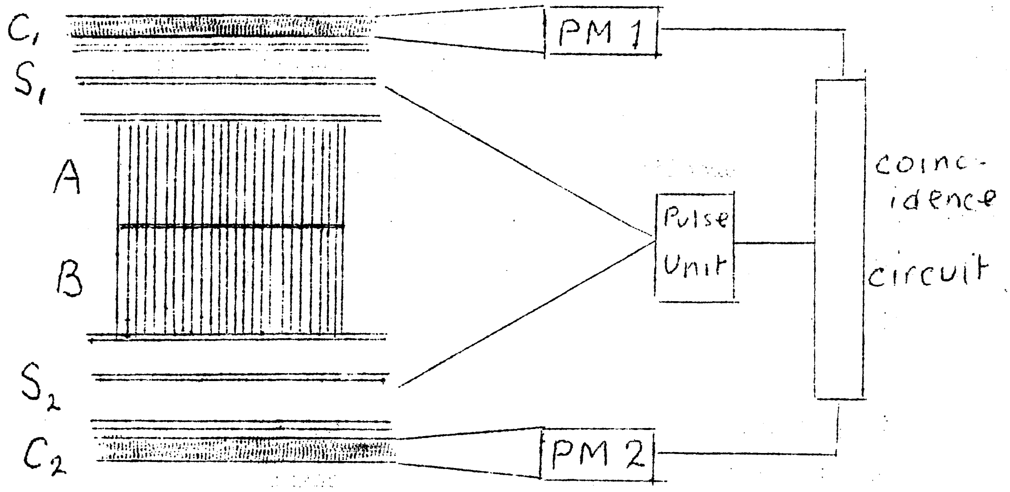

Figure 2

Stacks A and B are made separately from emulsion which has been exposed to sea level radiation for some months so that until they are placed together in the arrangement no tracks that can be followed through both stacks will be registered. They are placed between the two spark chambers S_1 , S_2 which are triggered by pulses through both coincidence counters C_1 and C_2. Approximately 100 pictures will be taken.

The track location and following can then be exactly the same as for the neutrino experiment. An "event" now corresponds to a track which can be located from its track in spark chamber S_1 and followed through from its entry into stack A to its exit from B. The point at which the track leaves stack B should be related to a trace in the spark chamber S_2. As an additional check the experiment could be performed in reverse using the trace in S_2 to locate the track in B.

The type of track to be searched for in this experiment and the background conditions will be exactly the same as for the ν experiment. The stack location system and spark chamber fiducials, the gridding system and the scanning procedure are all tested by this method.

Trigger counters 50 cm^2 area, 60 cm apart will give $\frac{50}{3600} \times 50 \times 0.8 \times$ $\times\ 10^{-2}$ events/sec, i.e. about 20 events per hour.

Old emulsion is readily available for proceeding with this trial experiment without delay.

7. Magnet

The experiment proposed here requires a magnetic field of about 10,000 gauss over a volume 60 x 70 x 100 cm in order to enable sign determination of the secondaries. In view of the delays experienced in obtaining delivery of new magnets it is very desirable that an existing magnet should be adapted for this purpose. A suitable magnet exists already, viz that built for the 2 metre Wilson cloud chamber. If this were available for this experiment it would undoubtedly provide the best solution.

An alternative which seems likely to give the required field over about the right volume is sketched in figure 2. It uses the coils from two standard 1-metre magnets and part of the iron circuit of one. The field would be fairly uniform except near the top and about 10 kg if a current of 830 Amps were used instead of the nominal 675 Amps. This is believed to be possible. Power consumption would be 0.3 megawatts. It is estimated that the proposed modifications would cost 8000 Swiss francs and take 2-3 months to carry out.

This solution gives a very compact magnet which would be easy to install in the shielding and which requires very little power. The coils and yoke of the magnet would provide an absorber of 400 gms/cm^2 between the chambers S_1 and S_3 of figure 1. It would not, however, be possible to make the absorber in sections interspersed with spark-chambers as would be the case in the Wilson chamber magnet. Neutrino interactions in the yoke upstream from the stack would provide an additional local source of background, although mostly of an easily recognisable type. The most serious disadvantage of the arrangement is that the restricted space makes it necessary to compromise in the sizes of the spark chambers and in the arrangement of the optics.

8. Arrangements for Carrying Out the Experiment

Dr. W. O. Lock has promised the support of the CERN emulsion group for this experiment. Dr. A. Lundby has expressed interest in the experiment and it is hoped that it may be possible to associate his group with it. The emulsion group of University College London would wish to participate while Dr. F. Heymann, also of University College, has offered the cooperation of the spark chamber group.

It is hoped therefore that the experiment can be carried out jointly by the following groups

(1) CERN Emulsion Group
(2) Spark chamber group of Dr. A. Lundby
(3) University College London, Emulsion Group
(4) " " " , Spark Chamber Group.

The processing of the stacks will require the use of facilities in other laboratories but no difficulty is expected in making suitable arrangements for these.

9. Cost of Equipment Required

The chief cost would be that of the emulsion. The current price is about 3000 Swiss francs per litre so that emulsion costs would run into 150,000 Swiss francs. Processing costs would add about 50 per cent on to this cost. The cost of adopting the 1 metre bending magnet would be about 8,000 Swiss francs. An expenditure of about 250,000 Swiss francs would therefore need to be envisaged for additional equipment.

This doesnot appear to be an unrealistic sum for the trying out of a technique which might prove to be of great value in neutrino physics in the future.

10. Time Scale of the Proposed Experiment

It is proposed to proceed immediately with the trial experiment outlined in § 6. This should not take more than 2 months to carry out.

It is hoped that provision could then be made for incorporating this experiment in the plans for the neutrino experiments for next year. The comparatively small volume involved should make it possible to introduce the equipment immediately behind the massive Fe absorption of the neutrino beam and the experiment should not interfere with other neutrino experiments.

11. Acknowledgements

The possibility of associating emulsion and spark chamber techniques to obtain some of the advantages of both was pointed out to us by Professor M. Danysz. The feasibility of using emulsions for studying neutrino interactions was stressed to one of us by Dr. Leona Marshall of Columbia University. The germ of the present proposal evolved in the course of a subsequent discussion with Dr. Maurice Goldhaber of the Brookhaven National Laboratory.

We wish to thank a number of people at CERN for preliminary discussion of these proposals, particularly Drs. G. Petrucci and A. Lundby. We are indebted also to Drs. C. Ramm, R. Voss and members of the CERN Heavy Liquid Bubble Chamber for allowing us to have access to the preliminary results of the neutrino interactions so far obtained in that chamber.

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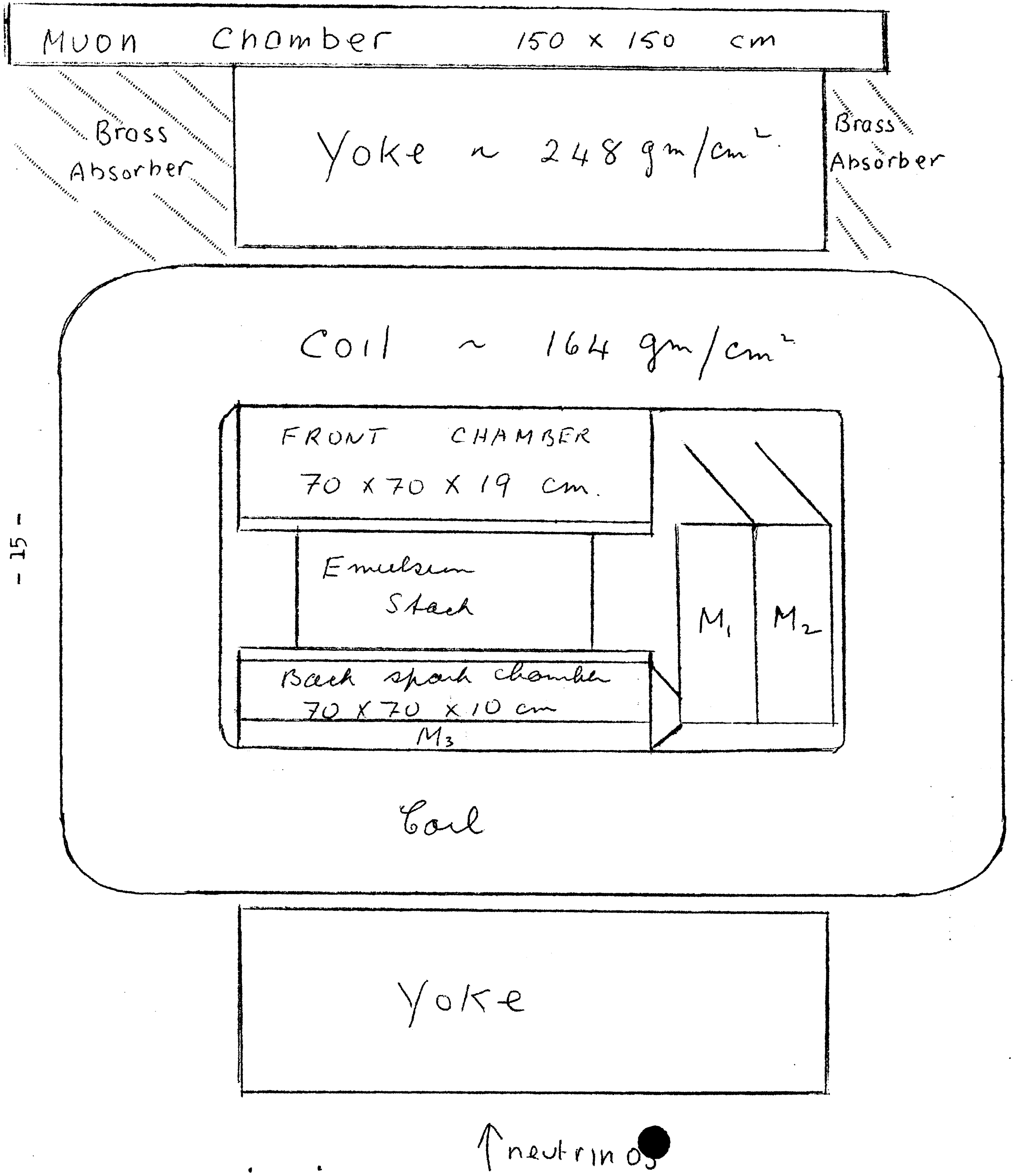


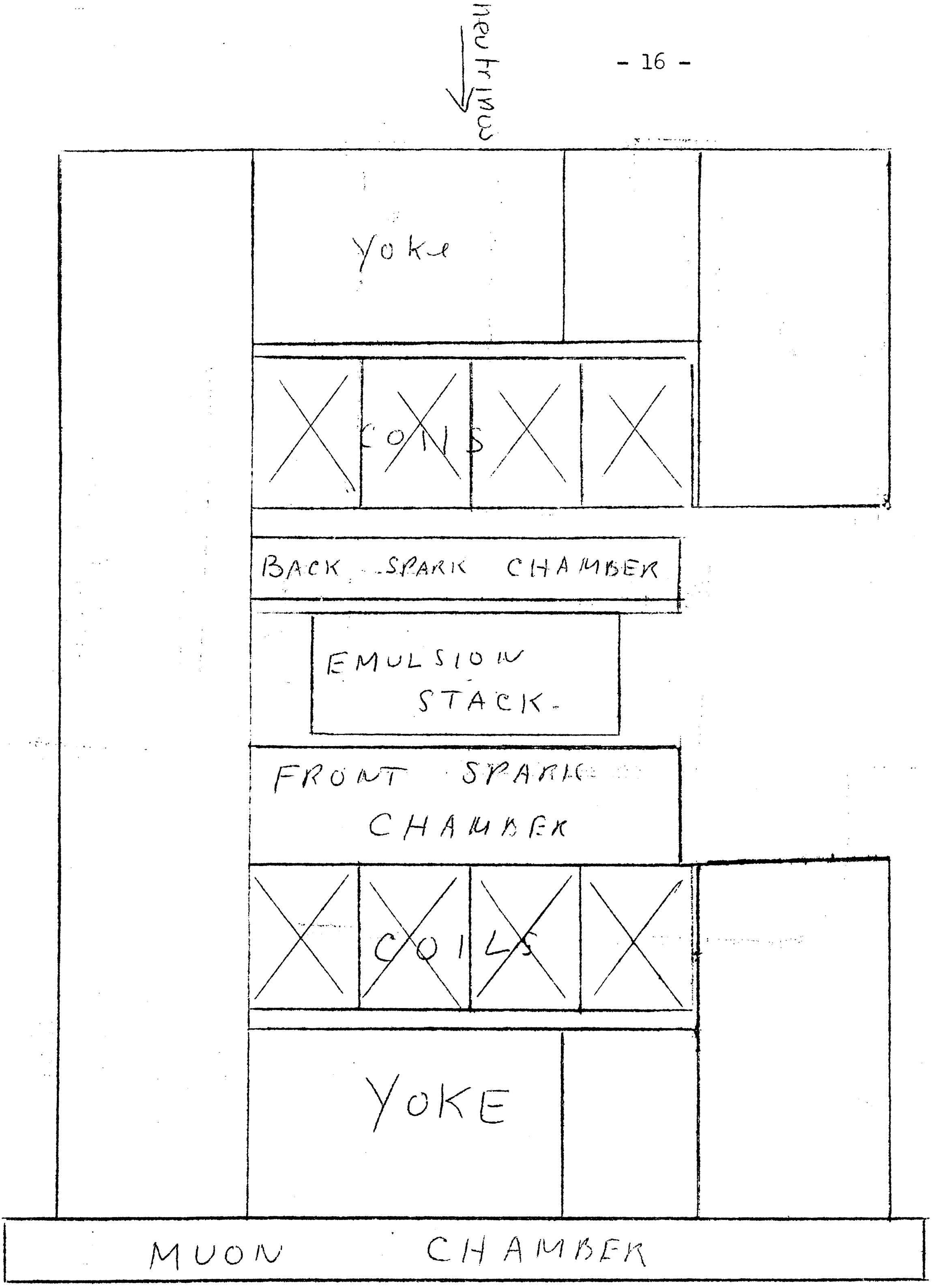
Fig 3a

Plan View of possible Arrangement. Only the optics contained within the coils is shown.

M_1 = Mirror for side view of bottom of front chamber.

M_2 = Mirror for side view of top of front chamber

M_3 = Mirror for side view of rear chamber.



Elevation (Side View)

Fig 3b

ADDENDUM TO THE PROPOSAL TO STUDY NEUTRINO INTERACTIONS USING THE PHOTOGRAPHIC EMULSION METHOD

1. Trial Experiment

A report of a test of the method of location of the tracks in emulsion by means of spark chambers is appended. It can be seen that the accuracy obtained is rather better than had been estimated in the original proposal.* The product of emulsion area and solid angle defined by the spark chamber coordinates is about five times smaller than was originally estimated. There should therefore be no difficulty in finding the events, and no problem arises from the cosmic ray background in the emulsion. The difficulty of finding tracks with dip angle greater than about 30° is probably not serious, as there are likely to be a comparatively small number of events and a fairly large scanning effort can be put into finding each event.

2. Geometrical Arrangement and Magnet

The detailed arrangement of spark chambers, counters and absorber is very dependent on the geometry of the magnet used. It appears that the magnet of the 30 cm. hydrogen bubble chamber will be available after the summer of 1964. Some modifications will be necessary, but these appear to be quite practicable. New side members will be required (shown shaded in figure 1) in order to increase the gap between the coils to 70 cm.

One possible complete arrangement is shown in figure 1. The spark chamber SC helps in the location of events in the emulsion block, which is 40 x 40 x 30 cm. (This is about 50 litres of emulsion). Counter C2 triggers the chamber and would have more than one photomultiplier in order to avoid triggering on dark current pulses. The counter C1 would be used in anti-coincidence to avoid triggering the spark chamber if there is an incoming charged particle. Counter C3, which would be made in at least three parts, would be used in coincidence with C2 to trigger the large range chambers at the far end of the magnet. (The exact number of these range chambers will depend on the amount of room available between the magnet and the shielding). Good optics would be required for the spark chamber SC, and it is proposed to use a perspex field lens about 70 cm. in diameter and mirrors M1, M2 and M3 to enable the top view of the spark chamber to be seen under the same field lens.

A computer study is being made to optimise the positions and sizes of all the components. It appears possible to install the equipment in a hole made in the shielding three ingots in from the end nearest to the present neutrino bubble chamber position. The total volume required for the apparatus would be about a three metre cube. After the equipment is installed all free space could be filled with absorber. It appears that the installation would take from two to three weeks.

3. Neutrino Event Rate and Detection Efficiency

The mass of the emulsion stack would be about 180 Kg compared with the fiducial volume of the bubble chamber, which is

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* See EmC 63/19

330 Kg. A calculation has been carried out, based on 177 bubble chamber events, which indicates that the detection system shown in figure 1 would observe about 45% of all the events produced in the emulsion stack. However, there is likely to be an increase in neutrino flux of about 35% in the region of the emulsion stack compared to the bubble chamber region. Thus, overall, the expected event rate would be about one third that of the bubble chamber rate. About 60% of the observed events would have the muon at an angle θ to the beam direction such that cos θ is between 0.9 and 1.0. 25% would be with cos θ between 0.8 and 0.9 and the rest of the observed events would be at larger angles.

4. Measurements

The momentum of outgoing muons can be measured by multiple scattering in the emulsion, curvature of the spark chamber track in the magnetic field and from the range of particles stopping in the range chambers.

Multiple scattering measurements can be made on flat tracks by the second difference method. Momenta of muons should be capable of measurement to within an error of the order of 5% at a momentum of 0.5 GeV/c to 15% at 5.0 GeV/c. For steeper tracks the surface angle method is more appropriate and should give measurements of muon momenta within an error of between 5% and 15%.

The curvature of the tracks in the spark chamber will give a measure of momentum in the region of 1 GeV to within an error of about 15%, assuming that the magnetic field is about 10,000 gauss. The sign of the muon will be determined up to momenta of the order of 5 GeV/c.

For muons leaving the emulsion with momenta up to say 1 GeV/c the sign will be determined and the momentum will be measured to the accuracy indicated in the last paragraph. Between 1 to 2 GeV/c the range of the muon will also be determined and the muon will have passed through about 6 geometric interaction lengths which should distinguish it from a pion. Some 30% of the observed events should fall in this latter momentum range and in these cases the properties of the muon should be well determined.

Some protons, with energy up to approximately 300 MeV, will stop in the emulsion stack and the range of these particles will give extra valuable information. The energy of protons leaving the stack with momentum up to 1 GeV/c may be determined to within an error of 10% by ionization measurements.

5. W Production

It can be seen from the present neutrino experimental results that the probability of intermediate boson production is small, and in the emulsion experiment at most only one or two cases will be observed. The comments in the first proposal still stand, but from recent information it appears that the negative muon is less likely to be fast than the positive muon. If the negative muon has between 0 and 200 MeV/c it will stop in the emulsion but it will probably not be possible to distinguish whether it is a muon or a pion. If its momentum lies between 1 and 2 GeV/c there will be a fairly clear indication that it is a negative muon as described in 4. Between 200 MeV/c and 1 GeV/C the sign is known and momentum determined to a reasonable accuracy, and if the momentum is above 500 MeV/c this corresponds to a muon range which is greater than 3 geometric interaction lengths and will therefore give an indication in counter C3.

The same sort of considerations apply to the positive muon except that in addition if it stops in the emulsion a muon-electron decay will be observed.

In the case of the electronic decay of the intermediate boson it will be essential to trigger the event through the observation of the negative muon.

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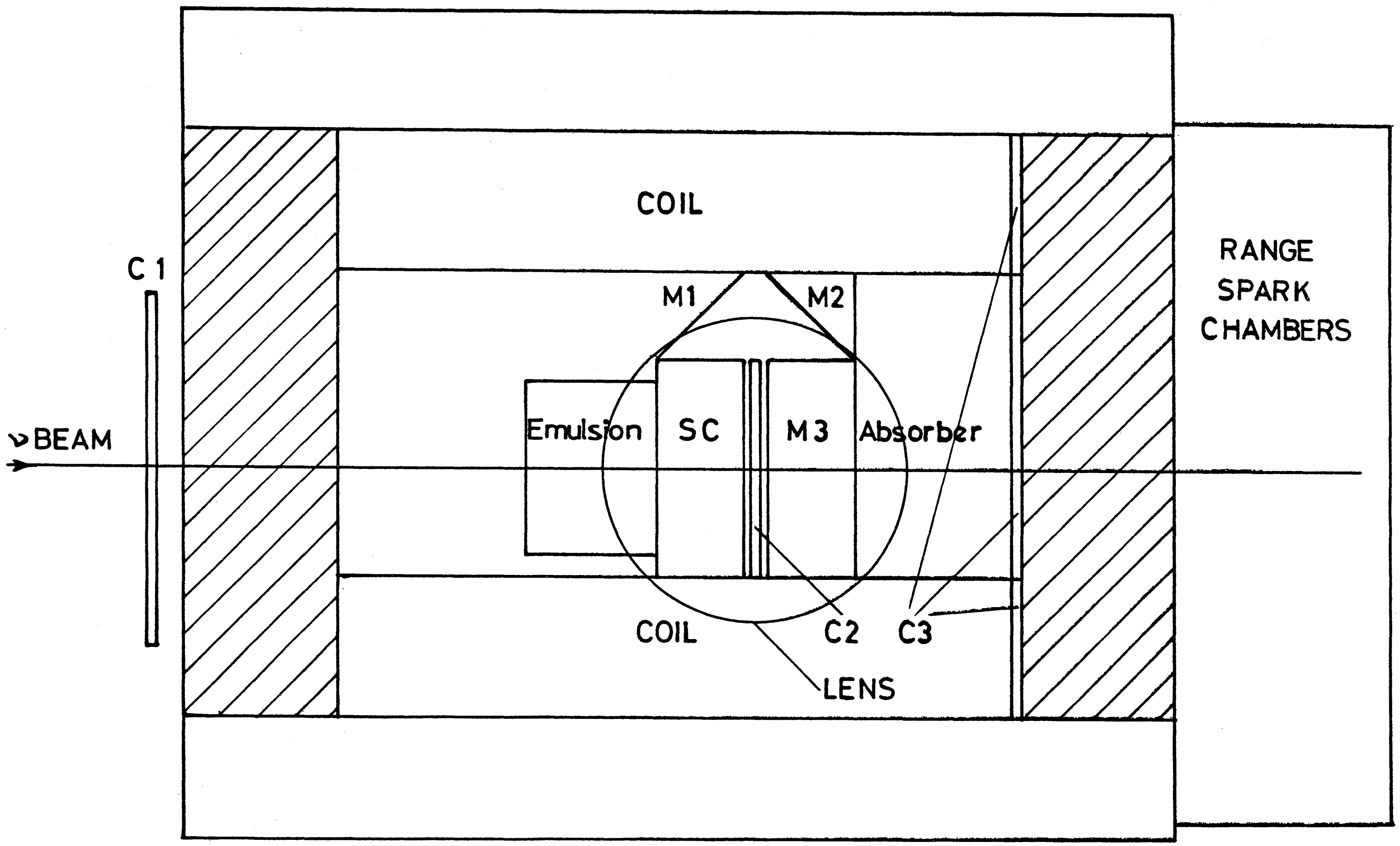

Fig.1 Side view of Apparatus (Schematic)