NAL PROPOSAL No. 86

Correspondent: J. J. Lubatti
Department of Physics
University of Washington
Seattle, Wash. 98105

FTS/Off-net: 206-583-0111
543-2100

A PROPOSAL TO STUDY INELASTIC DIFFRACTIVE PROCESSES BY OBSERVING COHERENT PRODUCTION OF MULTI-PION FINAL STATES FROM HE NUCLEI

P. L. Bastien, V. Cook, R. Kenyon, L. D. Kirkpatrick, H. J. Lubatti,
D. Wolfe
University of Washington

J. J. Veillet
Orsay

R. Harris, A. Jonckheere, S. Spencer

July 20, 1970

A PROPOSAL TO STUDY INELASTIC DIFFRACTIVE PROCESSES BY OBSERVING COHERENT PRODUCTION OF MULTI-PION FINAL STATES FROM HE NUCLEI

University of Washington and Orsay Collaboration

ABSTRACT

We propose to study the diffraction dissociation of pions into multi-pion final states, by obtaining the missing mass spectra from the reaction:

$$\pi^- + He \rightarrow n\pi^- + (n - 1)\pi^+ + He.$$

The missing mass is calculated from a measurement of the He recoil which is observed in a streamer chamber. In this first exploratory experiment we propose to count the outgoing fast particles, and to measure in a very crude fashion their momenta.

Names of Experimenters:

Ph.D.'s

P. L. Bastien, V. Cook R. Kenyon, L. D. Kirkpatrick, H. J. Lubatti, J. J. Veillet

D. Wolfe.

Students

R. Harris, A. Jonckheere, S. Spencer

Date:

July 20, 1970

Name of Correspondent:

H. J. Lubatti

I. INTRODUCTION.

We are proposing to study the surface states of the pion by observing the diffraction dissociation of pions into multi-pion final states. Such an experiment yields information about the "surface" because, by the nature of diffraction dissociation, we are constrained to small momentum transfers. In particular, in this experiment, we propose to use helium nuclei as a target. The form factor for the helium nucleus will then insure that the momentum transfer is less than ∿300 MeV/c. The physics in this experiment is not unlike that obtained when we have the collision of two carbon nuclei in which the incident nucleus has only a very peripheral collision, and we observe the excitation of surface waves on the nucleus (the analog of deep inelastic scattering for nuclei would then be those collisions in which nucleons are excited into the continuum). As is well known from the study of nuclei, both the excitation of surface states and the study of deep inelastic scattering is necessary for a good understanding of the physics; likewise, in order to understand the structure of a pion, it will be necessary to obtain detailed information about the surface states as well as detailed information about the deep inelastic scattering. This experiment proposes to study only the former, namely, the surface states of the pion.

This experiment is a rather simple one which is aimed at "getting a look" at the various surface states which exist. Therefore, we are purposely designing this experiment not to restrict ourselves in the trigger logic, because, while results at existing accelerator energies give us some indication of what we might expect, the extrapolation of the incident energy by an order of magnitude will undoubtedly provide many surprises. Hence, we are using existing experimental information as a guide, but we are designing with very loose criteria so that new and unsuspected occurrences will not be overlooked.

The experimental apparatus, which will be discussed in greater detail in Section III and IV consists of a streamer chamber filled with helium gas. The helium nuclei act as both target and detector. By placing the streamer chamber in a magnetic field, it will be possible to obtain good momentum and angle measurements of the recoiling helium nucleus. We will, therefore, be able to obtain the missing mass of the multi-pion system which is recoiling against the helium nucleus. In addition, the fast charged pions will be visible in the chamber, and we will be able to measure the laboratory opening angle. A Charpak chamber at the downstream end of the chamber will allow us to count the number of outgoing pions and use this, if necessary, in the trigger. However, at the outset we would propose to take all interactions where more than two fast particles come out. In Section II we discuss the intuitive ideas behind diffraction dissociation, and what one might expect at higher energies based on the rather sparse data which now exists. In Sections III and IV we discuss the experimental set-up and the resolution which we think we will be able to obtain in this experiment.

This experiment makes no request of NAL other than for a pion beam and power for operating the magnet. The magnet will be supplied by the group at Orsay. It is capable of 20 kg over a volume of 1 x .5 x .5 m^3 and has provisions for 3 view stereo photography. It is the Ecole Polytechnique magnet designed by A. Lagarrique's group for use with the Ecole's heavy liquid bubble chamber which has now been retired.

II. PHYSICS JUSTIFICATION.

A. Background on Diffraction Dissociation.

Diffraction dissociation was first proposed by Feinberg and Pomeranchuk in 1953$^{1)}$. It was then employed by Glauber in a discussion of deuteron stripping$^{2)}$. The concept was later applied to hadronic processes by Good and Walker in 1960$^{3)}$. It was this last paper which generated considerable interest in diffractive processes for the production of hadronic states and lead to a considerable amount of experimental work, using both nuclei and nucleons as targets.

The basic idea is that at high energies a particle of mass m can dissociate into a system of mass m* with only very little momentum transfer to the target M, such that the phase difference of the de Broglie waves of states m and m* are degenerate over the target. Another way of saying this is that as a particle passes through the nucleon or nucleus, it is a mixture of its eigen states in "nucleon stuff". Good and Walker pointed out that the absorption of the m* component would result in the Fraunhofer diffraction scattering of m*. Such a picture requires of the target that it absorb the incoming wave and take up whatever recoil momentum is necessary in order to account for the mass difference $\delta m = m^* - m$. We should note in passing that this is very much like the role of a proton or heavy nucleus in pair production. Now from such a picture, we would not expect any change in the internal quantum numbers $(C,G,T,Y,\sigma = P(-1)^J)$ of the incident particle. (There of course could always be a change in the angular momentum state.) We would, however, expect the cross section to be nearly constant with energy, since in diffractive processes the cross section depends only on the area of the absorbing disk. In addition, the diffractive nature of the interaction dictates that there be sharp forward peaking of the differential cross section. To summarize, we would expect for such diffractive processes:

(1) Sharp forward peaking (Fraunhofer diffraction).
(2) Small or no energy dependence of the cross section.
(3) No change in the internal quantum numbers of the dissociated particle.

In the modern language of particle exchange models, one would say that a diffractive process is one in which a Pomeron is exchanged between the incident and target particle, and since the target plays no role in the dynamics of the inelastic diffraction, such processes are sensitive probes of the surface structure of the pion.

B. Existing Information.

Coherent production of multi-pion final states has been studied in great detail by the Orsay-Saclay-Milan-Berkeley (OSMB) collaboration using a heavy liquid bubble chamber filled with C_2F_5Cl 4). In their experiment, the coherent production of three and five pion final states was observed. The momentum transfer to the nucleus observed by the OSMB experiment is shown in Figure 1. One notices two slopes: The slope is characteristic of the form factor of the nucleus involved, and for the OSMB experiments gives approximately 80 $(GeV/c)^{-2}$, while the second slope $\sim 10 (GeV/c)^{-2}$ represents events in which the nucleus has been broken up, and therefore the interaction is an incoherent one which takes place on a nucleon.

The 3π and 5π mass spectra which were observed in these experiments are shown in Figure 2. The first peak that occurs in the 3π mass spectrum occurs near the $\rho\pi$ threshold at 1.08 GeV/c^2 (a_1); indeed, the OSMB collaboration finds that the mass spectrum up to 1.4 GeV/c^2 consists almost entirely of $\rho\pi$ final states. They also observe an enhancement at approximately 1.6 GeV/c^2 which is mainly $f^\circ\pi$ ($A_{1.6}$). The coherently produced 5π events show a peak in the 5π mass spectrum at approximately 1.9 GeV/c^2($A_{1.9}$) which, as is noted in reference 1, is near the A_1 ρ threshold. In the OSMB data, although the statistics are not overwhelming, there is indication of A_1 and ρ.

Further evidence of coherent production of multi-pion final states has been obtained by a Russian collaboration at Serpukhov$^{5)}$. This experiment was performed using an emulsion stack as the target and detector. In this experiment, they did not measure the momentum of the outgoing particles, and therefore, could not observe the invariant mass spectrum. However, they did obtain a multiplicity plot which is shown in Figure 3. They found that the number of 3 pion events far exceeded the other multiplicities. For the events in which no nuclear breakup was observed, they found that $\Sigma_i \sin\theta_i$ peaked near zero, where θ is measured relative to the beam, while for nuclear breakup events the distribution is broader; since the $\Sigma_i \sin\theta_i$ is proportional to the longitudinal momentum transfer, it is very likely that this experiment is observing dissociation of a pion into 3 and 5 pions.

An experiment has been performed at CERN with a pion beam using several nuclei as targets. The beam momentum was approximately 16 GeV/c. The fast secondaries were detected by optical spark chambers placed in a magnet. Analysis of this experiment is nearly completed and private communications indicate that dissociation into three pions has been observed, and the effective mass spectrum has the classical diffraction shape of the OSMB experiment.

The apparent lack of events at the higher multiplicities in the existing experiments can be understood in terms of the momentum transfer necessary to produce the final state. At high energies the minimum momentum transfer which is necessary to produce a multi-pion state of invariant mass M is given by

$$q_1 = (M^2 - m_\pi^2)/2p_{inc} ,$$

where p_{inc} is the momentum of the incident pion. In Figure 4 we show typical minimum momentum transfers for various invariant masses and incident pion momenta between 50 and 250 GeV/c. The momentum transfer distribution for interactions on the nucleus, where a pion dissociates and a nucleus recoils without breaking up, is dependent on the nuclear form factor. This was demonstrated by the OSMB data in Figure 2, where the two slopes clearly show coherent recoil of the nucleus (slope of $\sim 80(\mathrm{GeV/c})^{-2}$), and a nucleon recoil (slope of $\sim 10(\mathrm{GeV/c})^{-2}$). Intermediate nuclei in the range of 12 - 40 nucleons have diffraction minima ranging from 150 to 200 MeV/c. The heavy nuclei such as Pb have the first minima occurring at 100 MeV/c or less. Therefore, the above experiments performed either at 16 GeV/c on intermediate nuclei, or at 60 GeV/c on heavy emulsion nuclei are not terribly sensitive to the heavier states into which a pion can dissociate.

There has been considerable controversy over the true nature of such diffractively produced mass enhancements. The question of whether such enhancements are in fact resonances in the usual sense, or are merely manifestations of the kinematics of the interaction has not been satisfactorily answered. A model known as the Drell-Hiida-Deck model has been proposed which gives rise to threshold enhancements in the $\rho\pi$ system at 1 GeV/c^2 (see Figure 5). In such a model the mass peak results purely from the kinematics and has no dynamical origin. Goldhaber et al., have suggested that a possible way to test such a model would be to measure the interaction cross section of the $\rho\pi$ system with nucleons7). The argument is that in the A_1 system has a cross section for interacting with nucleons which is essentially that of the π-nucleon or the ρ-nucleon cross sections rather than that of the sum of the two, then, the conclusion is that the $\rho\pi$ system does not behave as though it were a free ρ and π. The only way to measure such cross sections is to produce the system in question on nuclei and make use of the Glauber or high energy model in order to measure the attenuation of the multi-pion system as it leaves the nucleus. The details of this model have been worked out by Glauber and others[8)], and it is this model which has been used with great success by Ting and co-workers in obtaining the ρ-nucleon cross section from the photo production of ρ mesons on nuclei[9)]. Goldhaber et al. found that when they analyzed the OSMB data in this way, the effective A_1 nucleon cross section was compatible with the π-nucleon cross section, which argues against the A_1 being simply a Deck like kinematic effect.

C. Expectations at Higher Energies.

It is interesting to note that in the OSMB experiment the Q per pion is approximately 220 MeV in both the 1.09 and 1.9 GeV/c^2 peaks shown in Figure 2. If one extrapolates to a 7π system assuming 220 MeV per pion, we would expect the 7π system to show a peak near 2.6 GeV/c^2 which is, amazingly enough, approximately the threshold of the $A_{1.9} + \rho$, whereas the 1.9 GeV/c^2 (5π) enhancement occurs at approximately $A_1 + \rho$ threshold. This leads one to the interesting speculation that the pion is composed basically of many ρ's, and it dissociates by kicking out "one more ρ". The 9π peak in this simple model would then occur at approximately 3.4 GeV/c^2. A similar conclusion can be reached for the $f^\circ\pi$ system, where 1.6 GeV/c^2 enhancement implies a Q per pion of 410 MeV. Such a model suggests the multi-pion spectra shown in Figure 6. The solid lines indicate the enhancements which have been produced diffractively in the existing experiments. The dotted lines indicate the enhancements which are suggested by the constant Q per pion discussed above. We expect a mass resolution of $\Delta m_x = (100\text{-}150)/m_x$ MeV/c^2, where m_x is in GeV/c^2. This is sufficient for the spectra shown in Figure 6; however, it appears that the resolution may be improved. (See Appendix A.)

The cross section which has been obtained by the emulsion groups, indicates that at 100 GeV/c we should expect approximately 2 mb for the 3π channel alone, which will be ample cross section for us to observe.

IV. EXPERIMENTAL ARRANGEMENTS.

The ideal detector for investigating coherent production on helium (or other noble gas nuclei) is the streamer chamber. The chamber gas serves both as target and detector. The low density of the gas means that the recoil nucleus has a range long enough (> 2 cm in all cases) to allow us to measure the track curvature in a magnetic field. Below 200 MeV/c, a recoil He nucleus will stop in the gas, thus allowing us to use Range to determine the momentum as well (see Figure 7). The target density is still sufficient to give us a high trigger rate. For a fiducial volume 50 cm long, we have in He 1.5×10^{-6} interactions/mb of cross section/beam π. We envisage using a chamber 1 meter long by 50 cm wide. It will be a standard double gap chamber, with 15 cm gaps. A chamber of this size has already been successfully run using both pure helium and the standard 90%-10% Ne-He mixture.

In keeping with the large number of possible final states, we would like to use as flexible a trigger as possible. In Figure 8, the incoming beam direction is defined by small proportional chambers. C4 is also a proportional chamber, used as a logic element which allows us to predetermine the minimum number of particles desired for a trigger. Since no recoil nucleus can get through the walls of the chamber, the presence of particles out the sides indicates an event of no interest. Counter C5, a combination of scintillator and thin lead sheet, is to be used in an anti-coicidence mode. C5 is extended to cover the bottom of the chamber as well. Thus a complete trigger for the chamber would be

$$C1\ C2\ C3\ C4(X \geq n)\ \overline{C5}\ \overline{C6}\quad .$$

The chamber will be operated with a memory time of 2 to 5 μsec. using chemical clearing. Due to the extremely high multiple track efficiency, we do not foresee any difficulties with high beam rates or random extra tracks in the chamber. The magent in which the chamber will be placed is the one in which Professor Lagarrique's heavy liquid bubble chamber BP3 was previously housed.

As mentioned above the trigger requirements are designed to be initially as loose as possible. This will, of course, lead to a fairly large number of pictures. This is not a serious problem however, as we plan to use our PEPR automatic measuring machine for analysis. A developmental program to enable PEPR to read streamer chamber film is beginning. The advantage of using a proportional chamber for C4 is that the trigger requirement can easily be changed during the course of the experiment. We plan to trigger initially on three or more fast particles. If we then find that the majority of our triggers contain 3 pions, as we expect, we can use the proportional chamber to demand five tracks and concentrate on the higher multiplicities.

Aside from the beam, and of course, water and power for our analyzing magnet, there is essentially no contribution necessary from NAL. Our equipment is relatively simple. A prototype streamer chamber with a Marx generator and Blumlein already exists. As a result of the work of the SLAC streamer chamber group, optics is no longer a problem. Sufficiently fast film and lenses exist and are in hand. Proportional chambers have been built at the University of Washington and further development is in progress. Thus, we feel that this experiment is sufficiently simple so that we can be ready as soon as there is a pion beam. We envisage a set-up and testing time of 4 - 6 weeks with 50% or less of this actual beam time. This testing can be done parasitically or even before a 0.1% π beam is available. The beam rate needed is quite low, 10^5/pions/pulse would be sufficient.

We would like to collect approximately 10^5 events. Under the assumption of five to ten triggers/coherent event, we are then talking about 5×10^5 to 10^6 total pictures. With PEPR, this is not an unreasonably large number. The streamer chamber system is capable of two and possibly three triggers/pulse, if the beam rate and cross section are high enough to give us the triggers. We would then require about 800 hours of data taking time (at one trigger/pulse). The amount of time required will obviously be less if we can reduce the 10:1 pictures/event ratio. We plan to test the efficiency of our trigger and chamber arrangement in a high energy π beam at a machine either in the U.S.A. or at CERN.

IV. APPARATUS.

In the following table, we list the apparatus necessary for this experiment and by whom it shall be provided.

LIST	UW	Orsay	NAL
1 x .5 x .5 m^3 20 kg magnet with 3 cameras		X	
Streamer chamber	X		
Proportional Chambers	X	X	
Scintillator Counter and Electronic logic	X		
PEPR for Measuring Film	X		
Small Computer (PDP-8)	X		
Beam, $\pi^-(10^5 - 10^6)$/Pulse, $\Delta p/p = 0.1\%$			X
Power and Water for Magnet			X
Space Requirement of Approximately 10 - 12 Meters by 6 meters and trailer space			X

APPENDIX A

The ability to reconstruct the missing mass is critical to this experiment. In the reaction $\pi + \mathrm{He} \rightarrow \mathrm{He} + X$, the mass of X is given by

$$m_x{}^2 = m_\pi{}^2 + 2\, m_\alpha{}^2 + 2\, m_\alpha\, E_\pi - 2\, E_\alpha (E_\pi + m_\alpha) + 2\, p_\alpha\, p_\pi \cos\theta \,.$$

In this equation, m_π and m_α refer to the masses of the incident pion and the target nucleus respectively. $E_\pi (p_\pi)$ is the energy (momentum) of the incident beam, $E_\alpha (p_\alpha)$ is the energy (momentum) of the recoil nucleus, and θ is the scattering angle of the recoil nucleus. In order to make an estimate of whate the mass resolution will be, we form the following quantities:

$$\frac{\partial m_x}{\partial p_\pi} = - \frac{T_\alpha + p_\alpha \cos\theta}{m_x} \quad ,$$

where T_α is the kinetic energy of the recoil nucleus,

$$\frac{\partial m_x}{\partial p_\alpha} = \frac{1}{m_x} (p_\pi \cos\theta - \beta_\alpha (E_\pi + m_\alpha)) \ ,$$

$$\frac{\partial m_x}{\partial \theta} = - \frac{p_\alpha\, p_\pi \sin\theta}{m_x} \quad .$$

Since T_α , p_α and $\cos\theta$ are all rather small quantities $\frac{\partial m_x}{\partial p_\pi}$ is small.

As Δp_π , the uncertainty in the beam momentum, is also small (100 MeV/c), the uncertainty in m_x due to Δp_π is negligible. The analyses of the contributions of Δp_α and $\Delta\theta$ to Δm_x are not as simple Using a measuring error in p_α of 1 - 2% and an error in θ of 1 - 5 milliradions, we find that the error in m_x

$$\Delta m_x \approx \frac{100 - 150}{m_x} \ \mathrm{MeV} \quad .$$

A more careful calculation of the resolution to be expected by measuring the recoil alone is in progress. It must be pointed out, however, that we do have additional constraints in the problem. The combination of the streamer chamber and the downstream proportional chamber give us a very accurate determination of the directions of the outgoing pions and a measurement, albeit, not very accurate, of their momenta. These additional data will certainly improve our mass resolution. We are currently performing Monte Carlo calculations in order to better determine our mass resolution.

REFERENCES

1. I.Ia. Pomeranchuk and E.L. Feinberg, Dakl, Akad. Nauk SSSR 93,439(1953), Suppl. Nuovo Cimento 3, 652,(1956).
2. R.J. Glauber, Phys. Rev. 99,1515(1955).
3. M.L. Good and W. D. Walker, Phys. Rev. 120,1857(1960).
4. a) J.F. Allard, et al., Nuovo Cimento 46A, 737 (1966).
    b) B. Daugeras, et al., Phys. Letters 27B, 332 (1968).
    c) R. Huson, et al., Phys. Letters 28B, 209 (1968).
    d) J.J. Veillet, Proc. 1967 CERN Conf. on High Energy Collisions of Hadrons, CERN 68-7, p. 537.
5. E.V. Anzon, et al., Phys. Letters 31B, 241 (1970).
6. R. Deck, Phys. Rev. Letters 13, 169 (1964).
7. J. Ballam, et al., Phys. Rev. Letters 21, 934(1968)(A_1^-); W.B. Johnson private communication (preliminary results for A_1^+).
8. R.J. Glauber, Lectures in Theoretical Physics (Interscience Publishers, Inc., New York, 1959), Vol. I, p. 315; L. Stodolsky, Phys. Rev. 144, 1145(1966); A.S. Goldhaber and C.J. Joachain, ibid.171,1566(1968).
9. B. Margolis, Phys. Letters 26B, 524(1968); S.C.C. Ting, in proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 CERN Scientific Information Service, Geneva, Switzerland.

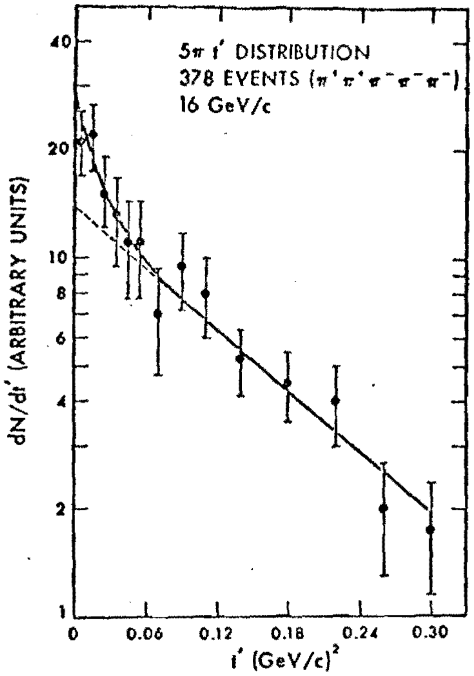


Fig. 2. Distribution in $t' = t - t_{min}$ for all data.

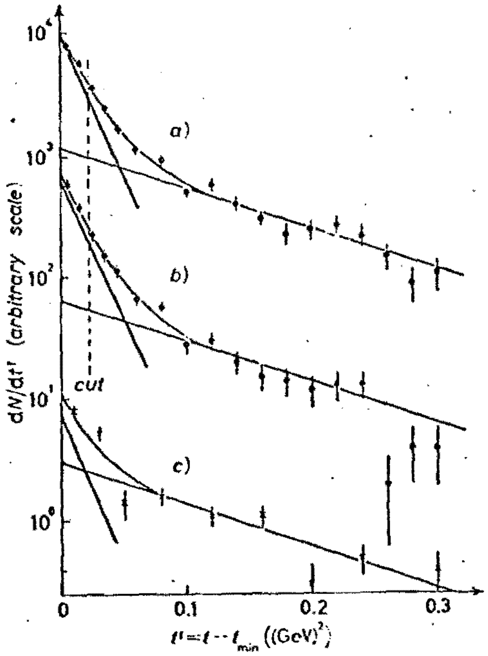


Fig. 1. – dN/dt' for a) all $\pi^+\pi^-\pi^-$, b) $\pi^-\rho^0$, c) π^-f^0 events. The steeper slope is 54 (GeV)$^{-2}$ (80 (GeV)$^{-2}$ after correcting for resolution) and the other 7.7 (GeV)$^{-2}$ (8.1 (GeV)$^{-2}$ after correcting for resolution). The cut taken for coherent events is shown by the dashed line.

Figure 1, Momentum Transfer Distribution for Production of 3π and 5π Charged Pions in the OSMB Experiment.

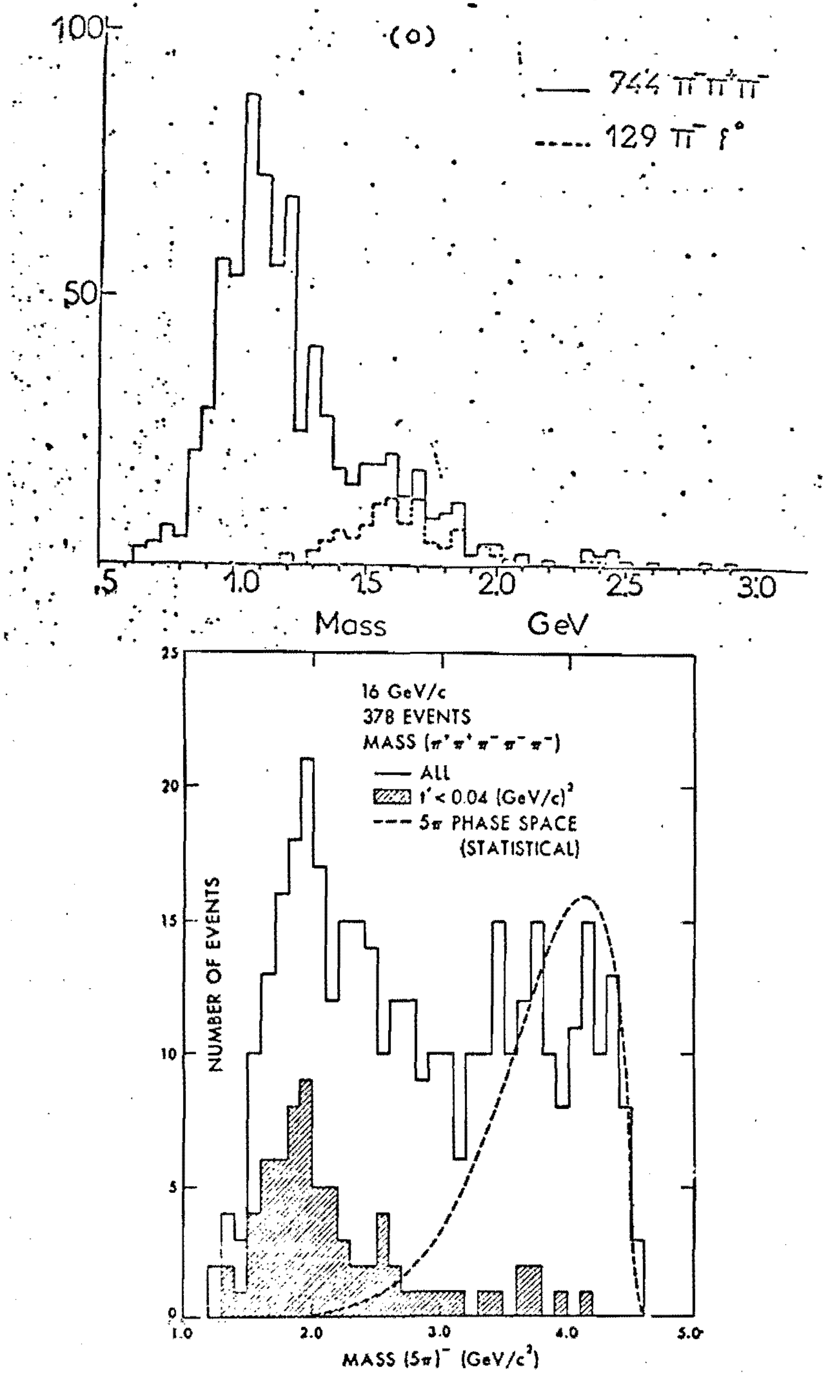


Figure 2, Mass Spectra in the OSMB Experiment.

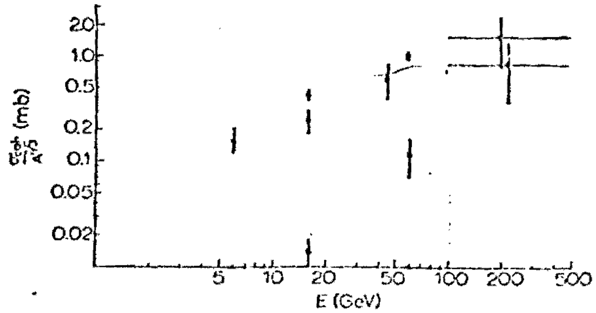


Fig.3a "Normalized" cross section $\sigma_{coh}/A^{2/3}$ for the coherent reactions $\pi^- \rightarrow 3\pi^\pm$ and $\pi^- \rightarrow 5\pi^\pm$ as a function of the primary energy E_0. A 20% correction for the contamination of the three-prong coherent events by the reaction (1) has not been introduced at 60 GeV/c since it cannot be done at 45 GeV/c and at ~200 GeV/c.

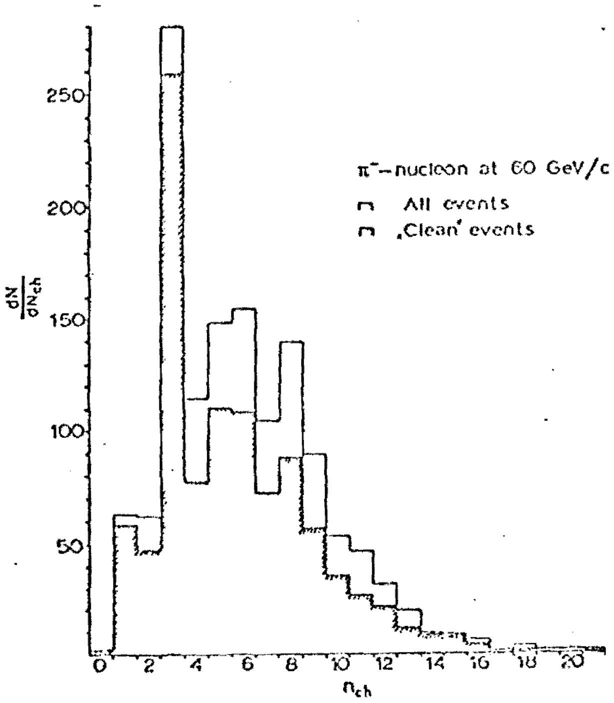


Fig.3b Prong-number distribution of π^--nucleon interactions at 60 GeV/c. The dashed distribution corresponds to the "clean" events.

Figure 3,Results of the Serpukhov Emulsion Experiment for 60 GeV/c Incident π^- .

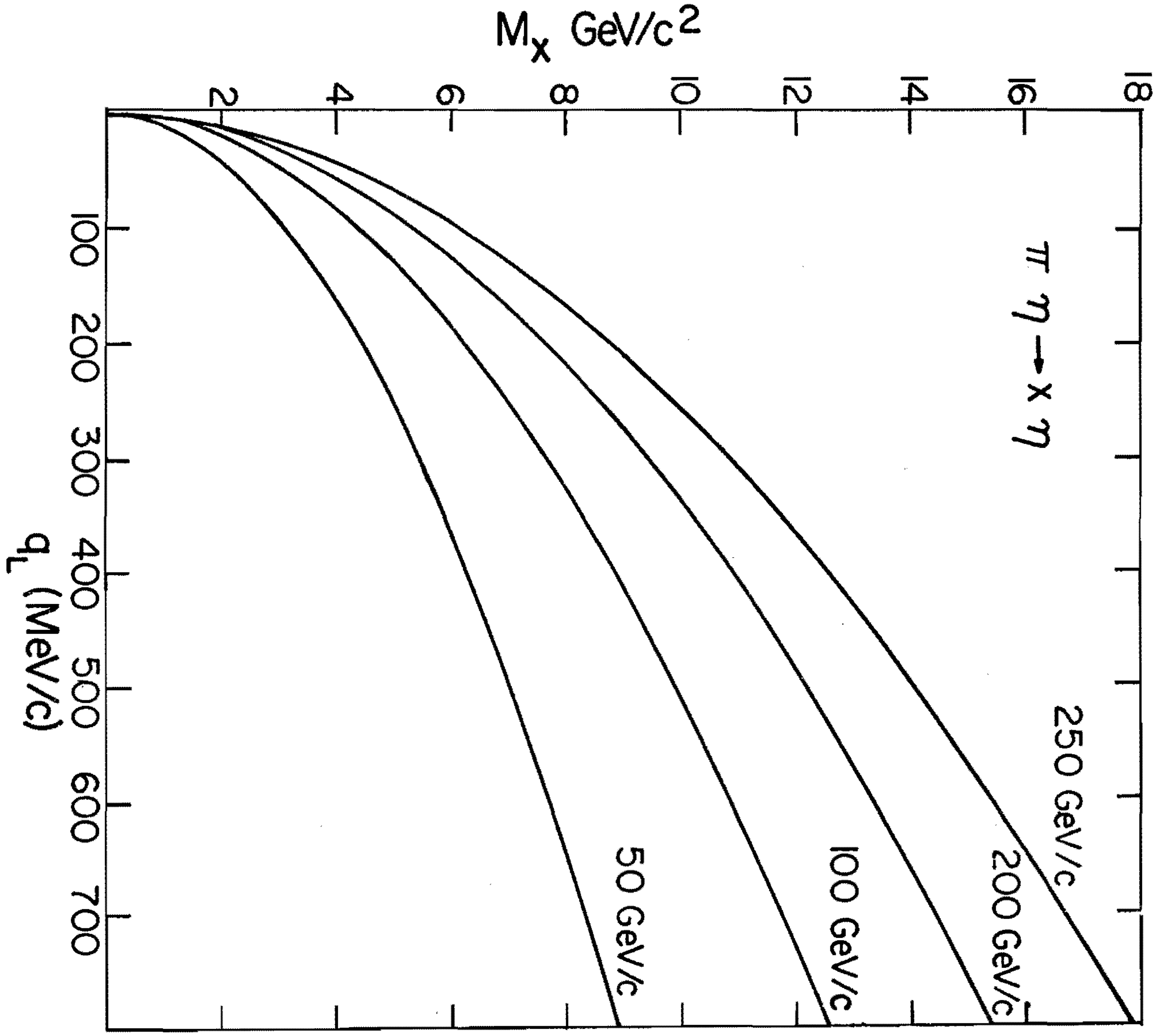


Figure 4, Minimum Momentum Transfer to the Nucleus in the dissociation of a pion into a system of mass M_x for incident momenta between 50 and 250 GeV/c.

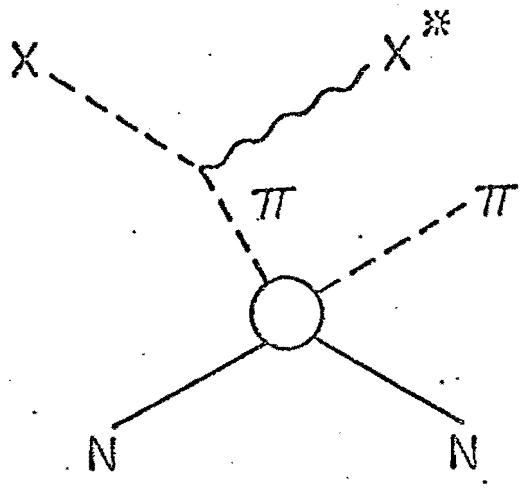


Figure 5, Diffraction Dissociation Diagram. For this case the X ≡ π, X* ≡ ρ.

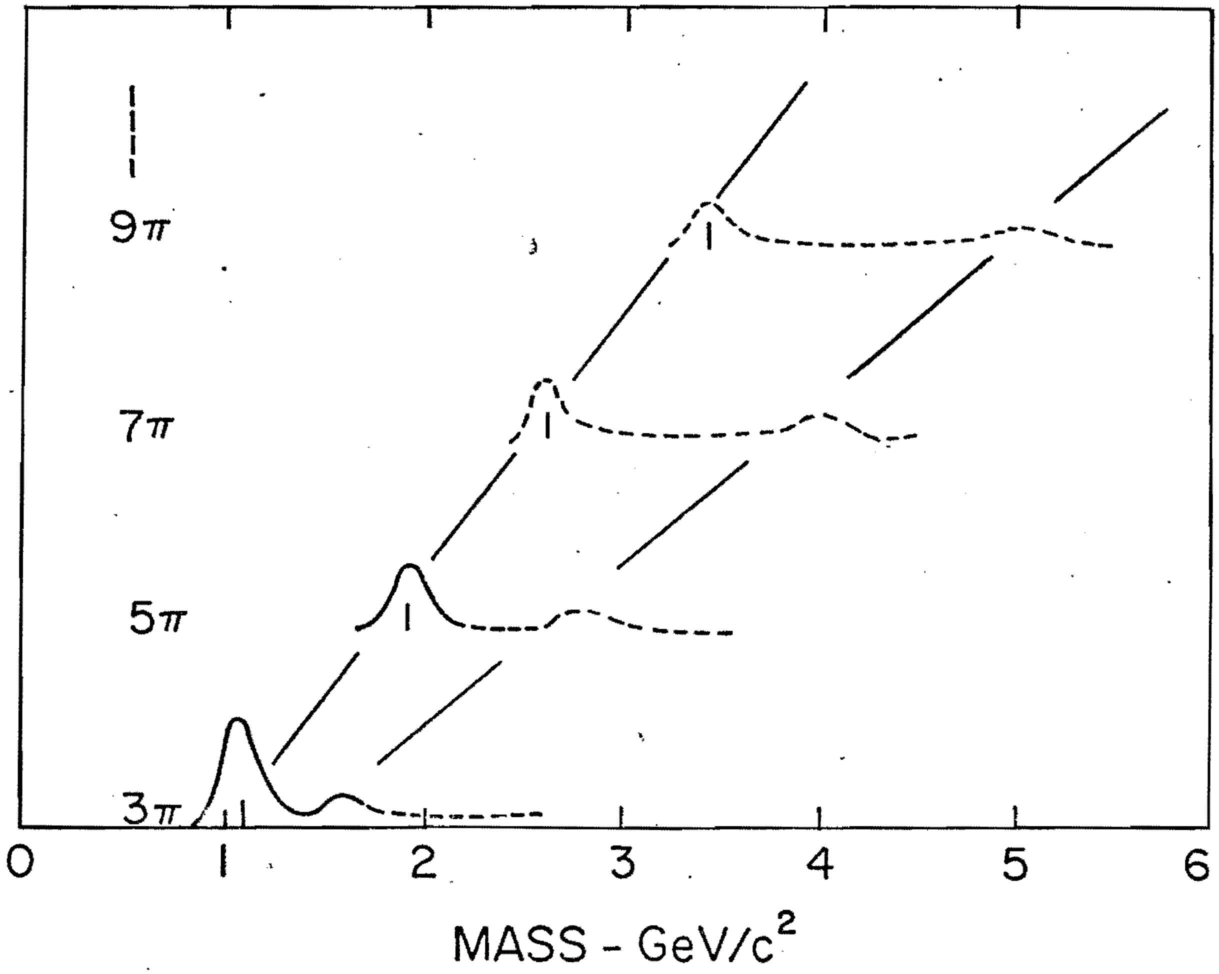


Figure 6, Mass Spectra for the Various Multiplicities into which a Pion can Dissociate. The solid curves indicate observed enhancements, while the dotted curves are prdictions based on the constant Q per pion hypothesis discussed in the text.

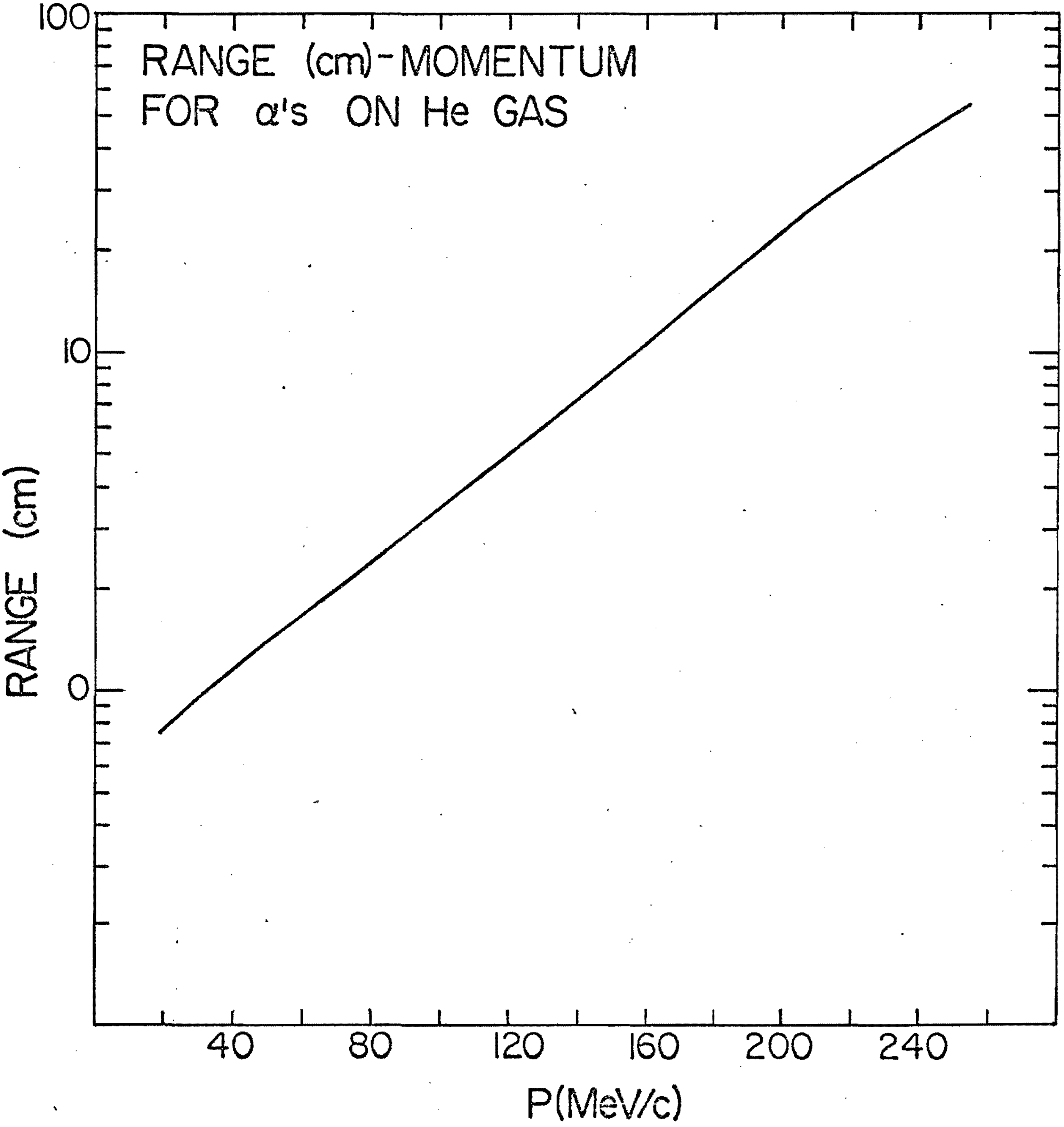


Figure 7, 2 Range in the He gas at 1 atmosphere.

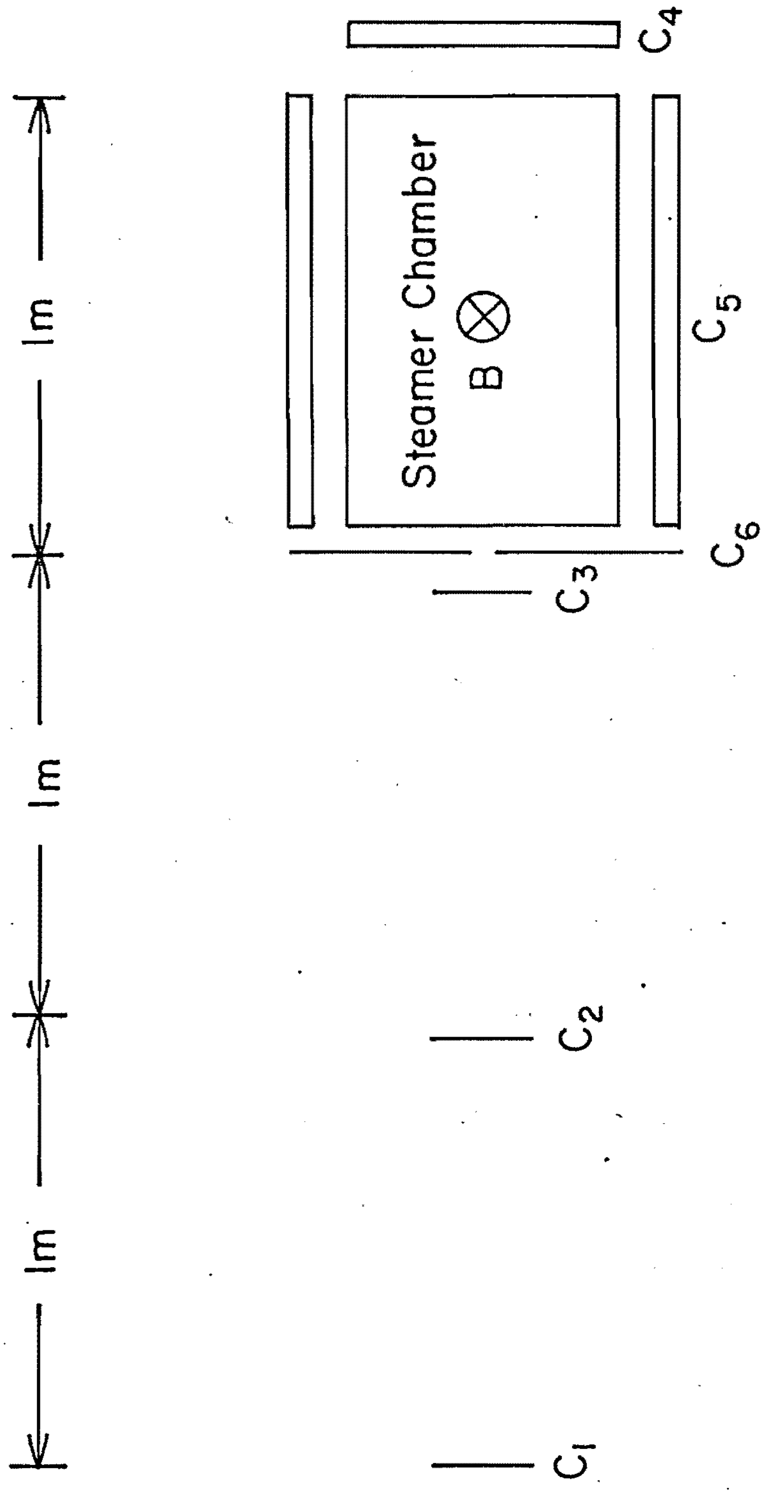


Figure 8, Experimental Arrangement.

NAL PROPOSAL No. 86-A

Correspondent: J. J. Lubatti
Department of Physics
University of Washington
Seattle, Wash. 98105

FTS/Off-net: 206-583-0111
543-2100

A PROPOSAL TO STUDY INELASTIC DIFFRACTIVE PROCESSES BY OBSERVING COHERENT PRODUCTION OF MULTI-PION FINAL STATES FROM HE NUCLEI

P. L. Bastien, V. Cook, R. Kenyon, L. D. Kirkpatrick, H. J. Lubatti,
D. Wolfe, R. Harris, A. Jonckheere, S. Spencer
University of Washington

D. Fournier, P. Heusse, F. Jacquet, A. Lagarrigue, J. J. Veillet
Orsay

July 20, 1970

Updated October 12, 1970

A PROPOSAL TO STUDY INELASTIC DIFFRACTIVE PROCESSES BY OBSERVING COHERENT PRODUCTION OF MULTI-PION FINAL STATES FROM HE NUCLEI

University of Washington and Orsay Collaboration

ABSTRACT

We propose to study the diffraction dissociation of pions into multi-pion final states, by obtaining the missing mass spectra from the reaction:

$$\pi^- + \mathrm{He} \rightarrow n\pi^- + (n - 1)\pi^+ + \mathrm{He}.$$

The missing mass is calculated from a measurement of the He recoil which is observed in a streamer chamber. In this first exploratory experiment we propose to count the outgoing fast particles, and to measure in a very crude fashion their momenta.

Names of Experimenters:

	Ph.D's	Students
University of Washington:	P.L. Bastien	R. Harris
	V. Cook	A. Jonckheere
	R. Kenyon	S. Spencer
	L. Kirkpatrick	
	H.J. Lubatti	
	D. Wolfe	
Orsay:	D. Fournier	
	P. Heusse	
	F. Jacquet	
	A. Lagarrigue	
	J.J. Veillet	

Date:

July 20, 1970, updated October 12, 1970

Name of Correspondent:

H.J. Lubatti

I. INTRODUCTION.

We are proposing to study the surface states of the pion by observing the diffraction dissociation of pions into multi-pion final states. Such an experiment yields information about the "surface" because, by the nature of diffraction dissociation, we are constrained to small momentum transfers. In particular, in this experiment, we propose to use helium nuclei as a target. The form factor for the helium nucleus will then insure that the momentum transfer is less than ∿300 MeV/c. The physics in this experiment is not unlike that obtained when we have the collision of two carbon nuclei in which the incident nucleus has only a peripheral collision and we observe the excitation of surface waves on the nucleus (the analog of deep inelastic scattering for nuclei would then be those collisions in which nucleons are excited into the continuum). As is well known from the study of nuclei, both the excitation of surface states and the study of deep inelastic scattering is necessary for a good understanding of the physics ; likewise, in order to understand the structure of a pion, it will be necessary to obtain detailed information about the surface states as well as detailed information about the deep inelastic scattering. This experiment proposes to study only the former, namely, the surface states of the pion.

This experiment is a rather simple one which is aimed at "getting a look" at the various surface states which exist. Therefore, we are purposely designing this experiment not to restrict ourselves in the trigger logic, because, while results at existing accelerator energies give us some indication of what we might expect, the extrapolation of the incident energy by an order of magnitude will undoubtedly provide many surprises. Hence, we are using existing experimental information as a guide, but we are designing with very loose criteria so that new and unsuspected occurrences will not be overlooked.

The experimental apparatus, which will be discussed in greater detail in Section III and IV consists of a streamer chamber filled with helium gas. The helium nuclei act as both target and detector. By placing the streamer chamber in a magnetic field, it will be possible to obtain good momentum and angle measurements of the recoiling helium nucleus. We will, therefore, be able to obtain the missing mass of the multi-pion system which is recoiling against the helium nucleus. In addition, the fast charged pions will be visible in the chamber, and we will be able to measure the laboratory opening angle. A Charpak chamber at the downstream end of the chamber will allow us to count the number of outgoing pions and use this, if necessary, in the trigger. However, at the outset we would propose to take all interactions where more than twc fast particles come out. In Section II we discuss the intuitive ideas behind diffraction dissociation, and what one might expect at higher energies based on the rather sparse data which now exist. In Sections III and IV we discuss the experimental set-up and the resolution which we think we will be able to obtain in this experiment.

This experiment makes no request of NAL other than for a pion beam and power for operating the magnet. The magnet will be supplied by the group at Orsay. It is capable of 20 kg over a volume of 1 x .5 x .5 m^3 and has provisions for 3 view stereo photography. It is the Ecole Polytechnique magnet designed by A. Lagarrigue's group for use with the Ecole's heavy liquid bubble chamber which has now been retired.

II. PHYSICS JUSTIFICATION.

A. Background on Diffraction Dissociation.

Diffraction dissociation was first proposed by Feinberg and Pomeranchuk in 1953 1). It was then employed by Glauber in a discussion of deuteron stripping 2). The concept was later applied to hadronic processes by Good and Walker in 1960 3). It was this last paper which generated considerable interest in diffractive processes for the production of hadronic states and lead to a considerable amount of experimental work, using both nuclei and nucleons as targets.

The basic idea is that at high energies a particle of mass m can dissociate into a system of mass m* with only very little momentum transfer to the target M, such that the phase difference of the de Broglie waves of states m and m* are degenerate over the target. Another way of saying this is that as a particle passes through the nucleon or nucleus, it is a mixture of its eigen states in "nucleon stuff". Good and Walker pointed out that the absorption of the m* component would result in the Fraunhofer diffraction scattering of m*. Such a picture requires of the target that it absorb the incoming wave and take up whatever recoil momentum is necessary in order to account for the mass difference $\delta m = m^* - m$. We should note in passing that this is very much like the role of a proton or heavy nucleus in pair production. Now from such a picture, we would not expect any change in the internal quantum numbers $(C,G,T,Y,\sigma = P(-1)^J)$ of the incident particle. (There of course could always be a change in the angular momentum state.) We would, however, expect the cross section to be nearly constant with energy, since in diffractive processes the cross section depends only on the area of the absorbing disk. In addition, the diffractive nature of the interaction dictates that there be sharp forward peaking of the differential cross section. To summarize, we would expect for such diffractive processes:

(1) Sharp forward peaking (Fraunhofer diffraction).
(2) Small or no energy dependence of the cross section.
(3) No change in the internal quantum numbers of the dissociated particle.

In the modern language of particle exchange models, one would say that a diffractive process is one in which a Pomeron is exchanged between the incident and target particle, and since the target plays no role in the dynamics of the inelastic diffraction, such processes are sensitive probes of the surface structure of the pion.

B. Existing Information.

Coherent production of multi-pion final states has been studied in great detail by the Orsay-Saclay-Milan-Berkeley (OSMB) collaboration using a heavy liquid bubble chamber filled with C_2F_5Cl 4). In their experiment, the coherent production of three and five pion final states was observed. The momentum transfer to the nucleus observed by the OSMB experiment is shown in Figure 1. One notices two slopes: The first slope $\sim 80\,(\mathrm{GeV}/c)^{-2}$ is characteristic of the form factor of the nucleus involved, while the second slope $\sim 10\,(\mathrm{GeV}/c)^{-2}$ represents events in which the nucleus has been broken up; therefore, the interaction is an incoherent one which takes place on a nucleon.

The 3π and 5π mass spectra which were observed in these experiments are shown in Figure 2. The first peak that occurs in the 3π mass spectrum occurs near the $\rho\pi$ threshold at 1.08 GeV/c^2 (a_1); indeed, the OSMB collaboration finds that the mass spectrum up to 1.4 GeV/c^2 consists almost entirely of $\rho\pi$ final states. They also observe an enhancement at approximately 1.6 GeV/c^2 which is mainly $f°\pi(A_{1.6})$. The coherently produced 5π events show a peak in the 5π mass spectrum at approximately 1.9 GeV/$c^2(A_{1.9})$ which, as is noted in reference 4c, is near the A_1 ρ threshold. In the OSMB data, although the statistics are not overwhelming, there is indication of A_1 and ρ.

Further evidence of coherent production of multi-pion final states has been obtained by a Russian collaboration at Serpukhov$^{5)}$. This experiment was performed using an emulsion stack as the target and detector. In this experiment, they did not measure the momentum of the outgoing particles, and therefore, could not observe the invariant mass spectrum. However, they did obtain a multiplicity plot which is shown in Figure 3b. They found that the number of 3 pion events far exceeded the other multiplicities. For the events in which no nuclear breakup was observed, they found that $\Sigma_i \sin\theta_i$ peaked near zero, where θ is measured relative to the beam, while for nuclear breakup events the distribution is broader; since the $\Sigma_i \sin\theta_i$ is proportional to the longitudinal momentum transfer, it is very likely that this experiment is observing dissociation of a pion into 3 and 5 pions.

An experiment has been performed at CERN with a pion beam using several nuclei as targets. The beam momentum was approximately 16 GeV/c. The fast secondaries were detected by optical spark chambers placed in a magnet. Analysis of this experiment is nearly completed and private communications indicate that dissociation into three pions has been observed, and the effective mass spectrum has the classical diffraction shape of the OSMB experiment.

The apparent lack of events at the higher multiplicities in the existing experiments can be understood in terms of the momentum transfer necessary to produce the final state. At high energies the minimum momentum transfer which is necessary to produce a multi-pion state of invariant mass M is given by

$$q_1 = (M^2 - m_\pi^2)/2p_{inc} ,$$

where p_{inc} is the momentum of the incident pion. In Figure 4 we show typical minimum momentum transfers for various invariant masses and incident pion momenta between 50 and 250 GeV/c. The momentum transfer distribution for interactions on the nucleus, where a pion dissociates and a nucleus recoils without breaking up, is dependent on the nuclear form factor. This was demonstrated by the OSMB data in Figure 2, where the two slopes clearly show coherent recoil of the nucleus (slope of $\sim 80 (GeV/c)^{-2}$), and a nucleon recoil (slope of $\sim 10 (GeV/c)^{-2}$). Intermediate nuclei in the range of 12 - 40 nucleons have diffraction minima ranging from 150 to 200 MeV/c. The heavy nuclei such as Pb have the first minima occurring at 100 MeV/c or less. Therefore, the above experiments performed either at 16 GeV/c on intermediate nuclei, or at 60 GeV/c on heavy emulsion nuclei are not terribly sensitive to the heavier states into which a pion can dissociate.

There has been considerable controversy over the true nature of such diffractively produced mass enhancements. The question of whether such enhancements are in fact resonances in the usual sense, or merely manifestations of the kinematics of the interaction has not been satisfactorily answered. A model known as the Drell-Hiida-Deck model has been proposed which gives rise to threshold enhancements in the $\rho\pi$ system at 1 GeV/c^2 (see Figure 5). In such a model the mass peak results purely from the kinematics and has no dynamical origin. Goldhaber et al. have suggested that a possible way to test such a model would be to measure the interaction cross section of the $\rho\pi$ system with nucleons$^{7)}$. The argument is that if the A_1 system has a cross section for interacting with nucleons which is essentially that of the π-nucleon or the ρ-nucleon cross section rather than the sum of the two, then the conclusion is that the $\rho\pi$ system does not behave as though it were a free ρ and π. The only way to measure such cross sections is to produce the system in question on nuclei and make use of the Glauber or high energy model in order to measure the attenuation of the multi-pion system as it leaves the nucleus. The details of this model have been worked out by Glauber and others8), and it is this model which has been used with great success by Ting and co-workers in obtaining the ρ-nucleon cross section from the photo production of ρ mesons on nuclei9). Goldhaber et al. found that when they analyzed the OSMB data in this way, the effective A_1 nucleon cross section was compatible with the π-nucleon cross section, which argues against the A_1 being simply a Deck like kinematic effect 7).

C. Expectations at Higher Energies.

It is interesting to note that in the OSMB experiment the Q per pion is approximately 220 MeV in both the 1.09 and 1.9 GeV/c^2 peaks shown in Figure 2. If one extrapolates to a 7π system assuming 220 MeV per pion, we would expect the 7π system to show a peak near 2.6 GeV/c^2 which is, amazingly enough, approximately the threshold of the $A_{1.9} + \rho$, whereas the 1.9 GeV/c^2 (5π) enhancement occurs at approximately $A_1 + \rho$ threshold. This leads one to the interesting speculation that the pion is composed basically of many ρ's, and it dissociates by kicking out "one more ρ". The 9π peak in this simple model would then occur at approximately 3.4 GeV/c^2. A similar conclusion can be reached for the $f°\pi$ system, where 1.6 GeV/c^2 enhancement implies a Q per pion of 410 MeV. Such a model suggests the multi-pion spectra shown in Figure 6. The solid lines indicate the enhancements which have been produced diffractively in the existing experiments. The dotted lines indicate the enhancements which are suggested by the constant Q per pion discussed above. We expect a mass resolution of $\Delta m_x = (100\text{-}150)/m_x$ MeV/c^2, where m_x is in GeV/c^2. This is sufficient for the spectra shown in Figure 6; however, it is possible that the resolution may be improved. (See Appendix A.)

The cross section which has been obtained by the emulsion groups, indicates that at 100 GeV/c we should expect approximately 2 mb for the 3π channel alone, which will be ample cross section for us to observe.

IV. EXPERIMENTAL ARRANGEMENTS.

The ideal detector for investigating coherent production on helium (or other noble gas nuclei) is the streamer chamber. The chamber gas serves both as target and detector. The low density of the gas means that the recoil nucleus has a range long enough to allow us to measure the track curvature in a magnetic field. Below $\sim$200 MeV/c, a recoil He nucleus will stop in the gas, thus allowing us to use Range to determine the momentum as well (see Figure 7). The target density is still sufficient to give us a high trigger rate. For a fiducial volume 50 cm long, we have in He 1.5×10^{-6} interactions/mb of cross section/beam π. We envisage using a chamber 1 meter long by 50 cm wide. It will be a standard double gap chamber, with 15 cm gaps. A chamber of this size has already been successfully run using both pure helium and the standard 90%-10% Ne-He mixture.

In keeping with the large number of possible final states, we would like to use as flexible a trigger as possible. The counters used in the trigger logic as shown in Figure 8a. The incoming beam direction is defined by small proportional chambers. C4 is also a proportional chamber, used as a logic element which allows us to predetermine the minimum number of particles desired for a trigger. Since no recoil nucleus can get through the walls of the chamber, the presence of particles out the sides indicates an event of no interest. Counter C5, a combination of scintillator and thin lead sheet, is to be used in an anti-coicidence mode. C5 is extended to cover the bottom of the chamber as well. Thus a complete trigger for the chamber would be

$$C1\ C2\ C3\ C4(X \geq n)\ \overline{C5}\ \overline{C6}\ .$$

The chamber will be operated with a memory time of 2 to 5 μsec., using chemical clearing. Due to the extremely high multiple track efficiency, we do not foresee any difficulties with high beam rates or random extra tracks in the chamber. The magnet in which the chamber will be placed is the one in which Professor Lagarrigue's heavy liquid bubble chamber BP3 was previously housed. (See Appendix B for details.) A floor plan of the experimental set-up is given in Figure 10.

As mentioned above the trigger requirements are designed to be initially as loose as possible. This will, of course, lead to a fairly large number of pictures. This is not a serious problem however, as we plan to use our PEPR automatic measuring machine for analysis. A developmental program to enable PEPR to read streamer chamber film is beginning. The advantage of using a proportional chamber for C4 is that the trigger requirement can easily be changed during the course of the experiment. We plan to trigger initially on three or more fast particles. If we then find that the majority of our triggers contain 3 pions, as we expect, we can use the proportional chamber to demand five tracks and concentrate on the higher multiplicities.

Aside from the beam, and of course, water and power for our analyzing magnet, there is essentially no contribution necessary from NAL. Our equipment is relatively simple. A prototype streamer chamber with a Marx generator and Blumlein already exists. As a result of the work of the SLAC streamer chamber group, optics is no longer a problem. Sufficiently fast film and lenses exist and are in hand. Proportional chambers have been built at the University of Washington and further development is in progress. Thus, we feel that this experiment is sufficiently simple so that we can be ready as soon as there is a pion beam. We envisage 4 to 6 weeks of set-up and testing in which only approximately %50 is beam time. This testing can be done parasitically or even before a 0.1% π beam is available. The beam rate needed is quite low, 10^5/pions/pulse would be sufficient.

We would like to collect approximately 10^5 events. Under the assumption of five to ten triggers/coherent event, we are then talking about 5×10^5 to 10^6 total pictures. With PEPR, this is not an unreasonably large number. The streamer chamber system is capable of two and possibly three triggers/pulse, if the beam rate and cross section are high enough to give us the triggers. We would then require about 800 hours of data taking time (at one trigger/pulse). The amount of time required will obviously be less if we can reduce the 10:1 pictures/event ratio. We plan to test the efficiency of our trigger and chamber arrangement in a high energy π beam at a machine either in the U.S.A. or at CERN if time permits.

IV. APPARATUS.

In the following table, we list the apparatus necessary for this experiment and by whom it shall be provided.

LIST	UW	Orsay	NAL
1 x .5 x .5 m^3 20 kg magnet with 3 cameras		X	
Streamer chamber	X		
Proportional Chambers	X	X	
Scintillator Counter and Electronic logic	X		
PEPR for Measuring Film	X		
Small Computer (PDP-8)	X		
Beam, $\pi^-(10^5 - 10^6)$/Pulse, $\Delta p/p = 0.1\%$			X
Power and Water for Magnet			X
Space Requirement of Approximately 10 - 12 Meters by 6 meters and trailer space			X

APPENDIX A

The ability to reconstruct the missing mass is critical to this experiment. In the reaction $\pi + \mathrm{He} \to \mathrm{He} + X$, the mass of X is given by

$$m_x^2 = m_\pi^2 + 2\, m_\alpha^2 + 2\, m_\alpha\, E_\pi - 2\, E_\alpha (E_\pi + m_\alpha) + 2\, p_\alpha\, p_\pi \cos\theta \ .$$

In this equation, m_π and m_α refer to the masses of the incident pion and the target nucleus respectively. $E_\pi (p_\pi)$ is the energy (momentum) of the incident beam, $E_\alpha (p_\alpha)$ is the energy (momentum) of the recoil nucleus, and θ is the scattering angle of the recoil nucleus. In order to make an estimate of what the mass resolution will be, we form the following quantities:

$$\frac{\partial m_x}{\partial p_\pi} = - \frac{T_\alpha + p_\alpha \cos\theta}{m_x} \ ,$$

where T_α is the kinetic energy of the recoil nucleus,

$$\frac{\partial m_x}{\partial p_\alpha} = \frac{1}{m_x} (p_\pi \cos\theta - \beta_\alpha (E_\pi + m_\alpha)) \ ,$$

$$\frac{\partial m_x}{\partial \theta} = - \frac{p_\alpha\, p_\pi \sin\theta}{m_x} \ .$$

Since T_α , p_α and $\cos\theta$ are all rather small quantities $\frac{\partial m_x}{\partial p_\pi}$ is small.

As Δp_π , the uncertainty in the beam momentum, is also small (100 MeV/c), the uncertainty in m_x due to Δp_π is negligible. The analysis of the contributions of Δp_α and $\Delta\theta$ to Δm_x are not as simple.Using a measuring error in p_α of 1 - 2% and an error in θ of 1 - 5 milliradians, we find that the error in m_x

$$\Delta m_x \approx \frac{100 - 150}{m_x} \ \mathrm{MeV} \ .$$

A more careful calculation of the resolution to be expected by measuring the recoil alone is in progress. It must be pointed out, however, that we do have additional constraints in the problem. The combination of the streamer chamber and the downstream proportional chamber give us a very accurate determination of the directions of the outgoing pions and a measurement, albeit, not very accurate, of their momenta. These additional data will certainly improve our mass resolution. We are currently performing Monte Carlo calculations in order to better determine our mass resolution.

APPENDIX B

The magnet has been used for the Ecole Polytechnique's heavy liquid bubble chamber. The chamber,which has now been retired, operated for several years and has taken over 3 x 10^6 pictures. A sketch of the magnet is given in Figure 10.

The visible volume is 1 x .5 x .5 m^3. There is additional free space on top and bottom which can be used for high voltage cables and anti-coincidence counters. If necessary the depth can easily be increased at the cost of slightly reducing the magnetic field. There is easy access to the useable volume at the beam entry and beam exit side of the magnet. The connection to the blumlein can be made at the entrance as is shown in Figures 10 a,b. The present optical system has a total stereo angle of 29°. The maximum magnetic field is 22 kg at a current of 7,500 amps, and a voltage of 575 volts, which implies 4.3 megawatts of power. Under these conditions cooling the magnet requires a water flow of 77 m^3/hour at a pressure head of 25 atmospheres. The temperature rise is then 50° C.

For this experiment a field of about 17 kg requiring only approximately 2 megawatts of power (see Figure 9) is adequate. Then maintaining the same Δt (temperature rise) a water flow of 35 m^3/hr would be sufficient.

Under these operating conditions we would require 5,000 amps at 400 volts; however, since electrical connections of the pancakes are accessible, it is possible to match the magnet to a generator of different characteristics.

REFERENCES

1. I.Ia. Pomeranchuk and E.L. Feinberg, Dakl, Akad. Nauk SSSR 93,439(1953), Suppl. Nuovo Cimento 3, 652,(1956).
2. R.J. Glauber, Phys. Rev. 99,1515(1955).
3. M.L. Good and W. D. Walker, Phys. Rev. 120,1857(1960).
4. a) J.F. Allard, et al., Nuovo Cimento 46A, 737 (1966).
    b) B. Daugeras, et al., Phys. Letters 27B, 332 (1968).
    c) R. Huson, et al., Phys. Letters 28B, 209 (1968).
    d) J.J. Veillet, Proc. 1967 CERN Conf. on High Energy Collisions of Hadrons, CERN 68-7, p. 537.
5. E.V. Anzon, et al., Phys. Letters 31B, 241 (1970).
6. R. Deck, Phys. Rev. Letters 13, 169 (1964).
7. A.S. Goldhaber, C.J. Joachain, H.J. Lubatti, and J.J. Veillet, Phys. Rev. Letters 22 , 802(1969).
8. R.J. Glauber, Lectures in Theoretical Physics (Interscience Publishers, Inc., New York, 1959), Vol. I, p. 315; L. Stodolsky, Phys. Rev. 144, 1145(1966); A.S. Goldhaber and C.J. Joachain, ibid.171,1566(1968).
9. B. Margolis, Phys. Letters 26B, 524(1968); S.C.C. Ting, in proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968 CERN Scientific Information Service, Geneva, Switzerland.

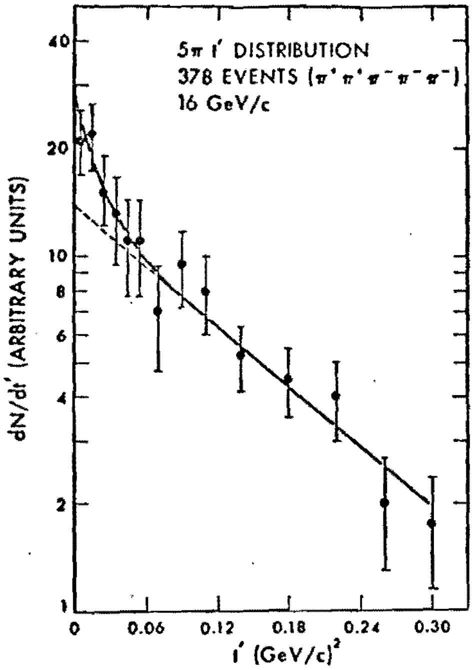


Fig. 2. Distribution in $t' = t - t_{min}$ for all data.

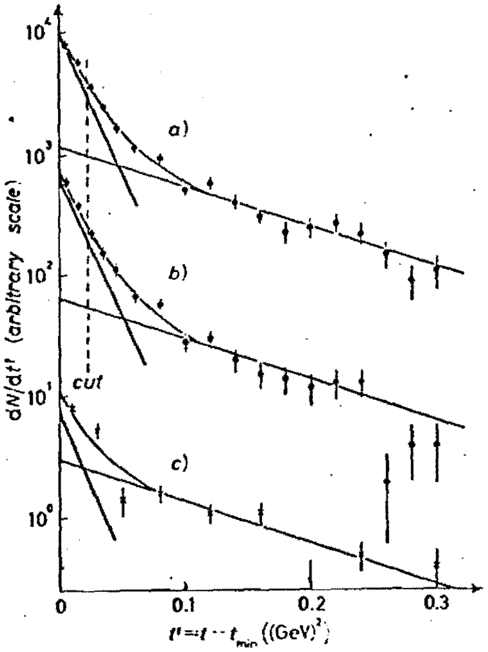


Fig. 1. – dN/dt' for *a*) all $\pi^+\pi^-\pi^-$, *b*) $\pi^-\rho^0$, *c*) $\pi^- f^0$ events. The steeper slope is 54 $(GeV)^{-2}$ (80 $(GeV)^{-2}$ after correcting for resolution) and the other 7.7 $(GeV)^{-2}$ (8.1 $(GeV)^{-2}$ after correcting for resolution). The cut taken for coherent events is shown by the dashed line.

Figure 1, Momentum Transfer Distribution for Production of 3π and 5π Charged Pions in the OSMB Experiment.

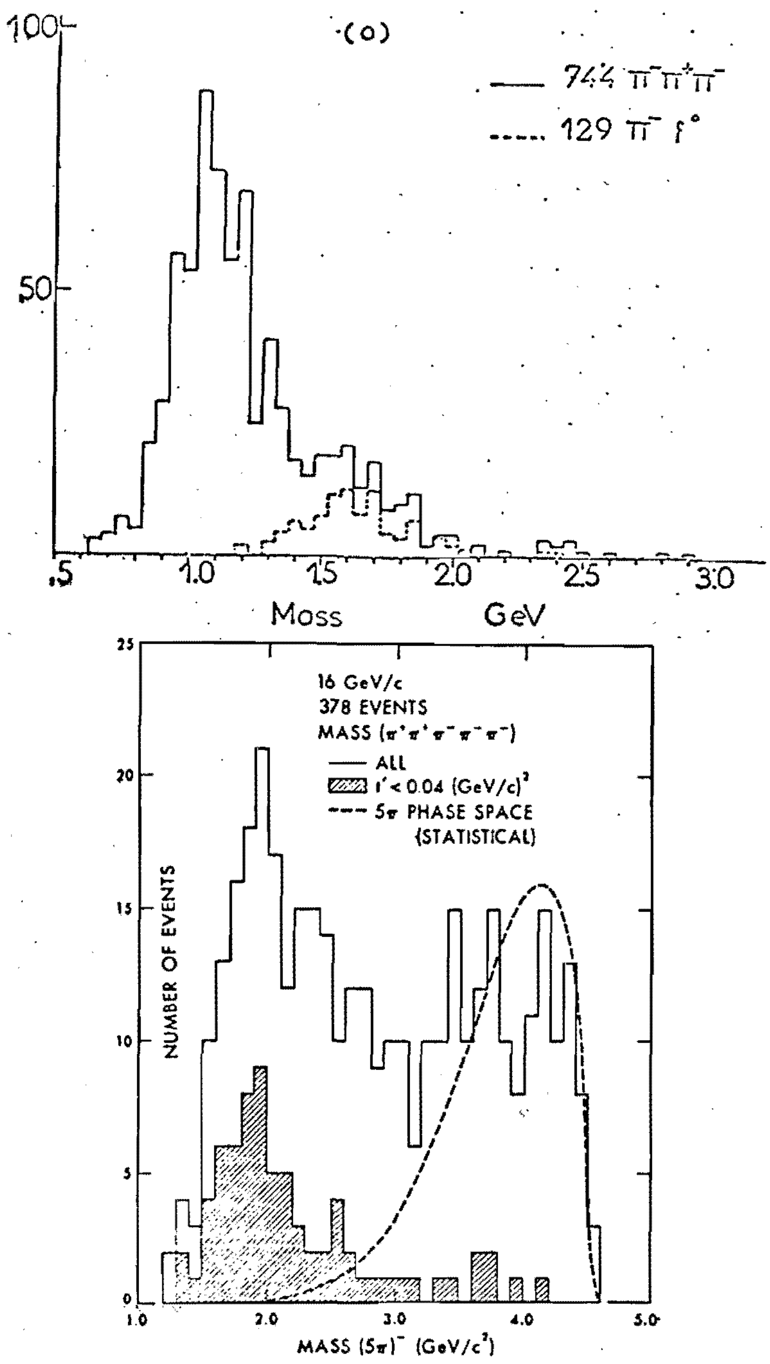


Figure 2, Mass Spectra in the OSMB Experiment.

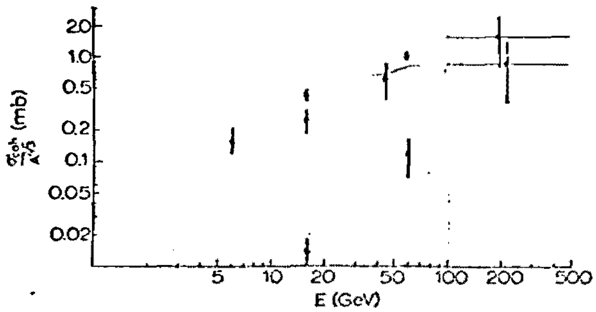


Fig.3a "Normalized" cross section $\sigma_{coh}/A^{2/3}$ for the coherent reactions $\pi^- \to 3\pi^\pm$ and $\pi^- \to 5\pi^\pm$ as a function of the primary energy E_0. A 20% correction for the contamination of the three-prong coherent events by the reaction (4) has not been introduced at 60 GeV/c since it cannot be done at 45 GeV/c and at ~200 GeV/c.

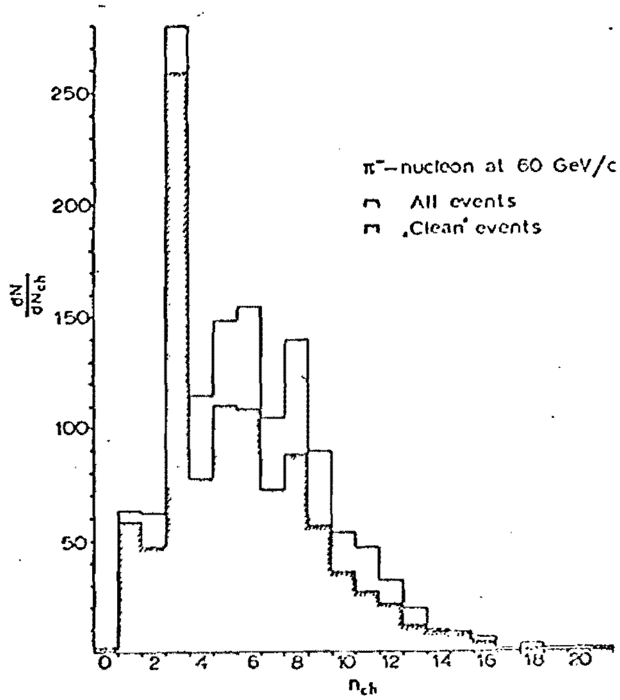


Fig.3b Prong-number distribution of π^--nucleon interactions at 60 GeV/c. The dashed distribution corresponds to the "clean" events.

Figure 3, Results of the Serpukhov Emulsion Experiment for 60 GeV/c Incident π^- .

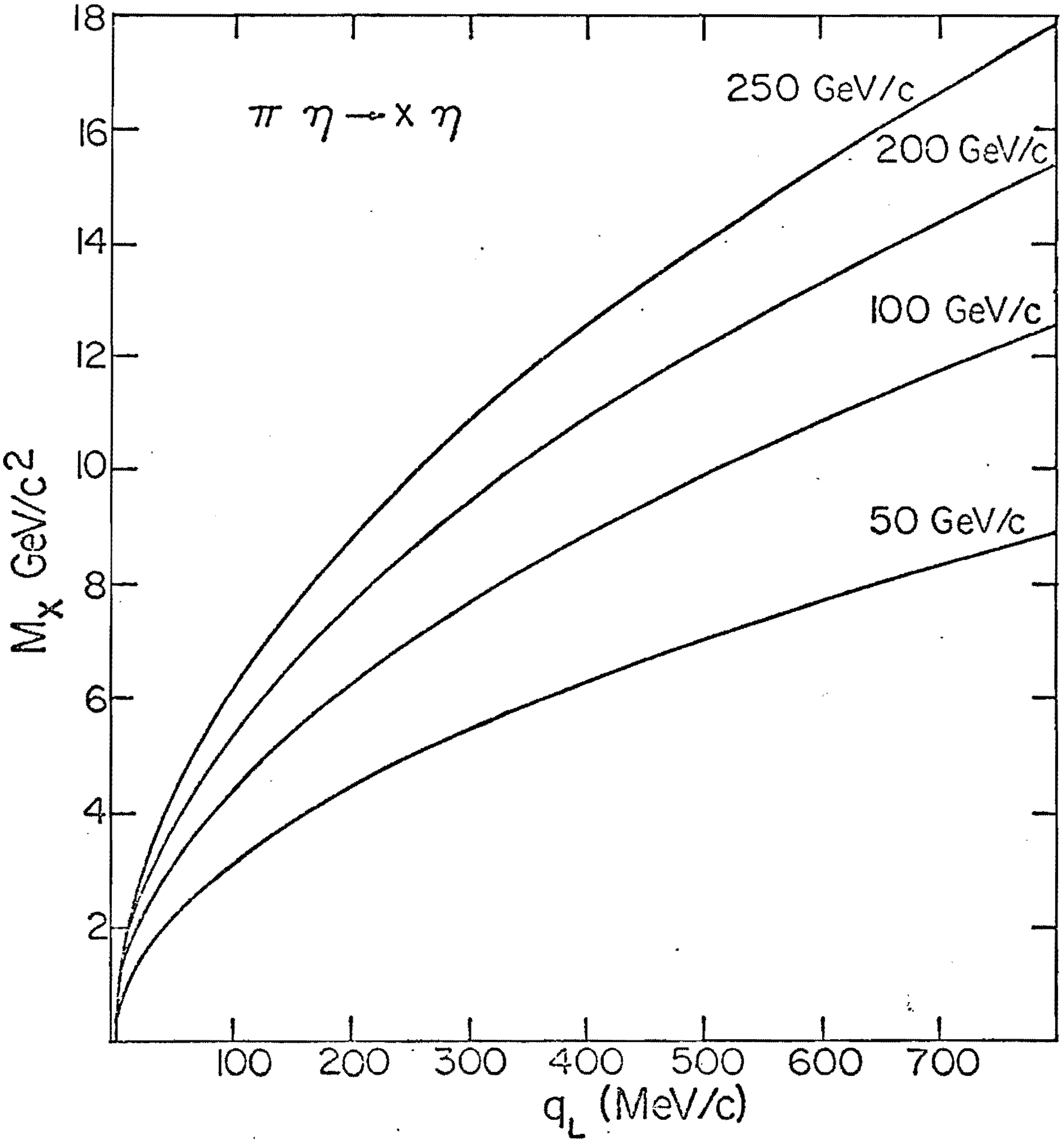


Figure 4, Minimum Momentum Transfer to the Nucleus in the dissociation of a pion into a system of mass M_x for incident momenta between 50 and 250 GeV/c .

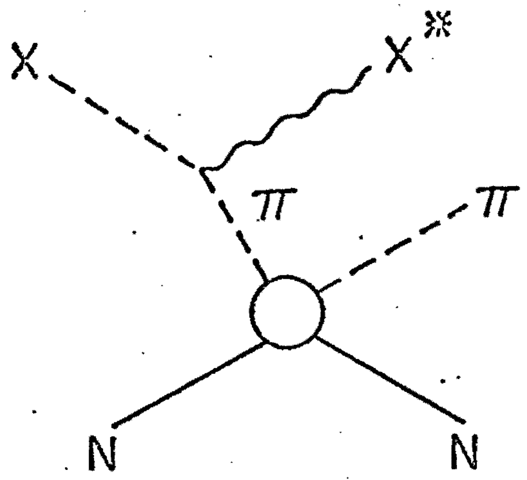


Figure 5, Diffraction Dissociation Diagram. For this case the X ≡ π, X* ≡ ρ.

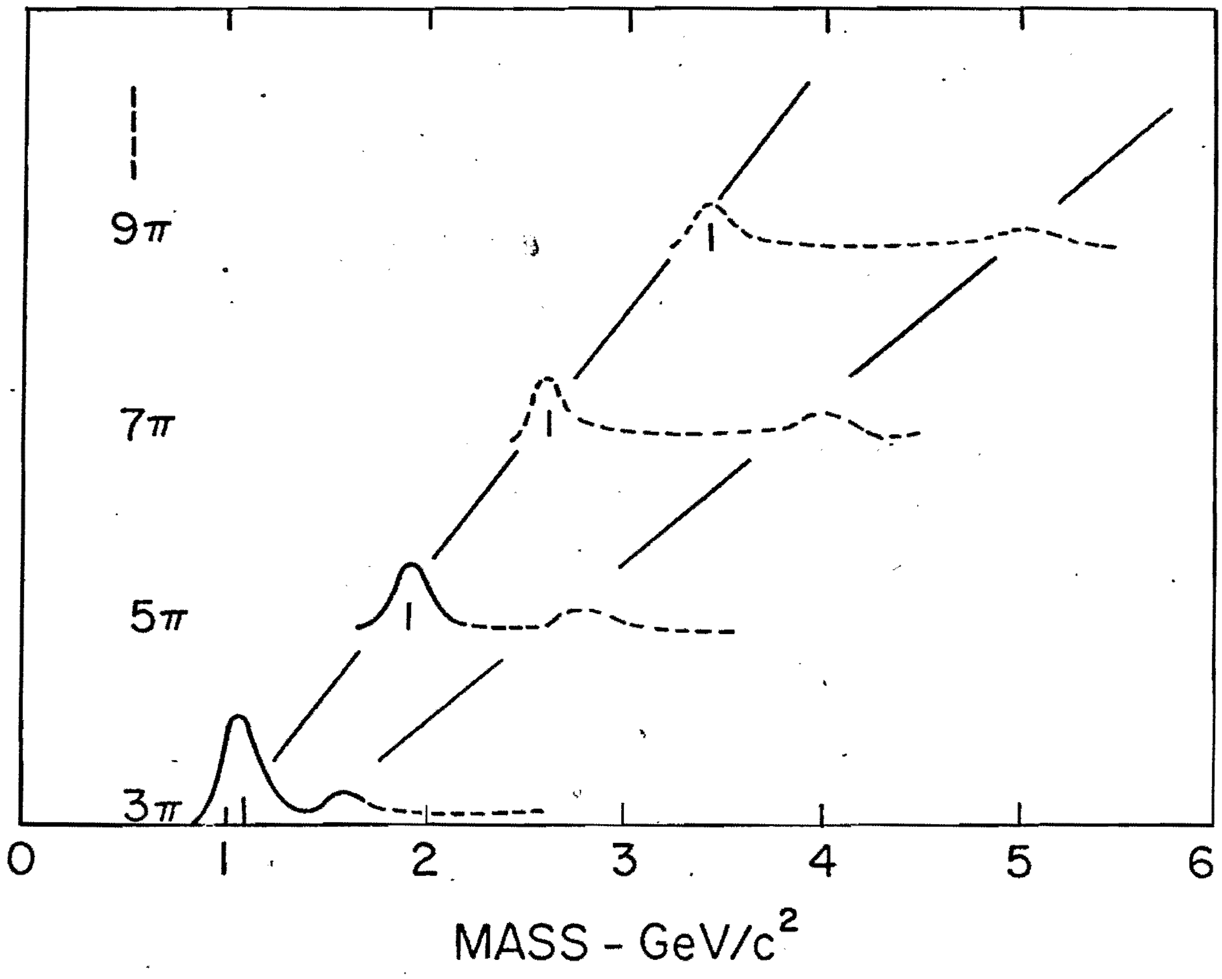


Figure 6, Mass Spectra for the various multiplicities into which a pion can dissociate. The solid curves indicate observed enhancements, while the dotted curves are prdictions based on the constant Q per pion hypothesis discussed in the text.

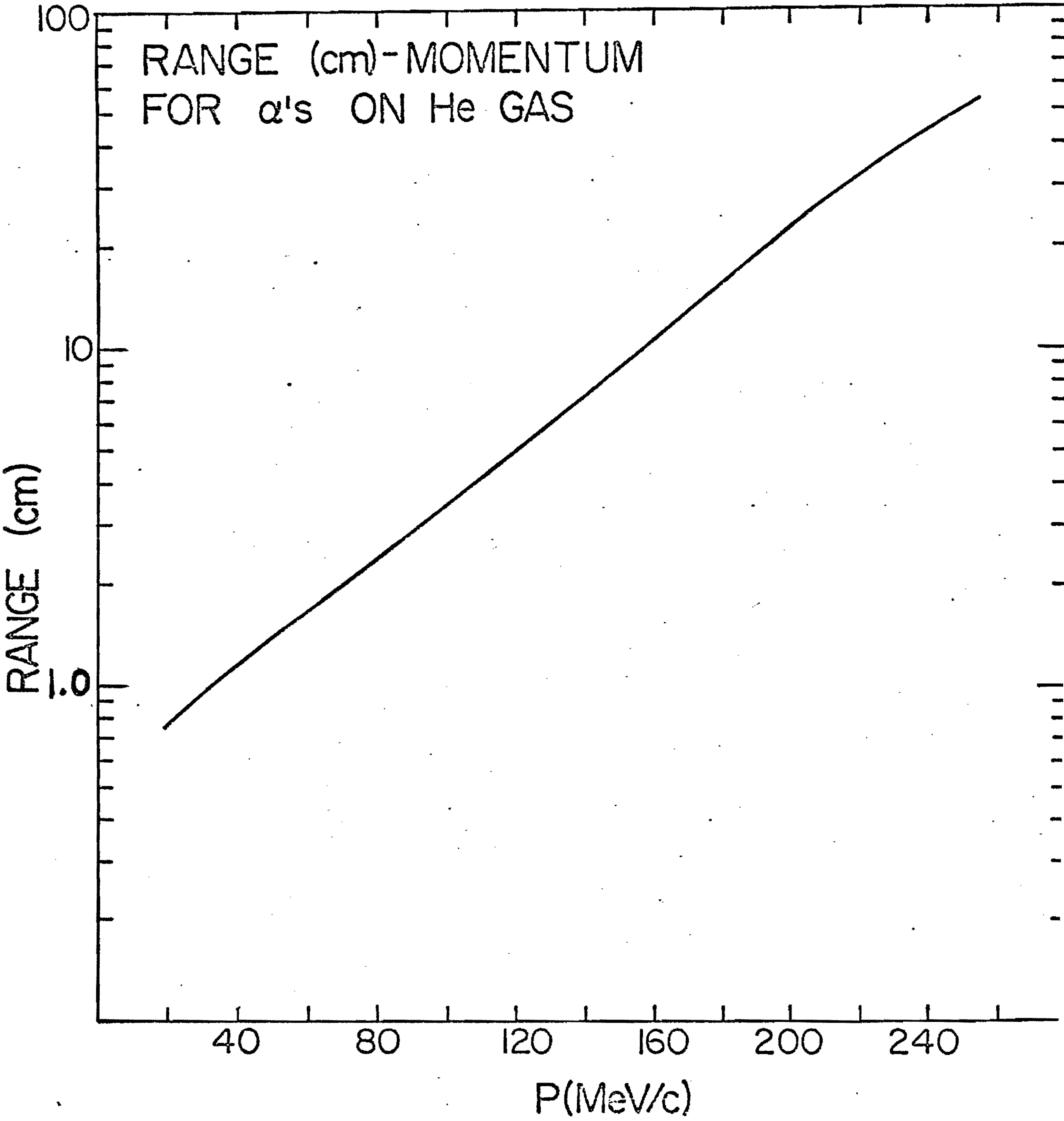


Figure 7, Range of He in He gas at 1 atmosphere.

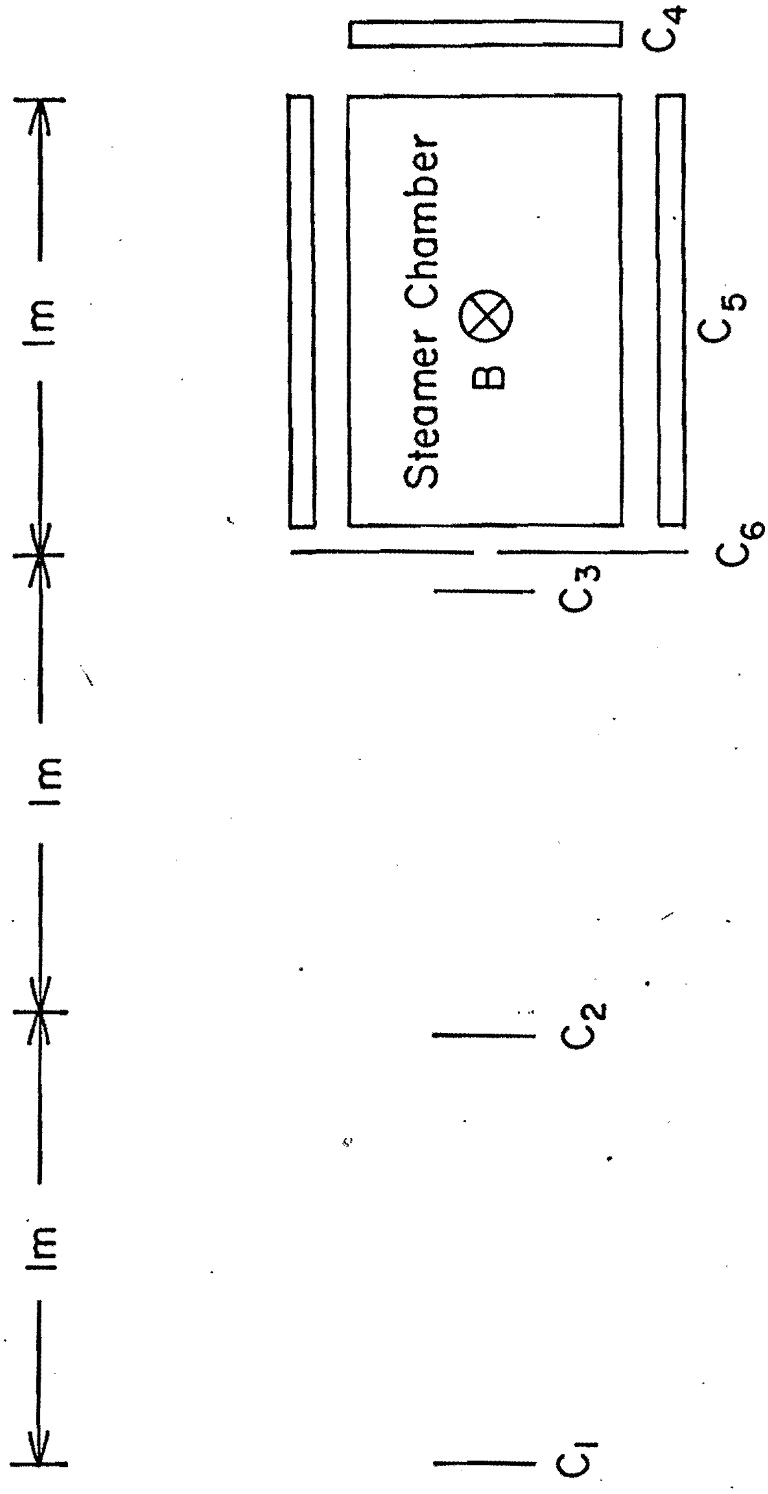


Figure 8a, Experimental Arrangement.

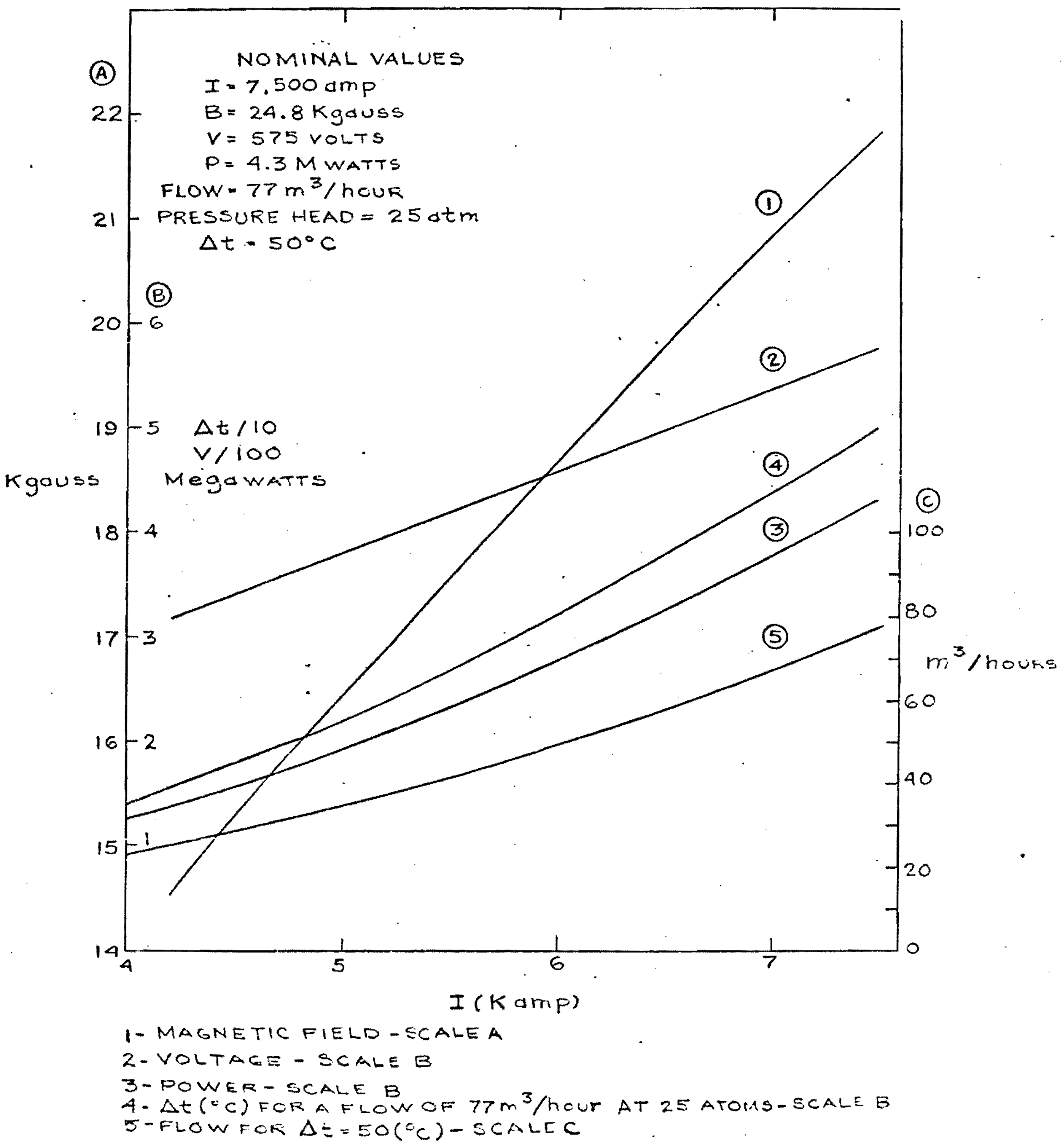


Figure 9 - Magnet Parameters

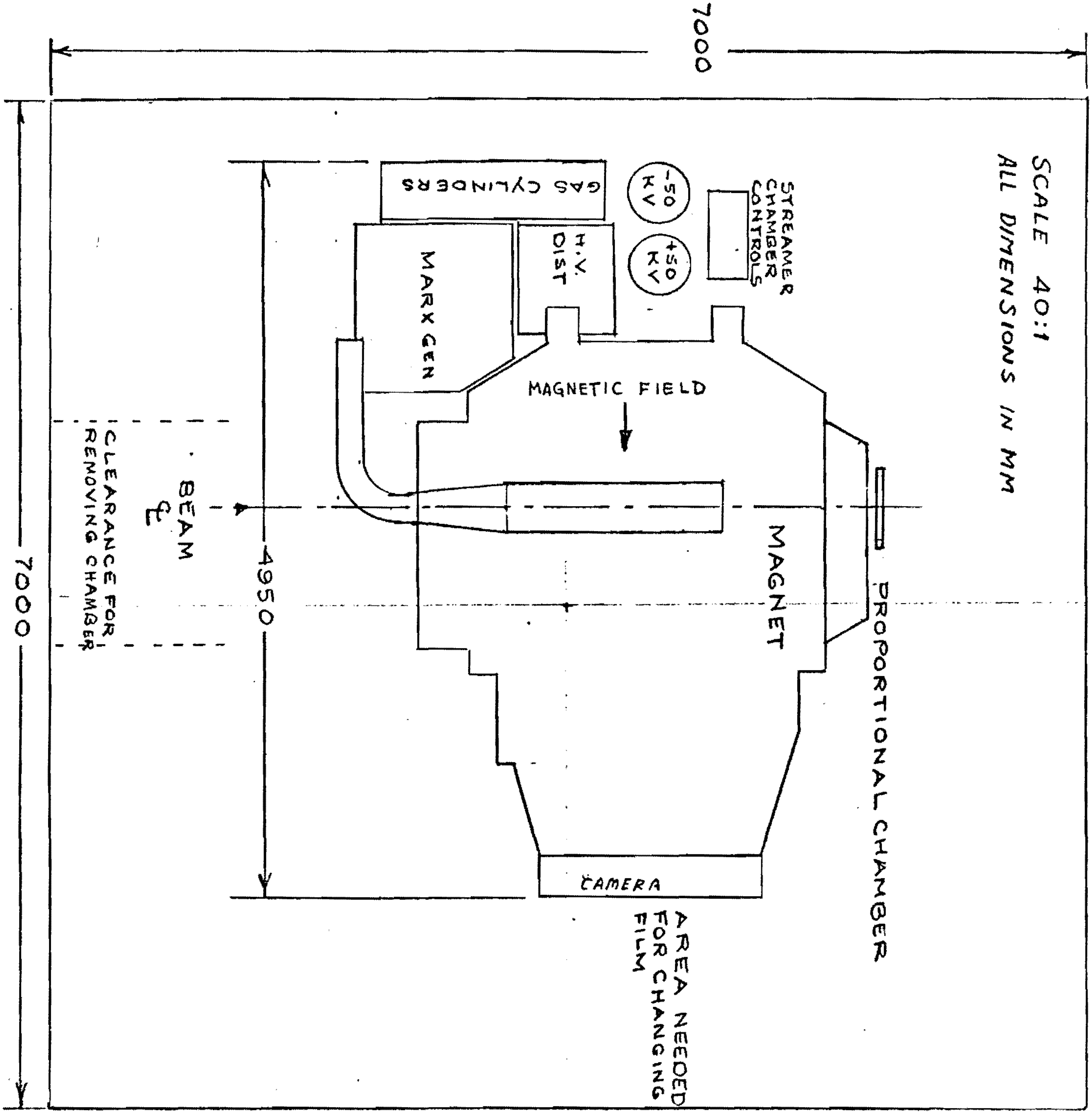
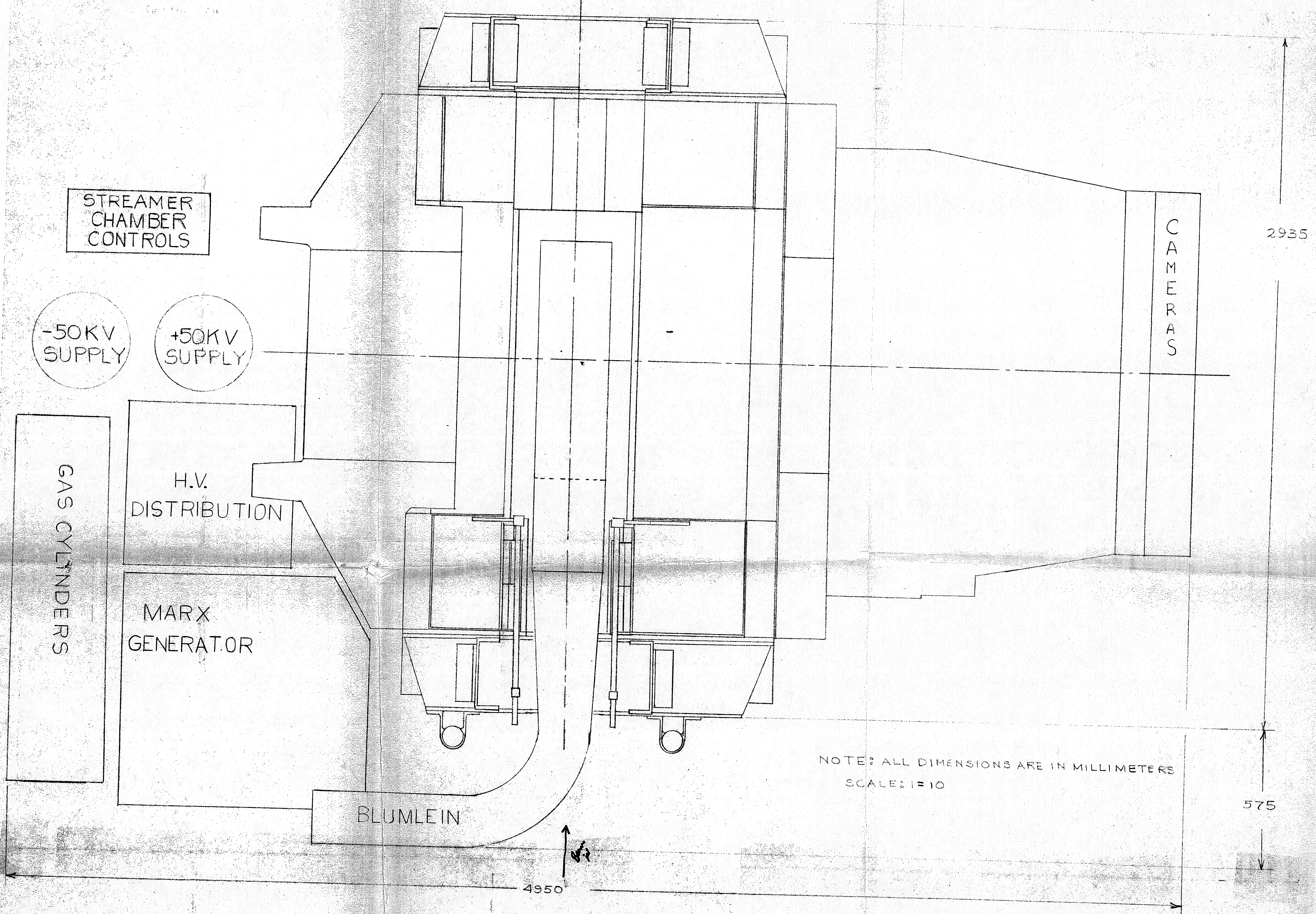


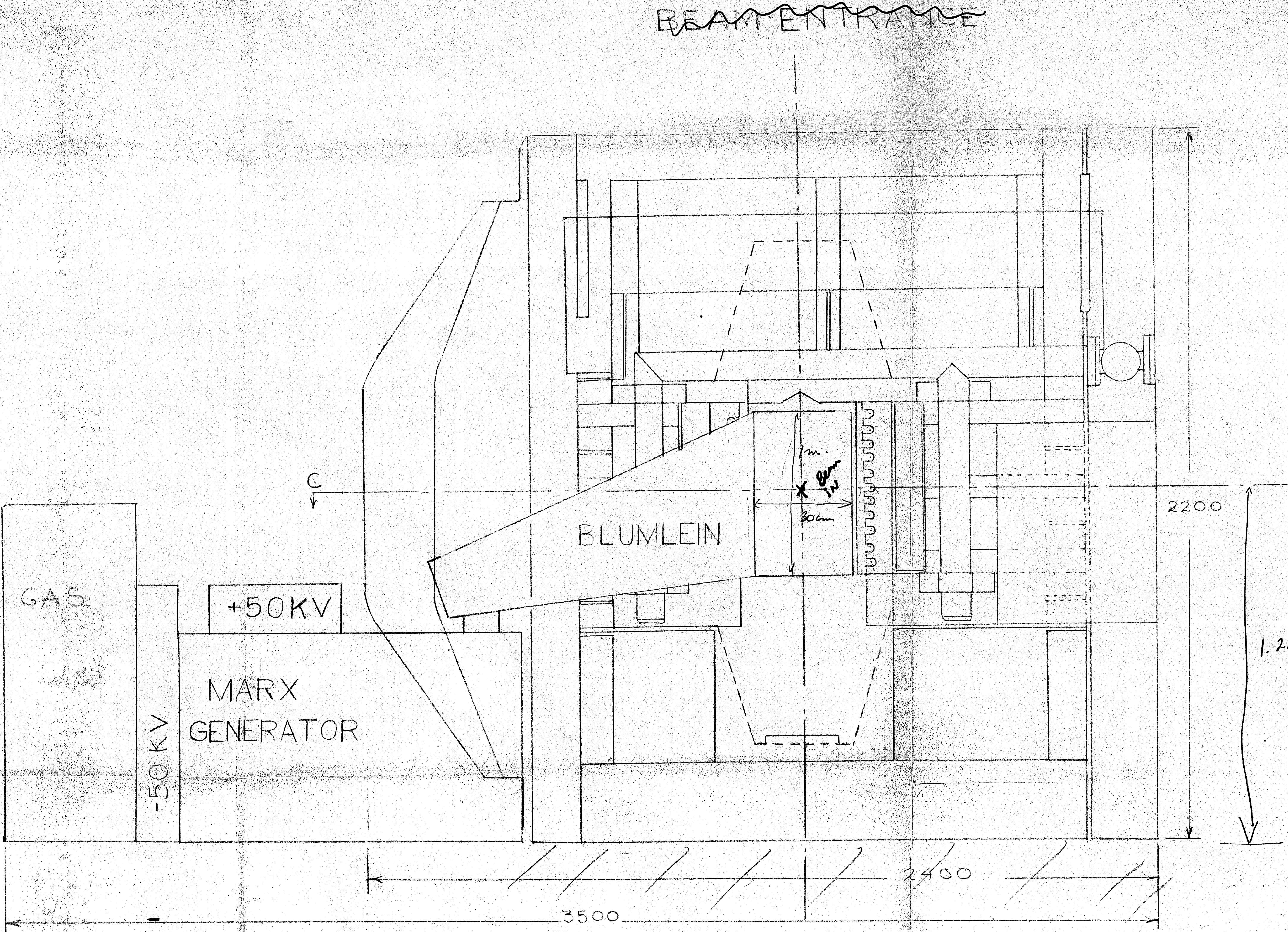
Figure 10, Top view of experimental layout - (Section taken through center of magnet) .

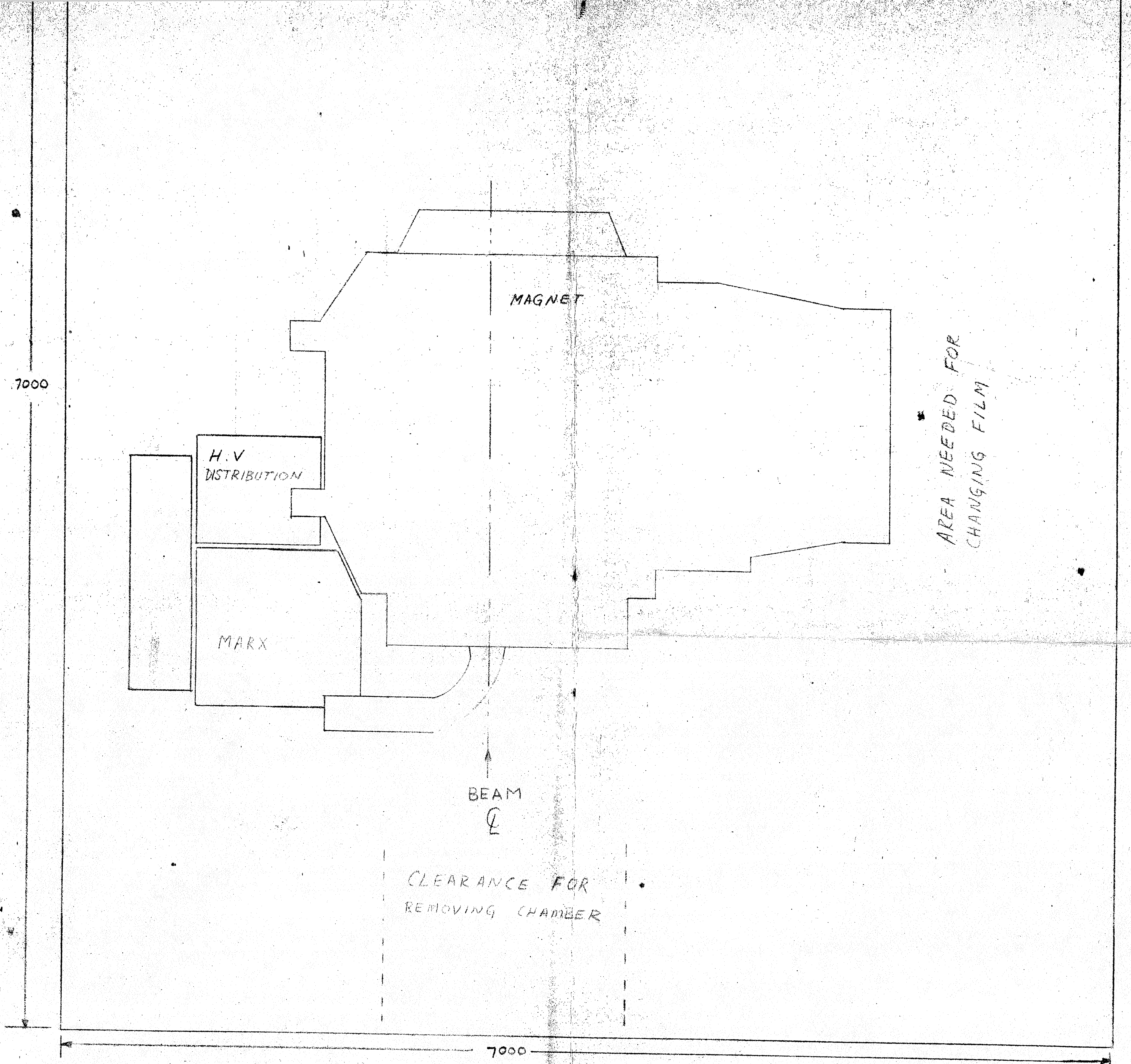

STREAMER CHAMBER CONTROLS
-50 KV SUPPLY
+50 KV SUPPLY
GAS CYLINDERS
H.V. DISTRIBUTION
MARX GENERATOR
BLUMLEIN
CAMERAS
2935
575
4950
NOTE: ALL DIMENSIONS ARE IN MILLIMETERS
SCALE: 1=10

SECTION C-D

~~Figure 86~~

86


~~BEAM ENTRANCE~~
C
D
GAS
+50KV
-50KV
MARX GENERATOR
BLUMLEIN
1m.
Beam IN
30cm
2200
1.215 m.
2400
3500



EXPERIMENT 86 FLOOR SPACE REQUIRMENTS
OCT 7 1970
SCALE 20:1 ALL DIMENSIONS IN MM.