

Search for H Dibaryon in (K^-, K^+) Reaction

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Abstract

We have studied (K^-, K^+) reaction from the emulsion target. The S=-2 H dibaryon has been searched for by the analysis of K^+ momentum spectrum together with emulsion data. No evidence of the H production was observed in the mass range of 1.90-2.16 GeV/ c^2 . Upper limits for the production cross section of the H are 0.2-0.6% of the quasi-free Ξ^- production at 90 % confidence level. The details of the experiment and data analysis are described.

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1 Introduction

1.1 H dibaryon

The H is an $S = -2$ dibaryon (ssuudd) which was first predicted by Jaffe in 1977.¹ The predicted value of M_H is $2150 \text{ MeV}/c^2$, which is $80 \text{ MeV}/c^2$ below two Λ threshold, and therefore the H is stable against strong decay. The binding of the H is mainly caused by the QCD color magnetic interaction term

$$\Delta = - \sum_{i>j} \sigma_i \cdot \sigma_j \lambda_i \cdot \lambda_j M(m_i, m_j), \quad (1)$$

where the σ_i and λ_i are the Pauli and Gell-Mann matrices, and m_i are the masses of the quarks and M measures the QCD interaction strength. This term corresponds to the lowest-order gluon exchange interaction and explains the hadron hyperfine mass splittings. In the SU(3)-symmetry limit ($m_s = m_u = m_d=0$),

$$\Delta = [8N - \frac{1}{2}C_6 + \frac{4}{3}J(J+1)]\bar{M}, \quad (2)$$

where $\bar{M} = M(0,0)$, N is the total number of quarks, J is their angular momentum, and C_6 is their colorspin Casimir operator. With the configuration of the H (charge zero, spin zero and strangeness=-2), C_6 has the largest eigenvalue (=144) and makes Δ negative.

The mass of the H has been calculated in various models as shown in Fig. 1 since Jaffe's first prediction. In all the cases, the configuration of the H lies at the lowest level in the $S=-2$ 6-quark mass spectrum.

As for bag model calculations,^{1,2,3,4,5} M_H ranges from $2.15 \text{ GeV}/c^2$ to around 2Λ mass depending on each set of bag parameters and various correction such as subtraction of spurious center-of-mass kinetic energy³ the contribution from the

pion field⁴, and inclusion of the surface energy of a bag⁵. Some of these predicted unbound H ($M_H > 2M_\Lambda$). However, Kerbikov⁶ claimed that because of coupling to hadronic channels $\Lambda\Lambda$, $N\Xi$ and $\Sigma\Sigma$, the mass of the H decreases by 150-200 MeV/ c^2 and it makes the H stable against the strong decay.

In the framework of a quark cluster model, the binding energy of the H with respect to the 2Λ threshold is calculated by using a resonating group trial wave function (RGM method). The predicted values of the binding energy were positive (unstable against the strong decay into 2Λ) mainly due to the effect of breaking SU(3)-flavor symmetry.^{7,8} However the recent calculation including of the mesonic potentials predicted the binding energy to be -15 ± 5 MeV.⁹

In the lattice QCD, the mass of the H can be determined from the exponential decay of the propagator. The first calculation predicted the H above $2M_\Lambda$.¹⁰ However, the calculation in a larger lattice ($16^3 \times 48$) suggested the possible existence of the light H (even below the two nucleon mass).¹¹

In a chiral (Skyrme) model, a topological excitation which has the same quantum numbers of the H state is identified as the H. The predicted values of M_H range from 1.03 to 2.10 GeV/ c^2 ,^{12,13,14} although they are less successful than other models like a quark cluster model in parametrizing the known hadron masses.

It is thus particularly interesting to search for the H experimentally, in order to test their respective predictions and to guess the good approximation which can be considered as satisfactory for 6-quark system. Moreover, the H attracts much attention from the astrophysical view point, because the same bag model parameters which predicted the H also predicted the strange quark matter and

strangelet,^{15,16} which is a possible candidate for the dark matter.

If the H lies above the 2Λ threshold ($2.230\text{GeV}/c^2$), it should decay very fast ($\tau \sim 10^{-20}$) into 2Λ by strong interactions. On the other hand, if $2.230\text{GeV}/c^2 > M_H > 2.055\text{GeV}/c^2$ (Λn threshold), the decay of the H needs the change of the strangeness number by one unit. The decay should proceed by first-order weak interactions which lead to a mean time to that of strange particles, i.e., $\tau \sim 10^{-10}$. In the case of weak binding (less than $10\text{ MeV}/c^2$) the nonleptonic weak decay $H \rightarrow p\Lambda\pi^-$ is expected to be favored; for a deeper bound state the characteristic baryon decay channels would be $H \rightarrow \Sigma^- p$, $H \rightarrow \Sigma^0 n$ and $H \rightarrow \Lambda n$. Jaffe¹ calculated the branching ratios in the case of $M_H = 2.150\text{GeV}/c^2$:

$$R(H \rightarrow \Xi^- p) = 0.5, R(H \rightarrow \Xi^0 n) = 0.3, \text{ and } R(H \rightarrow \Lambda n) = 0.2. \quad (3)$$

As the M_H decreases towards $2.055\text{GeV}/c^2$, the $H \rightarrow \Lambda n$ mode comes to dominate. The $\Sigma^- p$ signature is much clearer than Λn . If the Λn mode dominates, the H will be difficult to see from its decay fragments. If $M_H < 2.055\text{GeV}/c^2$, the decay needs a second-order weak interaction process and the mean time of the decay would be several days.¹⁷

Several experimental works on the H and double Λ hyper-nuclei have been published. Recently, the observation of a weak decay of the H (produced in p-C reaction) in the propane bubble chamber was reported:¹⁸

$$p + C \rightarrow H + X_1 + X_2 + \cdots, \quad H \rightarrow \Sigma^- + p. \quad (4)$$

However, the associated two kaons (K^+ and/or K^0) were not identified. Moreover, the same event topology can be produced by the reaction

$$p + C \rightarrow \Lambda + X_1 + X_2 + \cdots, \quad \Lambda + (n) \rightarrow \Sigma^- + p, \quad (5)$$

if the neutron inside the carbon nucleus has a momentum of ~ 40 MeV/c, which is possible for Fermi momentum.¹⁹

At BNL, the H in the mass range of 2.0-2.5 GeV/ c^2 was searched for in the reaction²⁰

$$p + p \rightarrow K^+ + K^+ + H. \quad (6)$$

As shown in Fig. 2, this process is represented by a double disconnected diagram, and should be greatly suppressed. The upper limits for the production cross section were too large to rule out its existence.

The light H below the two nucleon mass was searched by investigating double weak decays of two nucleons in nuclei to the H:²¹

$${}^A_Z N \rightarrow {}^{A-2}_{Z-1} N + H + \beta^+ + \nu \quad (7)$$

for d and ${}^{127}\text{I}$, and

$${}^A_Z N \rightarrow {}^{A-2}_Z N + H + \gamma \quad (8)$$

for ${}^{72}\text{Ge}$, ${}^{70}\text{Ge}$ and ${}^{10}\text{Be}$. The experimental data excluded the H with $M_H < 1875.1$ MeV/ c^2 (a few MeV/ c^2 below the two nucleon mass).

As for double Λ hyper-nuclei, two candidates of their weak decay in nuclear emulsions was reported.^{22,23} This may restrict the mass range to $M_H \geq 2.22$ GeV/ c^2 or $M_H \leq 1.90$ GeV/ c^2 . Because if the mass of the H is 1.90 GeV/ c^2 $\leq M_H \leq 2.22$ GeV/ c^2 , two Λ could decay into H by the strong interaction.⁶ However, the interpretation of the data is not quite settled because the (K^-, K^+) reactions were not identified and the statistics was rather poor. Therefore, in order to settle the problem, We have performed the experimental search for the H and/or double Λ hyper-nuclei by the emulsion-counter hybrid method.

1.2 Emulsion-Counter Hybrid Method

Even today a nuclear emulsion is the only detector that has position resolution of a few μm . However, since the emulsion is sensitive to all charged particles, the measurement using only emulsion in charged particle beam is not effective in searching for a very rare reaction. In order to overcome this weak point of the emulsion measurement, the emulsion-counter hybrid technique has been developed. In that technique, a specific reaction is selected by analyzing counter data, then the vertex of the selected event is studied in detail by the emulsion, taking advantage of its high position resolution. This technique has been successfully applied to the detection of short lived particles like charm and beauty hadrons with high energy beams at CERN ²⁴ and FermiLab. ²⁵

We have applied this method to a low energy experiment to search for the H. The experiment(E176) has been performed at the National Laboratory for High Energy Physics (KEK) using the 1.66 GeV/c K^- beam. The (K^-, K^+) reaction is identified by the counter system, which ensures that strangeness of -2 is transferred to a nucleus in an emulsion target. By tracing back the K^+ track in the emulsion we can study the event in detail.

The search for the H at the present experiment have been done by two complementary methods; (i) Search for the H and/or double Λ hyper-nuclei through Ξ^- absorption by a nucleus in the emulsion by means of scanning the emulsion near the Ξ^- stop point to find their characteristic decay fragments (Fig. 3) and (ii) Search for the H by the peak in the K^+ momentum spectrum due to the

direct H production.^{26,27}

In this thesis, we will concentrate on the second method, where the counter analysis plays the most important role. The H can be directly produced from the reaction

$$K^- + (pp) \rightarrow H + K^+, \quad (9)$$

where (pp) is a pair of protons in a nucleus (Fig. 4). If the mass of the H is sufficiently light, the out-going K^+ has higher momentum than that of the K^+ from quasi-free Ξ^- production process

$$K^- + (p) \rightarrow \Xi^- + K^+. \quad (10)$$

Therefore, the H can be identified by an isolated peak in the K^+ momentum spectrum. Independent of its decay mode, this method has the advantage of being sensitive to the H in a wide mass range except near the 2Λ threshold. Moreover, some background events can be removed by the emulsion analysis.

2 Experimental Apparatus

2.1 Overview

The experimental setup is shown in Fig. 5. Incident beam profile is monitored with four multi-wire proportional chambers (MWPC;BPC1-4). The K^- are identified with an aerogel Čerenkov counter(AČ1) at the trigger level. Time-of-flight information(T2-T1) confirms the identification of K^- in the off-line analysis. For the target, 13 modules of the emulsion stack containing a total of 30 liters of nuclear emulsion have been used. In order to find the (K^-, K^+) vertex in the emulsion, the position and direction of the K^+ track should be measured with very high precision. For this purpose, the emulsion target is sandwiched between silicon strip detectors(BSSD's and VSSD's). The K^+ scattered from the emulsion target are detected by a K^+ spectrometer which consists of a magnet, tracking devices, trigger and TOF counters and an aerogel Čerenkov counter (AČ2). the AČ2 is used for rejecting pions off-line. The trajectory and momentum of a scattered particle are measured with three MWPC's(PC's), drift chambers(DC's) and VSSD's. The velocity is calculated from the length of the trajectory and the time-of-flight between the T2 and TOF hodoscope. The mass of a particle is reconstructed from its velocity and momentum.²⁸

2.2 Beam line

The separated K^- beam of 1.66 GeV/c is provided by the K2 beam line of the 12GeV Proton Synchrotron at KEK. The beam line has been slightly modified from the original design²⁹ to improve the K/π ratio. Total length of the beam

line is 25.7m which is shorter than the original one by 2.2m in order to reduce the loss of K^- by the decay. As shown in Fig. 6, The beam line consists of a production target, dipole, quadrupole and sextupole magnets and an electro-static mass separator(6m long). The K^-/π^- ratio is optimized by adjusting the parameters of these components. The good K^-/π^- ratio is important especially for the emulsion experiment because the emulsion is sensitive to all charged particles. For a given amount of emulsion, the statistics of (K^-, K^+) reaction is limited by the total number of charged particles in the emulsion, not only by the K^- particles. The production target is a platinum bar whose size is 2mm in height, 6mm in width and 60mm in length. The magnification of the target image at the position of the mass slit is 0.88 in the vertical direction. The typical mass slit width is 1.5mm. The electro-static field of the separator has been typically 70 kV/cm during the experiment. The spacing between positive and negative electronodes is 10 cm. Ne-He(36%) gas is filled in the separator. The typical pressure of the gas is $\sim 4 \times 10^{-5}$ [Torr] and controlled automatically in order to prevent the electric discharge. The separation between the π^- peak and the K^- peak at the mass slit is about 5 mm at the mass slit as shown in Fig. 7. We have found that the emittance of the K^- beam at the target position is smaller than the background π^- . One of the reason is that some background π^- come from the K_s decay. The collimator of 100cm long heavy metal, which is inserted in the 100cm thick iron wall, is placed just after the final focusing magnet to improve the K^-/π^- ratio and also cut a beam halo. It improves the K^-/π^- ratio by 25%. Typical value of the K^-/π^- ratio is 1/3 at the intensity of 3×10^3 K^- /spill. The size of the beam at the target is 13 mm(FWHM) in the vertical direction and 15 mm(FWHM) in the horizontal direction (Fig. 8), which is small

enough to be covered with the silicon microstrip detectors ($50 \times 50 \text{ mm}^2$). An aerogel Čerenkov counter (AČ1) and TOF counters(T1,T2) are used in order to identify the beam particle on-line and off-line, respectively.

2.3 Spectrometer Magnet

The spectrometer magnet (USHIWAKA) is a window-frame-type dipole magnet which has an aperture of 40 cm in height and 80 cm in width, and it has 8 cm thick end-guard plates of larger aperture. A shape of the pole is rectangular and its length is 70 cm. The total length of the magnet including the end-guard plates is 140 cm. The distance between the target and the center of the magnet is 99.1 cm and solid angle of the magnet is 0.18 str. The typical value of the central field during the experiment is 10 kG which is far below the saturation (The maximum field is 15 kG). The bending angle at 10 kG is about 250 mrad for 1.1 GeV/c, which is a typical K^+ momentum for quasi-free Ξ^- production. The incident K^- beam of 1.66 GeV/c is deflected by -160 mrad. A map of the magnetic field was obtained at several excitations for the past experiment³⁰. We have used the existing data of those field measurements for the momentum reconstruction of the present experiment (see section 4). The vertical field strength of the D-magnet is shown in Fig. 9.

2.4 Chambers

The four MWPC's(BPC1-4) are used for measuring a beam track and also for tuning up the beam line. They have carbon-coated cathode planes. The spacing of the anode wire is 1mm and the wire is gold-plated tungsten whose diameter is 10 μ m. The gaps between cathode planes and anode wires are 4 mm. The typical supplied voltage is 4.4 kV.

Scattered particles are detected by three sets of MWPC's (PC1-3) and three sets of drift chambers(DC1-3). The PC1 is located at 17cm from the target and its wire spacing is 1mm. The anode-cathode gaps are 5 mm. They are typically operated at 5.3 kV. The PC2 is located at the front end of the magnet pole and its wire spacing is 2mm. The anode-cathode gap is 5 mm and typical supplied voltage is 4.8 kV. It has three planes (x,y,u) to solve the stereo ambiguity for the multiple tracks. The wire angles of U plane are 30 degrees from the direction of X plane. Both PC1 and PC2 have carbon-coated cathode planes like BPC's. The PC3 is placed at the downstream end of the magnet and its wire spacing is 2mm. The PC3 has large sensitive area and the cathodes are aluminized mylar glued on 10mm thick honeycomb boards. The anode wires in the y plane are supported by vinyl covered copper wire in the middle to avoid the instability due to the electrostatic force. The gaps between cathode planes and anode wires are 6 mm. The typical supplied voltage is 5.2 kV. These MWPC's are operated with the magic-gas-mixture of argon (73%), isobutane (24%), freon (0.5%) and methylal (3%).

The structure of each drift chamber is shown in Fig. 10. The DC1 is located just after the PC1. This duplication is important to measure the angle of the

scattered particle precisely and reliably. The DC1 has only one plane for both x and y, and left-right ambiguity is solved by using the PC1 and PC2 (see section 4). The position resolution of the DC1 is measured by using the sets of silicon microstrip detector which will be described later. The resolution of DC1 is 210 μm (rms). The DC2 and DC3 are placed at the downstream of the magnet. They are identical chambers whose sensitive area is 150 cm $\times$ 150 cm, except that the cathodes are aluminized mylar for DC3 and TiO coated mylar for DC2, both glued on the 2 cm thick acryl-foam board. They have double sense wires separated by 1 mm to resolve the left-right ambiguity. The drift distance is 11.5 mm and the gap between the sense wire and cathode plane is 6 mm. The typical position resolution is 300 μm (rms). The drift chambers are operated with a mixed gas of argon(50%) and ethane(50%).

Specifications and location of MWPC's are as follows:

Table 1

	wire spacing	# of read-out wires	location (from the target)
BPC1X	1mm	80	
BPC1Y	1mm	64	
BPC2X	1mm	112	
BPC2Y	1mm	64	
BPC3X	1mm	144	-2587mm
BPC3Y	1mm	64	-2571mm
BPC4X	1mm	80	-360mm
BPC4Y	1mm	64	-344mm
PC1X	1mm	144	150mm
PC1Y	1mm	96	165mm
PC2X	2mm	160	527mm
PC2Y	2mm	96	545mm
PC2U	2mm	176	563mm
PC3X	2mm	464	1739mm
PC3Y	2mm	256	1717mm.

And the geometrical parameters of the drift chambers are as follows:

Table 2

	sell size	# of read-out wires	location
DC1X	30 mm	9	214mm
DC1Y	30 mm	6	226mm
DC2X	12 mm	64	2058mm
DC2Y	12 mm	48	2302mm
DC3X	12 mm	64	2976mm
DC3Y	12 mm	48	3221mm.

2.5 Emulsion Target

The emulsion target system consists of the emulsion stack (Fig. 11) and the target-mover (Fig. 12) which is a movable holder of the emulsion stack.²⁴ The emulsion stack is a vertical type and exposed with the beam perpendicular to the emulsion surface.³¹ Each stack consists of 43 layers of the emulsion sheet. The area of each sheet is 23×23 cm and it is made in a way that $550 \mu\text{m}$ thick emulsion is coated on both sides of $70 \mu\text{m}$ thick polystyrene film except the last sheet at the down stream end of the stack. The last one is made of $500 \mu\text{m}$ Lucite sheet coated with $70 \mu\text{m}$ emulsion on both sides. These 43 emulsion sheets are packed in vacuum by using $200 \mu\text{m}$ thick multi-laminated paper. The total thickness of one emulsion stack is about 50 mm. The fabrication of the emulsion stack has been done at Nagoya University with the use of nuclear emulsion of gel-form (Fuji ET-7B)³¹. the composition [mol/cc] of the target material is shown in Table 3.

Table 3

material	nuclear emulsion	polystyrene film	target total [mol/cc]
I	7.93×10^{-5}	-	7.93×10^{-5}
Ag	1.33×10^{-2}	-	1.33×10^{-5}
Br	1.32×10^{-2}	-	1.32×10^{-2}
S	1.97×10^{-4}	-	1.97×10^{-4}
O	1.87×10^{-2}	-	1.87×10^{-2}
N	6.96×10^{-3}	-	6.96×10^{-3}
C	2.44×10^{-2}	4.74×10^{-3}	2.91×10^{-2}
H	5.72×10^{-2}	4.74×10^{-3}	6.19×10^{-2}

The density of the emulsion is 3.45 g/cm^3 and the averaged atomic number A is 23.1. The target area is inside the aluminum shield hat which is airconditioned, and the temperature and humidity have been kept constant and monitored during the measurement. The stack is mounted on the target-mover, which is controlled with a micro-computer to get the uniform irradiation by monitoring the beam intensity. The emulsion stack is moved in vertical and horizontal directions during off-spill time. The position of the stage is read by a CAMAC 16-bit input register module. The accuracy of the position encoder is about $1 \text{ } \mu\text{m}$. The target mover is placed on the high precision granite block together with SSDs and other detectors around the target. The alignment of the target-mover and SSDs were performed with a laser. The relative alignment of the SSDs and the chambers has been checked with straight beam particles without the target material. The several stacks has been exposed at the particle density of $9 \times 10^5 \text{ particle/cm}^2$ and others at the density of $6 \times 10^5 \text{ particles/cm}^2$. To help to find a K^+ track at such high particle density, we have used a special emulsion plate which is called a changeable sheet²⁵. The changeable sheet is made of $500 \text{ } \mu\text{m}$ thick lucite coated with $70 \text{ } \mu\text{m}$ thick emulsion on both sides and is packed with the laminated paper. It is attached to the downstream surface of the emulsion stack by means of a small vacuum pump. During an exposure of each emulsion stack, the change-

able sheet is changed 12 (10) times for high (low) density exposure. Therefore the particle density at the changeable sheet is 6×10^4 particle/cm² or 7.5×10^4 particle/cm² and it is easier to find the predicted K^+ track on this changeable sheet. Between the emulsion sheets, the connection of tracks is possible at higher particle density because of the better position resolution of the emulsion. An X ray generator of 67keV (maximum energy) with a fine collimator is employed to record the relative position between each changeable sheet and the emulsion stack. It is fixed to the upstream end-guard of the magnet. It makes several reference marks on each changeable sheet and the following emulsion sheets in the stack.

2.6 Silicon Strip Detectors

In order to find the (K^-, K^+) vertex in the emulsion, first the K^+ track should be identified in the emulsion sheet of the downstream end of the stack and followed up to the reaction vertex through the sequence of the emulsion sheet (see section 4.4). Because the emulsion is a storage type detector, many off-timing tracks are recorded. In order to find the predicted K^+ track in the high track density, the accuracy of the predicted position and angle of the K^+ track is crucial. Therefore the emulsion stack is sandwiched between silicon strip detectors which measure the position of both incoming K^- and outgoing particles with high precision. The location of the SSDs and the emulsion target is shown in Fig. 13. The sensitive area of the SSD itself is 50×50 mm² and the thickness is 300 μ m. It is fabricated on a 54cm $\times$ 33cm pc board. A strip pitch is 42 μ m. We have employed the method of capacitive charge division for the readout in order to

save the number of readout electronics without affecting the position resolution.³² The every third strip is connected to the pc board and readout electronics, and other strips remain floating. The hit position is obtained by calculating the ratio of the collected charge of the adjacent readout strips. To supply the bias voltage to the floating strips, a MOS gate structure has been developed and is utilized³² (Fig. 14). A signal from the readout strip is fed to a preamplifier on the pc board. Each pc board has 48 pieces of 8-channel preamplifier chips (Lecroy HQV810). It is a FET charge amplifier with a rather long time constant ($4 \mu\text{sec}$) and high conversion gain (-0.5 V/pc). The output signals from the preamplifiers are sent through 5 m long shielded flat cables to shaping amplifiers which are designed for this experiment. The voltage gain is 20 and the shaping time is 250 nsec. The output pulse is finally fed to TKO-ADC. The number of read-out strips for BSSDX, BSSDY, VSSDX, and VSSDY are 192, 256, 384, and 352, respectively. So, the total number of the ADC channel is 1184. In order to prevent the noise from outside, the SSDs and their readout electronics including ADCs are located inside the aluminum hat. The typical noise level during the experiment is 800 electrons(rms), where the capacitance of the strip is around 10 pF. This noise level is low enough compared to the signal, since the average number of electron-hole pairs produced by a minimum ionizing particle is 22000. A scattered plot of the pulse height of adjacent readout strips is shown in Fig. 15. The cluster of the pulse height corresponding to each strip is clearly observed. As shown in Fig. 16, the intrinsic position resolution of the detector was measured to be $16 \mu\text{m}$ (rms) by two SSDs whose strip pitch is much finer ($12.5 \mu\text{m}$).

The position resolution of the vertex detector system including DC1 and PC1 has been measured by the emulsion. Fig. 17 shows the distribution of

the difference between the position of a track predicted on the last emulsion sheet by the detector system and that actually measured by the emulsion. The results show that the position resolutions are $22\ \mu\text{m}$ in the horizontal direction and $34\ \mu\text{m}$ in the vertical direction. These values are consistent with the values estimated from the multiple scattering in these silicon detectors and their intrinsic resolution.

The position resolution of the vertex detector system is sufficient to locate the track in the emulsion with high efficiency. The reaction vertex position is also obtained with the use of BSSD and BPC3-4 which determine the position and direction of the incoming K^- beam. We have compared the predicted vertex position with the position actually found by the emulsion analysis. Fig. 18 shows the distribution of the difference in z-direction. Although the multiple scattering in the emulsion target is very large, it is useful to compare the vertex position for further confirmation of the emulsion analysis and to avoid a mistake during a process of following the K^+ track to the vertex point through the sequence of emulsion sheets.

2.7 Trigger and TOF Counters

Two timing counters, T1 and T2, are located at 700 cm and 56 cm upstream of the target position, respectively. They are 5 mm thick plastic scintillators (NE pilot-U) directly viewed by fast timing photo tubes (Hamamatsu R2083) on both ends. The supplied voltage is 3.0 kV. The area of the scintillator is 10cm (width) x 5 cm (height) for T1 and 5cm x 5cm for T2. The time difference between T1

and T2 is measured to identify the beam particle. The TOF(T2-T1) resolution is 85 psec(rms) whereas the TOF difference of K^- and pion is 850 psec.

The time difference between the T2 and the TOF hodoscope is measured to identify the scattered particle. The TOF hodoscope is located at 2.7 m downstream the target and consists of 14 plastic scintillators (Kyowa SCSN38). By using the beam particle, the performance of the TOF counters had been studied for various size of the scintillator and several photomultipliers to optimize the design³³. The size of each scintillator is 110cm (height) $\times$ 12cm (width) $\times$ 3cm (thickness) and it has fish-tail light guides and 2-inch photomultipliers (Hamamatsu H1949) on both ends. The typical supplied voltage is 2.5 kV.

The anode signal from each photomultiplier is used for both the trigger logic (see section 3.1) and for the time measurement (see section 4.2.2). The timing and resolution of each TOF counter are routinely calibrated with a pion beam and a typical value of the TOF resolution is 85 psec(rms), which is quite satisfactory. The TOF hodoscope is also used as a two dimensional tracking device. The vertical hit position is determined from the time difference between two photomultipliers on both ends of the scintillator with the resolution of 12mm(rms). A trigger hodoscope (TH) is placed at the front end of the magnet pole. It consists of 8 scintillation counters segmented in the horizontal plane. The size of each scintillator is 4.2cm(width), 22cm(height) and 2mm(thickness). They have long light guide on the upper end and are viewed by 1-1/8 inch photo tubes (Hamamatsu R1398) operated at 1.6 kV. The hodoscope is used to form the 8×12 matrix coincidence with the TOF hodoscope for the selection of the positive charge particles (see Fig. 22).

A scintillation counter (BV) is placed at the same position as the trigger hodoscope to kill the noninteracting beam particles. This is useful to reduce the trigger rate by vetoing the decay of K^- beam in the magnet. The size of the scintillator is 4 cm square and 2mm thick and it is viewed by a 2 inch photo tube (Hamamatsu R2490).

2.8 Aerogel Čerenkov Counters

Čerenkov radiation arises when a charged particle in a material medium moves faster than the speed of light in the medium. The threshold velocity is given by

$$\beta_{th} = 1/n, \quad (11)$$

where n is the index of the medium. Therefore, we can separate pions from kaons with the same momentum (p) if we choose the index of the medium to be

$$\frac{\sqrt{m_\pi^2 + p^2}}{p} < n < \frac{\sqrt{m_K^2 + p^2}}{p} \quad (12)$$

The AČ1 is placed at 75cm upstream of the target to identify K^- beam. Two layers of silica aerogel blocks, whose size is 15 x 15 cm and 3 cm thick, are installed in a light-shielded box. The Čerenkov light is reflected by a 45 ° mirror and detected by a 5 inch quantucon tube (RCA8854) as shown in Fig. 19. The index of the aerogel for the AČ1 is 1.04, which has been confirmed by measuring the threshold momentum of a pion beam. The intrinsic pion detection efficiency of AČ1 is obtained to be 99.7 % for 1.66 GeV/c pions by counting the number of events in the pedestal peak of ADC pulse height distribution. The distribution

for the number of photo-electron (ν) should be the Poisson distribution with the expected mean value μ ;

$$P_{\mu}(\nu) = e^{-\mu} \frac{\mu^{\nu}}{\nu!}, \quad (13)$$

Therefore, the average number of detected photo-electrons is expected to be ~ 6 because $1 - e^{-5.8} = 99.7\%$. However, the threshold of the discriminator for AČ1 has been set appropriately in order to prevent the loss of K^- caused by the noise of the photomultiplier. The pion rejection efficiency of AČ1 is 99.3 % at the trigger level.

The AČ2 is located between the DC1 and PC2 to separate scattered K^+ and π^+ . The silica aerogel radiator for AČ2 has a sensitive area of 15cm (height) $\times$ 25cm (width) and its total thickness is 9.5cm. To avoid the magnetic field, 50 cm long air light guide surrounded by the aluminized mylar is employed for the light collection to the two photomultipliers (RCA8854) as shown in Fig. 20. The gain of each photomultiplier was adjusted by monitoring the single photon peak. The typical supplied voltage is about 2.5 kV and that of the first dynode is 1 kV. The index of the aerogel for the AČ2 is 1.06. The threshold momentum for a pion and a kaon is 0.4 GeV/c and 1.4 GeV/c, respectively. The average number of the detected photo-electron is related with the velocity β by

$$N \propto 1 - \frac{1}{n^2\beta^2} \propto \frac{n^2 - 1}{n^2} + \frac{1}{n^2} \left(\frac{\beta^2 - 1}{\beta^2} \right). \quad (14)$$

Therefore, the inefficiency $\bar{\epsilon}$ is parametrized by

$$\bar{\epsilon} = \exp(-N) = \exp\left(a \frac{m^2}{p^2} + b\right). \quad (15)$$

Parameters a and b have been determined by using K^- and π^- beams with various momenta in order to obtain the index and detection efficiency in a reliable way. Fig. 21 shows the the detection efficiency of AČ2 for both π and K.

The nitrogen gas has been provided to both AČ1 and AČ2 to avoid the deterioration of the aerogel during the experiment.

2.9 Performance of the spectrometer

Fig. 22 shows the momentum dependence of the acceptance for positive charged particles, which is obtained by analyzing present data. Above 1.0 GeV/c, The acceptance is almost flat and about 0.15 str. By the measurement with a pion beam, the momentum resolution ($\Delta p/p$) is estimated about 2.5 %(rms) at 1.0 GeV/c depending on the cut-parameter of the track reconstruction(see section 4). The typical flight-length of a 1.0 GeV/c particle is about 2.8 m and the time of flight resolution is about 90 psec.

3 Data Acquisition

3.1 Trigger Logic

A block diagram of the electronics for the trigger logic is shown in Fig. 23. T1 counter, in coincidence with (T2·S1·Spill), provides the "beam" signal. The anti-coincidence of AČ1 identifies the K^- of the beam (" K^- beam"). The outputs of 8 TH counters and 14 TOF counters are sent to a matrix coincidence module to identify positive charged particles ("positive charge" signal). The matrix was determined with the result of the Monte-Carlo simulation. The coincidence of "positive charge" and " K^- beam" vetoed by BV gives the "event" signal. Finally, the "event" is vetoed by CPU busy and gives the "trigger" signal, which triggers the CAMAC action for data taking. Thus, the trigger requirement is that an incident particle is K^- and the charge of at least one scattered particle is positive. As shown in Fig. 23, signals from all TOF photomultipliers are split into two. The first pulse is fed to an ADC through 40 m delay cable, and the second one is fed to a leading-edge discriminator. One of the output pulses of the discriminator is fed to a TDC as a stop pulse and the other one is used for the trigger logic. The threshold voltage of discriminators is 35 mV for signals from T1, T2, S1, 100 mV for TOF hodoscope and BV, and 86 mV for AČ1. The timing of all signals in the trigger logic is adjusted in such way as the timing of the trigger signal can be determined by the timing of T1. The AČ2 is not usually in the trigger logic to detect (K^-, π^+) reaction simultaneously.

The total delay time between the physical occurrence of the event and the timing of the "trigger" signal is about 200 ns. The typical trigger rate is about 40 events/spill while the width of the spill gate is 600 msec and the typical number

of K^- is 2000/spill. The typical dead time is $\sim 13\%$. Most of (K^- , + charged particle) events are caused by (K, p) and (K^-, π^+) reactions. However, the decay of scattered K^- in the spectrometer and (K^-, nX) events cause many spurious trigger signals (See section 4).

3.2 Electronics

A schematic diagram of the data taking is shown in Fig. 24. The timing (TDC) and pulse height (ADC) information is encoded into the address and digitized value, and stored into a buffer memory module in the main crate of the CAMAC system, event by event during spill time. Signals from MWPCs are fed to amp-discriminator cards located near the counters through flat cables. The output signals of the cards are sent to latch modules through ~ 20 m twist-pair cables. The hit patterns in the latch modules are encoded into the wire address and transferred into a buffer memory. Signals from SSDs are read by ADCs of the TKO system.³⁴ New 32-ch ADC module has been developed for the present experiment. It has functions of pedestal subtraction and threshold discrimination for each channel. Each threshold value is set to be $\sim 2.5\sigma$ of the pedestal peak. The data is transferred into a buffer memory module (MP) in a camac crate linked by a interface module (CH). Signals from drift chambers are also read by the TKO system, which is operated in the common-stop mode. The target mover is controlled with a micro-computer to get the uniform irradiation by monitoring the beam intensity. The position of the target-mover is read by a CAMAC 16-bit input register module at the beginning of each spill.

All the data stored in the buffer memory modules and memory partners are transferred to a computer after each spill. The data taking system is controlled by a minicomputer (DEC μ VAX) through a crate controller (Kinetic 3922) in the CAMAC main crate. The typical event size is about 200 $\sim$ 300 of 16-bit words. The maximum data size per one spill is 5500 words for Camac ADC-TDC data, 2000 words for MWPC data, 1500 words for DC data and 6000 words for SSD data, which are determined by the on-line program described in the next section.

3.3 Online program

The online data acquisition and monitoring program is composed of five co-operative processes as shown in Fig. 25. The data buffer handling is based on KEKV, which was developed at KEK.³⁵ The real time I/O subprocess called CONTROLLER controls the data acquisition system (start and stop), and transfers the data into a region of the random access memory, called "V-buffer", which is shared with other processes. All the data written on "V-buffer" is continuously recorded on a magnetic tape by a subprocess called RECORDER. HISTOGRAMER analyzes sampled events and makes histogram data. The typical sampling ratio is about 15 %. The analysis part of HISTOGRAMER is basically the same as that of the off-line analysis program. However, the methods for the track reconstruction and the momentum reduction are much simplified for saving time at the expense of the reconstruction efficiency and momentum resolution. DRAWER displays on a graphic terminal the results of the analysis written on "Histocommon". HISTSERVER links Histcommon to each DRAWER.

The performance of the detectors is monitored by histogramming a large number of data such as ADC and TDC distributions, counter hit distributions, etc. Furthermore several physical quantities such as the momenta of the outgoing particles, the vertex points of the interactions, and even the masses of outgoing particles are also obtained at the on-line analysis. Some important histograms and a table of wire chamber efficiencies are printed out by a laser printer after each run. In addition to data taking, the μ VAX is used to set parameters of TKO-ADCs for SSDs.

4 Data Analysis

The total number of incident K^- is about 1×10^9 and that of triggered events is about 2×10^7 . Most of triggered events are caused by K^- decay, (K^-, p) reactions, conversions of neutral particles to charged particles in the TOF hodoscope after (K^-, nX) and (K^-, K^0X) reactions, γ events mainly due to (K^-, π^0X) reactions, and (K^-, π^+) reactions. The rate of (K^-, K^+) reactions has been found to be ~ 0.025 % of the total trigger. In this section, the procedure of the data analysis is described. The analysis can be divided into 4 steps;

1. The condensation of the data by rejecting apparent background events (the pre-sorting).
2. Event reconstruction.
3. Selection for the (K^-, K^+) events.
4. Detailed analysis of the (K^-, K^+) events by using emulsion data.

4.1 Pre-sorting

The aim of the pre-sorting is to reject background events as many as possible to reduce the amount of data to be analyzed in further steps, because the size of recorded data is about 8×10^9 words and it would take much time only to read it.

First, all the events are sorted into two types; "multi-track events" and "single-track events". If an event has ≤ 2 hits on VSSDX or VSSDY, the event is

taken as the multi-track event and accepted as a good event for further analysis without any more checks. The multi-track events are about 25 % of total events. The selection of good events from the single-track events is done by using information of tracking detectors (BPC3, BPC4, BSSD, VSSD, PC1 and PC2) only around the target. A good event must satisfy the following selection criteria;

1. At least one hit on both VSSDX and VSSDY are required because information of VSSD is essential for finding K^+ tracks in the emulsion.
2. At least one hit on PC1 or PC2 for both x and y directions are required in order to solve the left-right ambiguity of DC1.
3. One hit on more than 2 of 3 planes (BPC3, BPC4 and BSSD) are required to define one beam particle.
4. Scattering angle is more than 30 mrad.

The criterion 1 has rejected 30 % of the single-track events. About 60 % of the excluded events are out of the effective area of VSSD, and about 30 % of them are due to neutral particles (neutron and K_L^0), because it does not have a hit on PC1 either. Since detecting efficiencies of both VSSDX and VSSDY are more than 99 %, the loss of the true events due to the inefficiency of VSSDs is less than 2 %.

The criterion 4 has removed 37 % of the single-track events. Fig. 26-(a) and Fig. 26-(b) show the distributions of scattered angles for single-track events before and after the pre-sorting, respectively. The small scattering-angle events are mainly due to K^- decay in the magnet and also scatterings in AČ2.

The criteria 2 and 3 exclude about 4 % of the single-track events, which is

almost consistent with the efficiencies and acceptances of the detectors.

At last, the number of events has been reduced to 47 % of the total events. In addition to this fast rough event selection, the pre-sorting process converts the format of the original data to the compact one.

4.2 Event Reconstruction

In the process of the event reconstruction, we derive physical quantities, (i.e. vertex points, scattering angles, momenta and masses of outgoing particles, etc.), from the data of pre-sorted events. The results are recorded on data summary tapes for the event selection.

4.2.1 Track Reconstruction

Beam track is determined by the two MWPCs (BPC3 and BPC4) and one set of SSD (BSSDX and BSSDY). The track of a scattered particle from the emulsion target is reconstructed using hit information of SSDs (VSSDX and VSSDY), MWPCs (PC1, PC2 and PC3), three DCs (DC1, DC2 and DC3), and TOF hodoscope as a two dimensional position detector. The reconstruction procedure can be divided into three steps;

1. To list up all hit points.
2. To find one candidate for the good track after the D-magnet.
3. To find the best combination of hits before the magnet and calculate the momentum.

Step 1: A hit position on a MWPC is obtained by clustering adjacent hits and by taking the center of the cluster. A hit position of a drift chamber is calculated by converting the timing information (TDC) into the position assuming a constant drift velocity. If both PC1X(Y) and PC2X(Y) have only one hit, the left-right ambiguity of DC1 is solved by choosing the nearest hit to the straight line which connects the hits on PC1 and PC2. Otherwise, this ambiguity is solved in step 3. A hit position of a SSD is calculated by the method of charge division; i.e. if two adjacent strips (at X_1 and $X_2 = X_1 + 125 \mu\text{m}$) have hits, the hit position $X_p [\mu\text{m}]$ is calculated by

$$X_p = X_1 + 125 \times \frac{Q_2}{Q_1 + Q_2}, \quad (16)$$

where Q_1 and Q_2 are the pulse heights of the strips at X_1 and X_2 , respectively. X position of a hit on the TOF hodoscope is assumed to be the center of the scintillator with the hit, and y position is calculated from the time difference between the two signals from two photomultipliers on both ends of the scintillator. The maximum numbers of multiplicities on one plane to be analyzed are set to be 1 for BPC3, BPC4 and BSSD, 10 for VSSD, 8 for PC1, 10 for DC1 (allow the stereo ambiguity), and 5 for PC2, PC3, DC2 and DC3, which are large enough.

Before going to the next step we require at least two planes which have at least one hit for both x and y directions at both sides of the magnet. The events that do not satisfy this requirement are mainly caused by neutral particles, $n \rightarrow p$ conversion in the TOF hodoscopes, for example. The interpretation is confirmed by Fig. 27.

Step 2: At the present experiment, low momentum particles have been swept away by the magnet, and most of events have only one or two hits on the TOF hodoscope. Therefore, first of all, a "good track" after the magnet is searched. In order to be accepted as a good track, it must satisfy two conditions;

- (i) It must have a corresponding hit on TOF hodoscopes ($\delta x \leq 65$ mm and $\delta y \leq 65$ mm).
- (ii) The y position of the track extrapolated at $z = 0$ must be near the target ($|y| \leq 100$ mm).

Fig. 28 shows the distribution of the difference between the calculated position by the TOF difference and the predicted position by the chambers (PC3, DC2 and DC3). The standard deviation (σ) of the difference is about 12 mm. Therefore 65 mm corresponds to 5.4σ . The distribution of y position at $z = 0$ is shown in Fig. 29. The standard deviation is about 20 mm and 100 mm is about 5σ .

Both requirements are effective to kill K^- decay events, and the hit position information from the TOF hodoscope is useful to solve the stereo ambiguity of multi-track events.

Step 3: Since the hit multiplicity of each counter before the magnet is rather high, we must choose the best combination out of all possible combinations of the hits. The selection is done by comparing the values of χ^2 obtained in the momentum analysis procedure. This procedure calculates the momentum by fitting both the track with a quintic spline and the magnetic field with a cubic

spline.³⁶ This procedure requires several iteration to make the track consistent with the field and constant momentum, and it takes up most of the CPU time. In order to reduce the CPU time, before the spline fitting, following conditions are checked on the straight track obtained by a least square fitting of a trial combination of hits on PC1, DC1 and PC2.

- (i) The track must have a corresponding hit on VSSD. Fig. 30 shows the distributions of the discrepancy between the straight track determined by chambers (PC1, DC1 and PC2) and the nearest hit point of VSSD. The wider distribution in x-direction reflects the effect of a leak field out of the pole tip. This requirement is useful to reduce background events caused by scattering from AČ2.
- (ii) The z position of the intersection of the two straight track obtained by fitting hits before and after the magnet must be near the magnet center. Fig. 31 shows the distribution of the z position. The z position depends on both the momentum and direction of the outgoing particle. However, the difference from the magnet center due to this dependence is small (at most 20 mm above 1.0 GeV/c) at the present acceptance. The positions of the gate are set to be ± 90 mm (about $4 \sigma(\text{rms})$ of the distribution). This condition is also effective to cut K^- decay events (see section 4.3.3).

After one track is reconstructed, we exclude all the hits that have been associated with the track and try to find another track only with unused hits again. This procedure is repeated until it becomes impossible to reconstruct a track anymore. The efficiency of the track reconstruction has been estimated

about $\sim 95\%$, mainly due to the inefficiencies of the SSDs and the wire chambers, although the number of chambers are redundant (we require at least 2 planes with hit both before and after the magnet besides hits on VSSDs).

Efficiencies of MWPCs are $\geq 95\%$, that of DC1 is $\sim 99.5\%$, and that of DC2 is $\sim 95\%$, while that of DC3X is $\sim 77\%$ and that of DC3Y is 62% . This rather low efficiency of DC3 is due to its small acceptance (long distance from the target) compared with the TOF hodoscope.

4.2.2 TOF analysis

All the scintillation counters used for the TOF measurements are viewed by two photomultipliers at both ends. The timing at each scintillator is calculated by averaging the timing of signals from two photomultipliers. The output signals of the photomultipliers are divided and fed to ADC and TDC (stop signal). Since the leading edge discriminators are used, the timing of a signal from each photomultiplier needs to be corrected by the pulse height. The corrected timing, t^c , is obtained by using the following formula:

$$t^c = t + k/\sqrt[4]{q}, \quad (17)$$

,where t and q are the timing(TDC) and pulse height(ADC) of the signal. The coefficient k is determined to minimize the TOF resolution of each counter. Fig. 32-(a) and Fig. 32-(b) show scatter plots of the timing and pulse height of signals from a TOF scintillator before and after the correction, respectively. As shown in Fig. 33, the time resolution after the correction is 85 psec.

In addition to the pulse-height dependence, correlation between the timing of TOF hodoscope and the hit position (y) has been measured by using a π^+ beam. Fig. 34 shows the hit-position dependence of the averaged timing of two t^c s from both ends of a scintillator. Since the hit position linearly depends on the difference of the timing at the both ends as shown in Fig 35, the correction δt^y from the hit position is given by

$$\delta t^y = C |t_u^c - t_d^c|, \quad (18)$$

where t_u^c and t_d^c are the corrected timing at the up and down ends, respectively. For the constant C , we use the same value for all counters of the TOF hodoscope. For the timing of T1 and T2, we neglect the hit-position dependence because of their small size.

The TOF of the beam particle is measured with the two counters, T1 and T2. The distance between the two counters is ~ 6.4 m. For a momentum of 1.66 GeV/c the TOFs are 21.56 ns for π and 21.41 ns for K , while the TOF resolution is 85 psec (rms).

The TOF of outgoing particle is measured with T2 and the TOF hodoscope of 14 scintillators. The average path length from target to the TOF hodoscope is ~ 2.8 m. Fig. 36 shows the TOFs for π , K and protons as functions of the momentum. For a momentum of 1.1 GeV/c (a typical value of K^+ from the quasi-free Ξ^- production), the TOFs are 9.2 ns for π , 10.0 ns for K , and 11.9 ns for protons, the overall TOF resolution is estimated to be 90 psec (rms) from the mass resolution.

Actually, the TOF measured by each counter contains each additive con-

stant. To obtain the correct time, we adjust the constant for each counter so that the mean value of reconstructed masses of protons have the correct value. Fig. 37 shows the typical changes of the constants during the experiment.

4.2.3 Reconstruction of the mass

The mass of a scattered particle is reconstructed from the velocity and momentum, i.e.

$$m = p\sqrt{1 - \beta^2}/\beta, \quad (19)$$

where p is the reconstructed momentum and β is the velocity calculated from the time-of-flight, T_{TOF-T2} , between the T2 and TOF hodoscope:

$$\beta = \frac{L_{TOF-VTX}}{T_{TOF-T2} - (L_{VTX-T2}/\beta_{K^-})}, \quad (20)$$

where $L_{TOF-VTX}$ and L_{VTX-T2} are the path length from the vertex point to TOF hodoscope and the path length from T2 to the vertex point, respectively, and β_{K^-} is the velocity of the incident K^- .

4.3 Selection for the (K^-, K^+) events

As mentioned in section 3.1, AČ1 veto is always in the trigger, which excludes most π^- from the incident beam. In the off-line analysis, time-of-flight information between T1 and T2 is used to identify incident K^- . Fig. 38 shows the TOF distribution of T2-T1. While the TOF resolution is 85 psec (rms), the time difference of K^- and π^- is about 850 psec. The arrows in Fig. 38 indicate the

range to select K^- . The contamination of π^- into the range is found to be less than 10^{-6} by the measurement with π^- beam.

The scattered particle is basically identified by the reconstructed mass. If the reconstructed mass is in the range of $0.4-0.6 \text{ GeV}/c^2$, the particle is identified as a kaon. Up to $1.3 (1.6) \text{ GeV}/c$, more than 99 (92) % of K^+ should be in this range according to the present mass resolution. In addition to the mass, the pulse-height information of AČ2 is used to distinguish π^+ from K^+ . Fig. 39 show momentum-mass scatter plots of outgoing particles with the AČ2 veto.

4.3.1 π^+ rejection

The momentum of the π^+ from quasi-free Σ^- production is about $1.4 \text{ GeV}/c$, which is $0.3 \text{ GeV}/c$ higher than that of the K^+ due to quasi-free Ξ^- production. Fig. 40 shows the momentum distribution of scattered π^+ . The number of events from quasi-free Σ production is about 10 times larger than that of (K^-, K^+) events. Above $1 \text{ GeV}/c$, the mass resolution of π^+ are mainly determined by the TOF resolution, since the velocity of π^+ is almost the light velocity. For a $1.3-1.6 \text{ GeV}/c$ pion, the mass of $0.4 \text{ GeV}/c^2$ corresponds to about 3σ of the TOF resolution. Without AČ2 veto, the number of events in the mass range of $0.4-0.6 \text{ GeV}/c^2$ and in the momentum range of $1.3-1.6 \text{ GeV}/c$ is 41 as shown in Fig. 41, which might be partially due to from the K^- decay (see section 4.3.3). Since the detection efficiency of π^+ of AČ2 in this momentum region is 99.4%, the expected number of backgrounds due to misidentification of π^+ as K^+ in the

momentum range of 1.3-1.6 GeV/c is less than 0.25 event.

4.3.2 Proton rejection

The number of the proton events is very large compared with that of (K^-, K^+) events, because the (K^-, p) reactions do not have to create a $s\bar{s}$ pair. Moreover, the momentum of a proton is kinematically allowed up to ~ 2 GeV/c as shown in Fig. 42. Since the threshold momentum of AČ2 for a proton is 2.67 GeV/c, the reconstructed mass is the only parameter to distinguish K^+ from protons in the off-line counter analysis. The proton-mass resolution is mainly determined by the momentum resolution because of the low velocity. By tightening χ^2 cut on the tracks, the momentum resolution ($\Delta p/p$) is improved up to 2.5 % (rms) at 1.0 GeV/c. The momentum resolution is limited by multiple scattering in the materials like AČ2 after the target. Since the distribution of the deflections resulting from the multiple scattering is roughly Gaussian only for small angles ($\leq$ a few θ_{rms}), and shows much greater probability for large-angle scattering than the Gaussian distribution would suggest, we have estimated the number of misidentified protons (with a measured mass ≤ 0.6 GeV/ c^2) as K^+ by fitting the tail of the proton peak with an exponential curve as shown in Fig. 43. The expected number of the background events in the momentum range of 1.0-1.6 GeV/c is about 3.3, which corresponds to 6.6×10^{-6} of total proton events in the same momentum range.

4.3.3 Rejection of K^- decay

Background events can be also caused by the decay of K^- , $K^- \rightarrow \mu^- + \bar{\nu}$, in the analyzing magnet. Since the most tracks of these events have a kink in y-direction, they are excluded in the track reconstruction process as mentioned in section 4.2.1. However some of the K^- decay events can not be excluded (Fig. 44) and make a locus in the mass-momentum scatter plot in a rather high momentum region. Fig. 45 shows possible pairs of the calculated momentum and mass due to $K^- \rightarrow \mu^-$ decay for four different decay points in the magnet.

For K^- -decay events, the z position of the intersection of two straight track obtained by fitting hits before and after the magnet are distributed in wide ranges, while those of ordinary tracks are distributed near the center of the magnet. The background events can be reduced by tightening the intersection-cut (see section 4.2.1.). In addition to the intersection-cut, we reduced K^- -decay events by cutting events of small scattering angle (≤ 60 mrad).

It should be noted that the number of events due to K^- decay is reduced by AČ2 veto, because the detection efficiency of K^- of AČ2 is about 75 % at 1.66 GeV/c. Without AČ2 veto, the number of events in the momentum range of 1.5-1.6 GeV/c is 8 (see Fig. 41). If they are caused by the K^- decay, the expected number of such background events is 2.

We have applied rather severe criteria (vertex point, χ^2 , scattering angle, etc.) to select (K^-, K^+) events for the H search in the K^- momentum spectrum. The number of (K^-, K^+) events has been reduced down to 75 % by these severe criteria. It has been confirmed that the cuts on the outgoing track have no mo-

momentum dependence above 0.9 GeV/c by comparing two momentum distributions of protons before and after the cuts as shown in Fig. 46.

4.4 Emulsion analysis

In order to find a (K^- , K^+) interaction vertex in emulsion, we have applied "SCAN-BACK" method instead of the traditional volume scanning method. Since the vertex point predicted as an intersection of a K^- beam and a K^+ track has large uncertainty due to the multiple Coulomb scattering in emulsion, it is quite difficult to find the vertex by the volume scanning. The "SCAN-BACK" is performed as follows.

First, we have scanned an area of $300 \times 350 \mu m^2$ around the predicted point of each K^+ track on a changeable sheet. If the difference in angles between the predicted K^+ track by the counter system and a track found by the emulsion analysis is smaller than the sum of uncertainties of the emulsion measurement (5 mrad) and the counter measurement (1 mrad), we regard that the predicted track has been found. More than three reference tracks which belong to other triggered events predicted around the K^+ event are scanned at the same time for confirmation.

As the result of the preliminary scanning, good candidate tracks have been found in 93 % of the predicted events, about 2 % have double candidates and 5 % have no candidate. Therefore we can locate 95 % of the predicted tracks on changeable sheets (see section 2.6).

K^+ tracks are connected from a changeable sheet to the thin emulsion

sheet of the target stack by using X-ray marks as coordinate references. This connection is done by the semi-automatic scanning system with a stage which has a large stroke ($25 \times 25 \text{ cm}^2$). This connection is confirmed by the connection of the reference tracks. From thin plate to thick plate and from thick plate to thick plate, the following-up procedure is repeated until the interaction point is found.

The rate of the misconnection of tracks in the procedure of following up is estimated as follows. Arbitrary 20 tracks which have a similar angle with a typical K^+ track ($\sim 100 \text{ mrad}$) have been picked up on a changeable sheet and traced back in the emulsion stack. As a result, 7 tracks go through out the target stack, 3 tracks come from the beam interaction, and 10 tracks are found to be electron tracks from their large deflections due to multiple Coulomb scatterings in the emulsion. Therefore, if we make misconnection of a track during the scanning, the track will end up with these categories at this ratio. Thus the number of fake events among the observed vertices can be estimated as follows:

$$N_{fake} = N_{electron} \times (3/(10 - 3)), \quad (21)$$

where N_{fake} is the number of background events, and $N_{electron}$ is that of electron events found in the emulsion.

As the result of the preliminary scanning, we have found 756 events in our emulsion. In addition, 18 electron events have been found, therefore the number of background among the 756 interactions is estimated to be about 8. In the present emulsion analysis, 99 % of the observed vertices are true ones which are identified by the counters, and it shows that the quality of our analysis is quite satisfactory in spite of high beam density of the exposure.

The search for the H in the emulsion analysis is done by means of scanning the emulsion near the Ξ^- stop point to find the characteristic weak decay of the heavy H ($M_H \geq 2135 MeV/c^2$):

$$\Xi^- + (p) \rightarrow H \rightarrow \Sigma^- + p, \quad \Sigma^- \rightarrow p + \pi^-, \quad (22)$$

and a high energy π^- due to the light H ($M_H \ll 2120 MeV/c^2$):

$$\Xi^- + (n) \rightarrow H + \pi^-. \quad (23)$$

The emulsion analysis is now in progress.

5 Results and Discussions

5.1 Results of the counter analysis

The obtained mass spectra in three momentum ranges are shown in Fig. 48. The mass resolution for K^+ of $0.9 \leq P_{K^+} \leq 1.2$ GeV/c is $28 \text{ MeV}/c^2$. It is consistent with the momentum resolution and the time-of-flight resolution mentioned in the previous sections.

Fig. 49 shows the momentum distribution of the scattered K^+ as a solid line. A dashed line is the result of the Monte-Carlo simulation of the quasi-free reaction, $K^- + (p) \rightarrow \Xi^- + K^+$. The configuration and conditions of the simulation are;

- (a) isotropic angular distribution in the center of mass system,
- (b) no energy dependence of the cross section,
- (c) fermi motion of a proton in a nuclei,
- (d) the acceptance and momentum resolution of the spectrometer,
- (e) loss of K^+ due to the decay.

The width of the peak caused by quasi-free Ξ^- production is well reproduced by the simulation. The number of events from the quasi-free Ξ^- process is estimated to be about 1700 by fitting the peak. On the assumption that the angular distribution of K^+ from the quasi-free Ξ^- reactions is flat in our acceptance, the laboratory cross section for the emulsion target is calculated to be $96 \mu\text{b}/\text{str}$ from the relation;

$$Y_{K^+} = N_{K^-} N_{\bar{A}} \frac{d\sigma}{d\Omega} d\Omega \eta_{RC} \eta_{K^+} \eta_{cut}, \quad (24)$$

where Y_{K^+} is the number of the (K^-, K^+) events, $N_{K^-} = 8.56 \times 10^8$ is the effective flux of incident K^- , $d\Omega = 0.14$ is the solid angle, $N_A = 4.32 \times 10^{23}/\text{cm}^2$ is the average number of nuclei per unit area, $\eta_{K^+} = 0.67$ is the survival rate of K^+ , $\eta_{RC} = 0.68$ is the product of trigger efficiency (0.87) and reconstruction efficiency (0.78) which is mainly due to AČ2 veto (thermal noise) and chamber's inefficiencies, and $\eta_{cut} = 0.75$ is due to the strict cuts for the direct-H search (see section 4).

With the use of information of the target mass number dependence of the quasi-free (K^-, K^+) reaction³⁷, the cross section for $K^- p \rightarrow K^+ \Xi^-$ is calculated to be $\sim 35 \mu\text{b}/\text{str}$, which is consistent with previous measurements.³⁸ No distinct peak from the direct H production is observed in the spectrum.

5.2 Results of emulsion analysis

There are 4 events above 1.3 GeV/c, which are consistent with the number of background events due to the tail of the proton peak and the K^- decay. We have studied the vertices of these 4 events in the emulsion and two of them are found to be caused by background reactions using information from the emulsion stack.

In one of those 2 events ($P_{K^+} = 1.58 \text{ GeV}/c$), two charged particles are emitted from the reaction vertex. Their total energy (kinetic and binding energy) has been estimated to be more than 120 MeV from their track lengths.³⁹ Therefore, kinematically, this event should not be caused by the direct production of the H unless it is extremely light(below $2M_N$). In the other event ($P_{K^+} = 1.53 \text{ GeV}/c$), a meson(π or K) is emitted from the vertex. This meson can

not be due to a pion emission by the H trapped by the target nuclei since the mass of the H corresponding to this K^+ momentum is estimated to be ~ 1.95 GeV/ c^2 and it is below both ΛN and $NN\pi$ threshold. This event is most likely caused by a misidentified proton, $K^- + A \rightarrow p(\sim 1.5 \text{ GeV}/c) + K^- (\text{ or } \pi^-) + X$. As to the other two background events, one ($P_{K^+} = 1.40 \text{ GeV}/c$) can not be located, because its reaction point is at the edge of the emulsion. And the other event ($P_{K^+} = 1.32 \text{ GeV}/c$) has no extra charged particle emission at the vertex. Therefore, it is a candidate for a long-lived H. However, we cannot exclude the possibility that the event is caused by other reactions; decay of a K^- after an elastic scattering in emulsion (see section 4.3.3), re-scattering of a proton or a K^+ in AČ2 and so on.

As for the heavy H, the background mainly comes from the high momentum tail of the peak due to the quasi-free Ξ^- production. By analyzing 12 events with $1.2 \leq P_{K^+} \leq 1.3 \text{ GeV}/c$ in the emulsion, we have found 4 events in which Ξ^- escaped from the target nuclei. They are excluded from the H candidates. The rest of the events are considered to be the background in the calculation of the upper limits for the H production.

5.3 Upper Limits for direct H production

Fig. 50 shows the upper limits for the ratio of the direct H production cross section to that of the quasi-free Ξ^- production. The momentum dependence of the detection efficiency of K^+ due to AČ2 veto (Fig. 21), momentum dependence of K^+ survival rate and the mass resolution are considered in the calculation. The

width of the direct H production peak is assumed to be 100 MeV/c, considering the excitation of a residual nucleus and the momentum resolution.

5.4 Comparison with Theoretical Estimation

Theoretically, Aerts and Dover calculated the cross section of the H production for the reaction²⁶

$$K^- + {}^3\text{He} \rightarrow K^+ + n + H. \quad (25)$$

The lowest-order process for the H production is shown in Fig. 51. The evaluation of the cross section requires three ingredients; the two-body amplitude f for $K^- + p \rightarrow K^+ + \Xi^-$, the fusion amplitude Γ for $\Xi^- + p \rightarrow H$ and the target wave function. In their calculation, the off-shell amplitude f was replaced by its on-shell amplitude which was parametrized by using the experimental data of the cross section for $K^-p \rightarrow K^+\Xi^-$. The fusion amplitude Γ was approximated by the wave-function overlap of Ξ^-p and H assuming the wave function for each proton is Gaussian. For $m_H = 2.1 \text{ GeV}/c^2$ and $P_{K^-} = 1.8 \text{ GeV}/c$, the cross section was about $0.5 \text{ } \mu\text{b}/\text{str}$, which increases monotonously as m_H decreases. The detail of the calculation is described in Appendix (A.1).

To compare our result with a theoretical estimation, we calculate the cross section of the reaction $X(K^-, K^+ X')H$ for the various nuclei which are components of the emulsion. This is a straightforward extension of the previous calculation. For a nucleus with the mass number A and the proton number Z , we calculate the cross section for a pair of protons and multiply it by an effective number of proton pairs in relative 1S_0 state, since other states do not contribute to the H production. To get the target wave function, a wave function of each

proton is approximated by

$$\rho(r) = \frac{\rho_0}{(1 + \exp((r - R_0)/a_0))} \quad (26)$$

where $\rho(r)$ is a charge density distribution of a nucleus, which was determined by elastic electron scattering.⁴⁰ It was approximated by

$$\frac{\rho(r) = \rho_0}{(1 + \exp((r - R_0)/a_0))}, \quad (27)$$

where $R_0 = 1.158A^{1/3} - 0.628A^{-1/3}$ fm and $a_0 = 0.47$ fm.

To simplify the calculation we assume that the remaining nucleons act as spectators. So, only the distribution of their center-of-mass motion can affect the calculation through total momentum conservation law. A wave function of the residual nucleus in terms of its center-of-mass momentum is assumed to be

$$\psi_{A-2}(\vec{k}) = \psi_p\left(\frac{\vec{k}}{\sqrt{A-2}}\right). \quad (28)$$

It makes the distribution of the momentum of the residual nucleus $\sqrt{A-2}$ times wider than that of the proton. With an appropriate normalization factor, the internal target wave function is obtained by removing the center-of-mass motion of the nucleus (two protons and the residual nucleus). Then the target wave function is fed to the original equation (see Appendix-1) to calculate the cross section for a pair of protons.

Fig. 52 shows the H production cross sections for a pair of protons in the various nuclei as a function of M_H assuming two protons are in the relative 1S_0 state. The cross section decreases as the mass number increase. This dependence reflects the fact that H production occurs only when the Ξ^-p relative momentum is small, and this condition is satisfied with rather high momentum of the proton.

The wide spatial distributions of protons in heavy nuclei give small possibility that a proton could have high momentum.

The probability of each proton pair's being in the relative 1S_0 state is calculated by assuming that each proton is in a one-particle shell model state (nlj) in the harmonic oscillator well.⁴¹ In Appendix (A.2), the detail calculations are described. The probability decreases rapidly as protons have larger values of n and l . The effective number of pairs in 1S_0 state for each nuclei is obtained by summing up the product of each probability and the number of pairs. By multiplying the effective number by the cross section for one pair, the H production cross sections for various nucleus are calculated. The magnitudes of the cross sections have been obviously overestimated, since we have neglected the absorption of K^- and K^+ in a nucleus. Moreover, the calculated cross sections have an uncertainty due to that of the elementary cross section; $K^-p \rightarrow K^+\Xi^-$. To reduce the uncertainty and cancel some parts of absorptive effects, we take the ratio of the H production to quasi-free Ξ^- production, since the H production cross section is proportional to the elementary cross section. The quasi-free Ξ^- production cross section is estimated by simply multiplying the forward laboratory cross section $(d\sigma/d\Omega_L)_{K^-p \rightarrow K^+\Xi^-}^{0^\circ}$ ²⁶ by a proton number Z . The ratio for the emulsion target is shown in Fig. 53

The ratio for the emulsion target has been estimated with use of information of a target mass number dependence of the cross section for the quasi-free (K^-, K^+) reaction³⁷. The ratio as a function of the H mass is shown as a solid line in Fig. 50. In the mass range of 1.90-2.10 GeV/ c^2 , the ratio is 0.40-0.25 %, which is nearly equal to or smaller than upper limits obtained here. It indicates the absence of the H in this mass range (1.90-2.10 GeV/ c^2). It should

be noted, however, that we have neglected the fact that the absorptive effects could be different in two types of reactions. The H production should be related to two-particle density while quasi-free Ξ^- production should be proportional to one-particle density. This difference brings a uncertainty in the theoretical estimation of the ratio, especially for heavy nuclei. But, this uncertainty brings only small effect to the ratio for the emulsion target since the H production cross section for the emulsion target is mainly contributed by lighter nuclei. The ratio in the assumption that only C,N,O contribute the H production is shown as a dashed line in Fig. 50.

Since the calculation should have a large uncertainty due to the fusion vertex Γ , we have to await more reliable estimates of the H production cross sections and/or experiments of higher statistics to exclude the possibility of the H in this mass range.

As for the heavy H ($2M_\Lambda \geq M_H \geq 2.10\text{GeV}/c^2$), we cannot exclude the possibility of the existence. However, the question about the existence of the heavy H and the double Λ hyper nuclei can be answered by studying the Ξ^- stop point to find their characteristic decay fragments in the emulsion, which is now in progress.

6 Conclusion

We have searched for the H by the analysis of the K^+ momentum spectrum in the (K^-, K^+) reaction from the emulsion target with information of reaction vertices in the emulsion. Upper limits for the production cross section of the H in the mass range $(1.90 \leq M_H \leq 2.16 \text{ GeV}/c^2)$ are 0.2-0.6 % of the quasi-free Ξ^- production at 90 % confidence level.

A theoretical estimation of the ratio of the H production to the quasi-free Ξ^- production for the emulsion target has been performed. In the mass range of 1.90-2.10 GeV/c^2 , the calculated ratio is nearly equal to or smaller than upper limits obtained here.

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Appendix

A.1 Cross section for $K^- + {}^3\text{He} \rightarrow K^+ + n + H$

The integrated cross section can be represented as

$$\sigma = \frac{1}{(2\pi)^5} \int \frac{d^3 k'}{2E_{k'}} \int \frac{d^3 p_n}{2E_n} \int \frac{d^3 p_H}{2E_H} \delta^{(4)}(P - k' - p_n - p_H) \times |M|^2 / 2\lambda^{1/2}(s, m_{He}^2, m_K^2), \quad (29)$$

where k' , p_n and p_H are the four-momenta of the outgoing K^+ , neutron, and H dibaryon, respectively, with $E_{k'} = \sqrt{k'^2 + m_K^2}$, etc. Further, s is the total invariant mass squared of the initial and final states,

$$P = \left(\vec{k}_L, m_{He} + (k_L^2 + m_K^2)^{1/2} \right), \quad (30)$$

where k_L is the momentum of incident K^- , and

$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2(ab + bc + ca) \quad (31)$$

is the usual triangle function.

For the lowest order process of Fig. 51, The M in the first equation is given by

$$M = (2E_H 2M_{He} 2E_n)^{1/2} \int \frac{d^3 k_p}{(2\pi)^3} \psi_{He}(\vec{k}_\rho, \vec{k}_\lambda) T(\vec{k}_L, \vec{p}; \vec{k}', \vec{k}_\Xi) \times \Gamma(\vec{k}_\Xi - \vec{k}_p) / (2E_{p'} 2E_\Xi)^{1/2}, \quad (32)$$

where ψ_{He} is the internal wave function of the ${}^3\text{He}$ target, T is the dimensionless amplitude corresponding to the $K^- + p \rightarrow K^+ + \Xi^-$ reaction and Γ is the fusion amplitude for $\Xi^- + p \rightarrow H$. The relevant momenta are defined by

$$\vec{k}_\rho = -(2\vec{k}_p + \vec{p}_n) / \sqrt{2}, \quad (33)$$

$$\vec{k}_\lambda = -\sqrt{3/2}\vec{p}_n, \quad (34)$$

$$\vec{p}' = -\vec{k}_p - \vec{p}_n, \quad (35)$$

$$\vec{k}_\Xi = \vec{k}_H - \vec{k}_p. \quad (36)$$

The internal wave function is given by

$$\psi_{He}(\vec{k}_\rho, \vec{k}_\lambda) = N \exp(-\frac{b^2}{2}(k_\rho^2 + k_\lambda^2)), \quad (37)$$

where N is an appropriate normalization factor and $b = 1.70$ fm. This wave function is obtained by removing the center-of-mass motion from the product of the three nucleon's wave function which are labeled by $\vec{p}'$, $\vec{k}_p$ and $\vec{k}_n$. It can be easily seen by the relation

$$k_\rho^2 + k_\lambda^2 = p'^2 + k_p^2 + k_n^2, \quad (38)$$

in the condition of $p' + k_p + k_n = 0$. For the off-shell amplitude T , it is replaced by the on-shell amplitude T . It is related to a differential laboratory cross section by

$$\left[\frac{d\sigma}{d\Omega_L} \right]_{K^-p \rightarrow K^+\Xi^-}^{0^\circ} = \frac{(k_2')^2}{16\pi^2} |T|^2 / [\lambda(s_2, m_K^2, m_p^2), \lambda(s_2, m_K^2, m_\Xi^2)]^{1/2}. \quad (39)$$

In their work, a simple parametrization for the forward laboratory cross section is used in the form

$$\left[\frac{d\sigma}{d\Omega_L} \right]_{K^-p \rightarrow K^+\Xi^-}^{0^\circ} = 66 \left[1 - \frac{k_{thr}^2}{k_L^2} \right]^{1/2} \exp \left[- \left[\frac{k_L - k_0}{\Delta k} \right] \right] \quad (40)$$

in $\mu\text{b/sr}$, where $k_{thr} = 1.046$ GeV/c is the laboratory threshold momentum, and $k_0 = 1.75$ GeV/c, $\Delta k = 0.6$ GeV/c. The fusion amplitude is approximated by the wave-function overlap:

$$\begin{aligned} \Gamma(\vec{k}_p, \vec{k}_\Xi) &= \frac{1}{(2\pi)^{18}} \int \frac{d^3k_1}{dE_1} \cdots \int \frac{d^3k_6}{dE_6} \psi_{H,pH}(\vec{k}_1 \cdots \vec{k}_6) \\ &\times \psi_{p,\vec{k}_p}(\vec{k}_1, \vec{k}_2, \vec{k}_3) \psi_{\Xi,\vec{k}_\Xi}(\vec{k}_4, \vec{k}_5, \vec{k}_6) \end{aligned} \quad (41)$$

By using Gaussian wave functions for each quark, Γ is found to be

$$\Gamma(\vec{k}_p, \vec{k}_\Xi) = (2\pi)^3 (2E_H 2E_p 2E_\Xi)^{1/2} \delta^3(\vec{k}_H - \vec{k}_p - \vec{k}_\Xi) \tilde{\Gamma}(\vec{k}_p - \vec{k}_\Xi), \quad (42)$$

where

$$\tilde{\Gamma}(\vec{k}_p - \vec{k}_\Xi) = \Gamma_0 \left[\frac{2R_p R_H}{R_H^2 + R_p^2} \right]^3 \left[\frac{2R_\Xi R_H}{R_H^2 + R_\Xi^2} \right]^3 \left[\frac{8R_H^2}{3} \right]^{3/4} e^{-\frac{R_H^2}{12}(\vec{k}_p - \vec{k}_\Xi)^2}, \quad (43)$$

and R_H , R_Ξ and R_p are the oscillator parameters for the H, Ξ^- and p, respectively. They are all set to be 0.83 fm. Γ_0 is the color-spin-flavor recoupling part of the amplitude. Since the H can be written in terms of $Q^3 \otimes Q^3$ component as

$$|H\rangle = \sqrt{\frac{4}{5}}|8_c \otimes 8_c\rangle + \sqrt{\frac{1}{10}}|\Xi N\rangle_{I=0} - \sqrt{\frac{1}{40}}|\Lambda\Lambda\rangle + \sqrt{\frac{3}{40}}|\Sigma\Sigma\rangle_{I=0}, \quad (44)$$

and the diproton of ${}^3\text{He}$ is in the singlet state due to the Pauli principle, Γ_0 is $\sqrt{1/10}$ for ${}^3\text{He}$. Various differential cross sections can be derived by removing one or two integrations from the equation (24).

A.2 1S_0 components in the relative motion of two protons

First, we consider the hamiltonian for two nucleons in a harmonic oscillator potential of frequency ω

$$H = \frac{1}{2} \left(\vec{p}_1^2 / m \right) + \frac{1}{2} m \omega^2 \vec{r}_1^2 + \frac{1}{2} \left(\vec{p}_2^2 / m \right) + \frac{1}{2} m \omega^2 \vec{r}_2^2, \quad (45)$$

where $\vec{r}_1$, $\vec{r}_2$ and $\vec{p}_1$, $\vec{p}_2$ are the coordinates and momenta of two nucleons and m is their mass. All two particle states can be spanned by the basis

$$|n_1 l_1, n_2 l_2, \lambda \mu\rangle = \sum_{m_1, m_2} \langle l_1 l_2 m_1 m_2 | \lambda \mu \rangle |n_1 l_1 m_1\rangle \otimes |n_2 l_2 m_2\rangle, \quad (46)$$

where n_i , l_i and m_i are the radial, angular and magnetic quantum numbers of the particle i , respectively. λ and μ are the total angular and magnetic quantum numbers. $\langle l_1 l_2 m_1 m_2 | \lambda \mu \rangle$ is a Clebsch-Goldan coefficient.

It should be noted that the value of the radial quantum number, n , is always more by 1 in the present formulation than it is in Ref. 41.

Then, the relative coordinate $\vec{r}$ and the center of mass coordinate $\vec{R}$ are defined by the relations

$$\vec{r} = \frac{1}{\sqrt{2}} (\vec{r}_1 - \vec{r}_2), \quad \vec{R} = \frac{1}{\sqrt{2}} (\vec{r}_1 + \vec{r}_2) \quad (47)$$

The corresponding momenta are

$$\vec{p} = \frac{1}{\sqrt{2}} (\vec{p}_1 - \vec{p}_2), \quad \vec{P} = \frac{1}{\sqrt{2}} (\vec{p}_1 + \vec{p}_2), \quad (48)$$

so that the hamiltonian can also be written as

$$H = \frac{1}{2} (p^2/m) + \frac{1}{2} m\omega^2 r^2 + \frac{1}{2} (P^2/m) + \frac{1}{2} m\omega^2 R^2. \quad (49)$$

Therefore, the two particle system can be also spanned by the set of

$$|nl, NL, \lambda\mu\rangle, \quad (50)$$

where the radial and orbital quantum numbers n, l correspond to the relative motion, and N, L to that of center of mass.

The talmi-moshinsky transformation brackets are defined by the relation

$$|n_1 l_1, n_2 l_2, \lambda\mu\rangle = \sum_{nNL} |nl, NL, \lambda\mu\rangle \langle nl, NL, \lambda | n_1 l_1, n_2 l_2, \lambda \rangle \quad (51)$$

Note that the transformation brackets does not depend on magnetic quantum numbers. The values of the brackets are listed in Ref. 41. Because of conservation of energy the bracket has a non-zero value only if the following relation is satisfied:

$$2n_1 + l_1 + 2n_2 + l_2 = 2n + l + 2N + L, \quad (52)$$

since energy of a nucleon in each shell model state (n,l) is

$$E_{nl} = 2n + l + \frac{1}{2}. \quad (53)$$

The inclusion of each spin of each nucleon is straightforward:

$$\begin{aligned} |n_1 l_1 \frac{1}{2} j_1; n_2 l_2 \frac{1}{2} j_2; J\rangle &= \sum_{\lambda s} \sum_{nlNL} |(nl, NL, \lambda); s; J\rangle \\ &\times \sqrt{(2\lambda + 1)(2s + 1)(2j_1 + 1)(2j_2 + 1)} \begin{Bmatrix} l_1 & \frac{1}{2} & j_1 \\ l_2 & \frac{1}{2} & j_2 \\ \lambda & s & J \end{Bmatrix} \langle nl, NL, J | n_1 l_1, n_2 l_2, \lambda \rangle, \end{aligned} \quad (54)$$

where J is the total angular momentum, s is the total spin, and $\{\dots\}$ is Wigner's 9j coefficient.

We need to calculate the probability that two protons are in the relative 1S_0 state ($n = 1, l = 0$):

$$w_{\alpha_1 \alpha_2 J} = \sum_{NL} (2J + 1)(2j_1 + 1)(2j_2 + 1) \begin{Bmatrix} l_1 & \frac{1}{2} & j_1 \\ l_2 & \frac{1}{2} & j_2 \\ J & 0 & J \end{Bmatrix}^2 \langle 10, NL, J | n_1 l_1, n_2 l_2, J \rangle^2, \quad (55)$$

where $\alpha = (n, l, j)$.

If both α_1 and α_2 are occupied, the contribution of all pairs in the two states to the effective 1S_0 number is

$$W_{\alpha_1 \alpha_2} = \sum_J (2J + 1) w_{\alpha_1 \alpha_2 J}, \begin{cases} \text{if } \alpha_1 \neq \alpha_2 & J = |j_1 - j_2|, |j_1 - j_2| + 1, \dots, j_1 + j_2 \\ \text{if } \alpha_1 = \alpha_2 & J = 0, 2, \dots, 2j - 1 \end{cases} \quad (56)$$

Table A-1

α_1	α_2	$W_{\alpha_1\alpha_2}$
1s1/2	1s1/2	1
1p3/2	1p3/2	1.1666
	1s1/2	1
1p1/2	1p1/2	0.1666
	1s1/2	0.5
	1p3/2	0.8333
1d5/2	1d2/5	0.975
	1s1/2	0.75
	1p3/2	1
	1p1/2	0.875
2s1/2	2s1/2	0.2083
	1s1/2	0.245
	1p3/2	0.4166
	1p1/2	0.2083
	1d2/5	0.4375
1d3/2	1d3/2	0.1833
	1s1/2	0.5
	1p3/2	1.0833
	1p1/2	0.1666
	1d2/5	1.4
	2s1/2	0.2916
1f7/2	1f7/2	0.7839
	1s1/2	0.5
	1p3/2	0.75
	1p1/2	0.75
	1d2/5	0.825
	2s1/2	0.375
	1d3/2	1.425
2p3/2	2p3/2	0.4375
	1s1/2	0.25
	1p3/2	0.4583
	1p1/2	0.2916
	1d2/5	0.525
	2s1/2	0.2916
	1d3/2	0.4958
	1f7/2	0.4875

α_1	α_2	$W_{\alpha_1\alpha_2}$
1f5/2	1f5/2	0.1339
	1s1/2	0.375
	1p3/2	1
	1p1/2	0.125
	1d2/5	1.5375
	2s1/2	0.2812
	1d3/2	1.425
	1f7/2	1.816
	2p3/2	0.5625
	2p1/2	0.0875
2p1/2	1s1/2	0.125
	1p3/2	0.2916
	1p1/2	0.0833
	1d2/5	0.3975
	2s1/2	0.1458
	1d3/2	0.1166
	1f2/7	0.4125
	2p3/2	0.2625
	1f5/2	0.1125
	1g9/2	0.6504
1g9/2	1s1/2	0.3125
	1p3/2	0.5208
	1p1/2	0.5729
	1d2/5	0.6406
	2s1/2	0.2864
	1d3/2	0.2604
	1f7/2	0.6786
	2p3/2	0.401
	1f5/2	1.8292
	2p1/2	0.3724

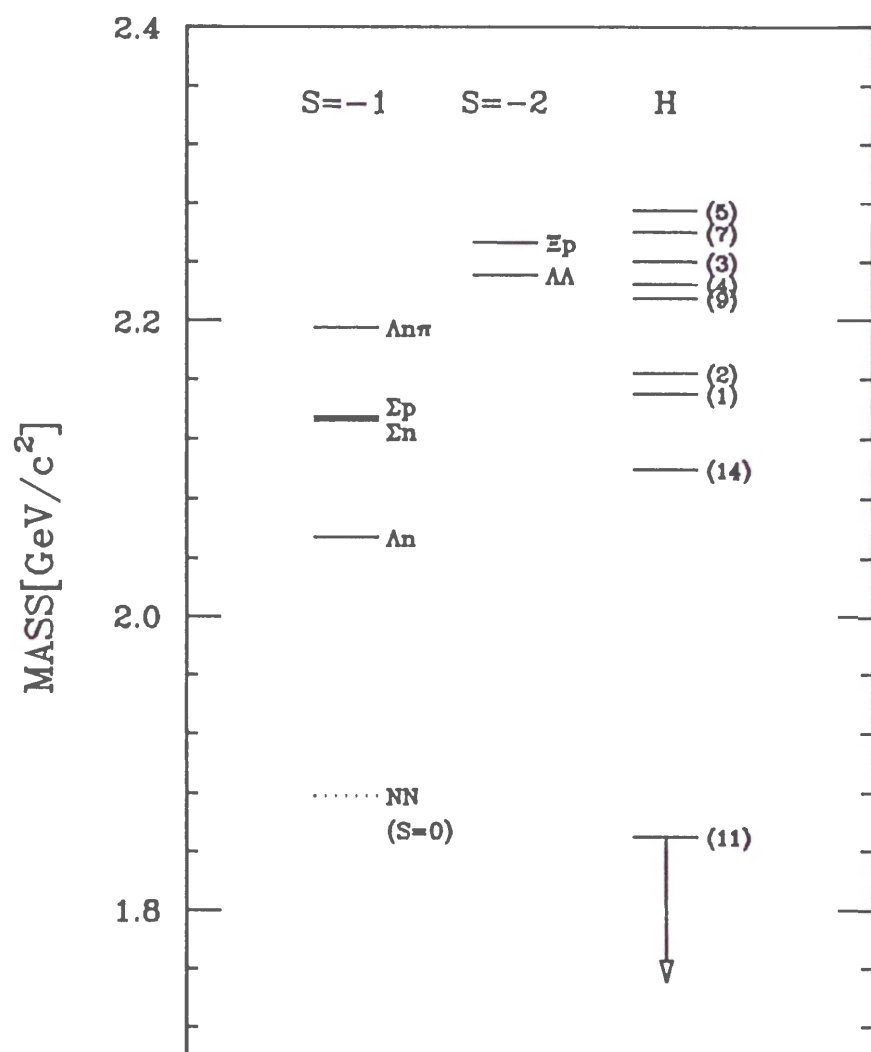


Figure 1

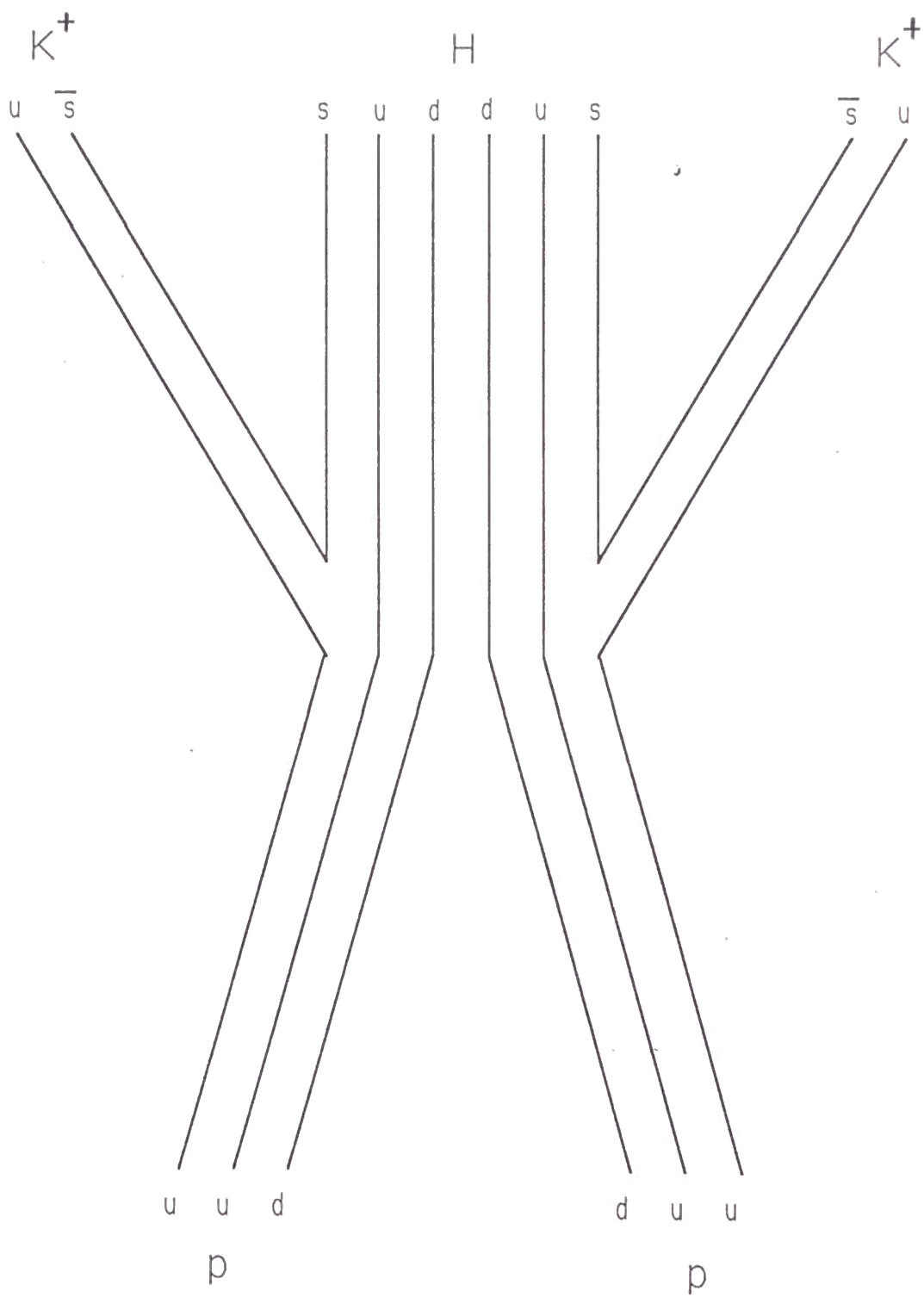
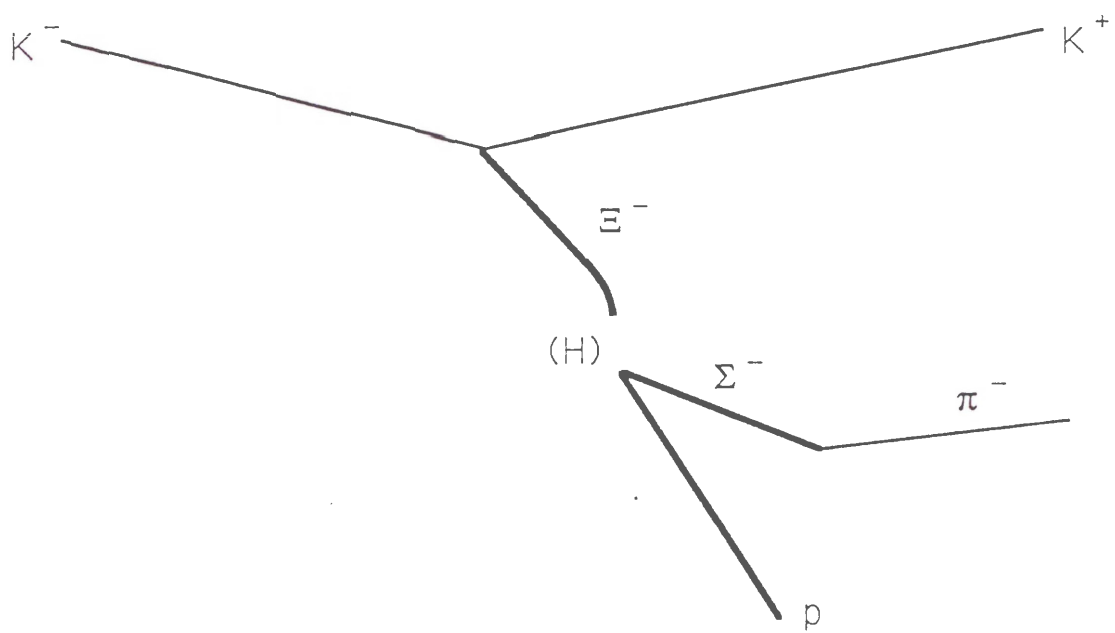


Figure 2

(a)



(b)

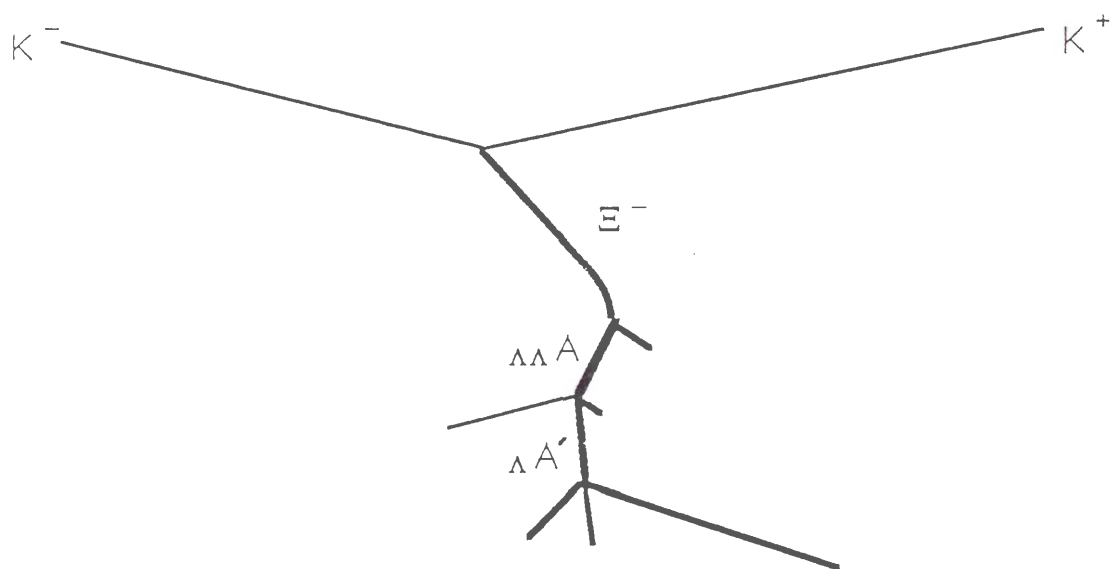


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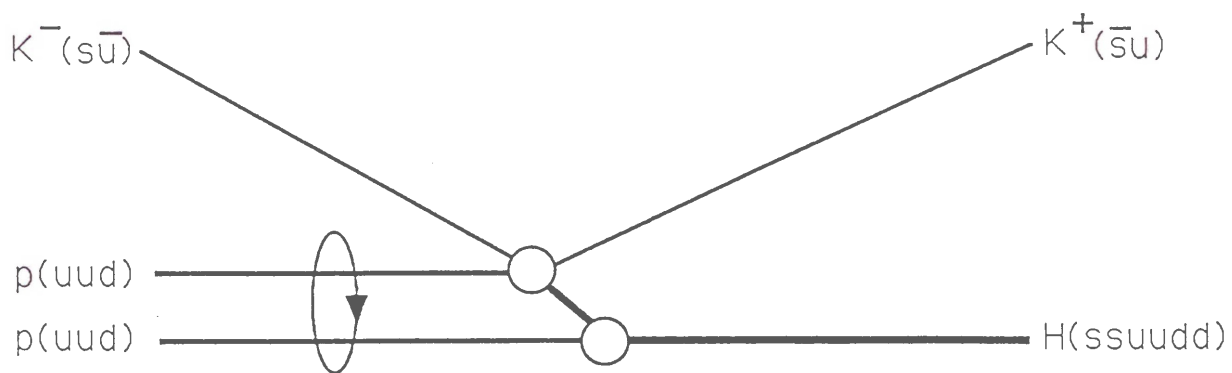


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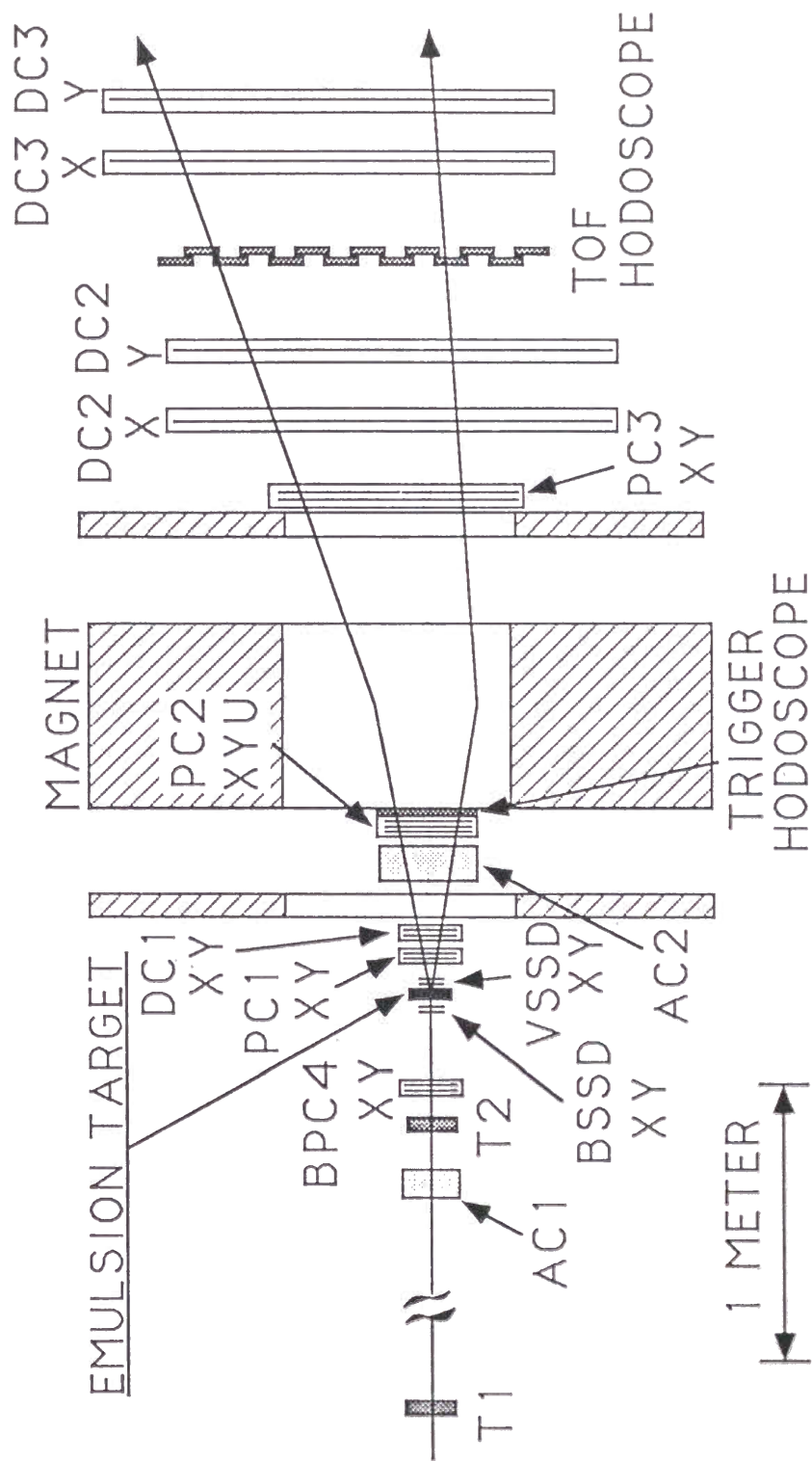


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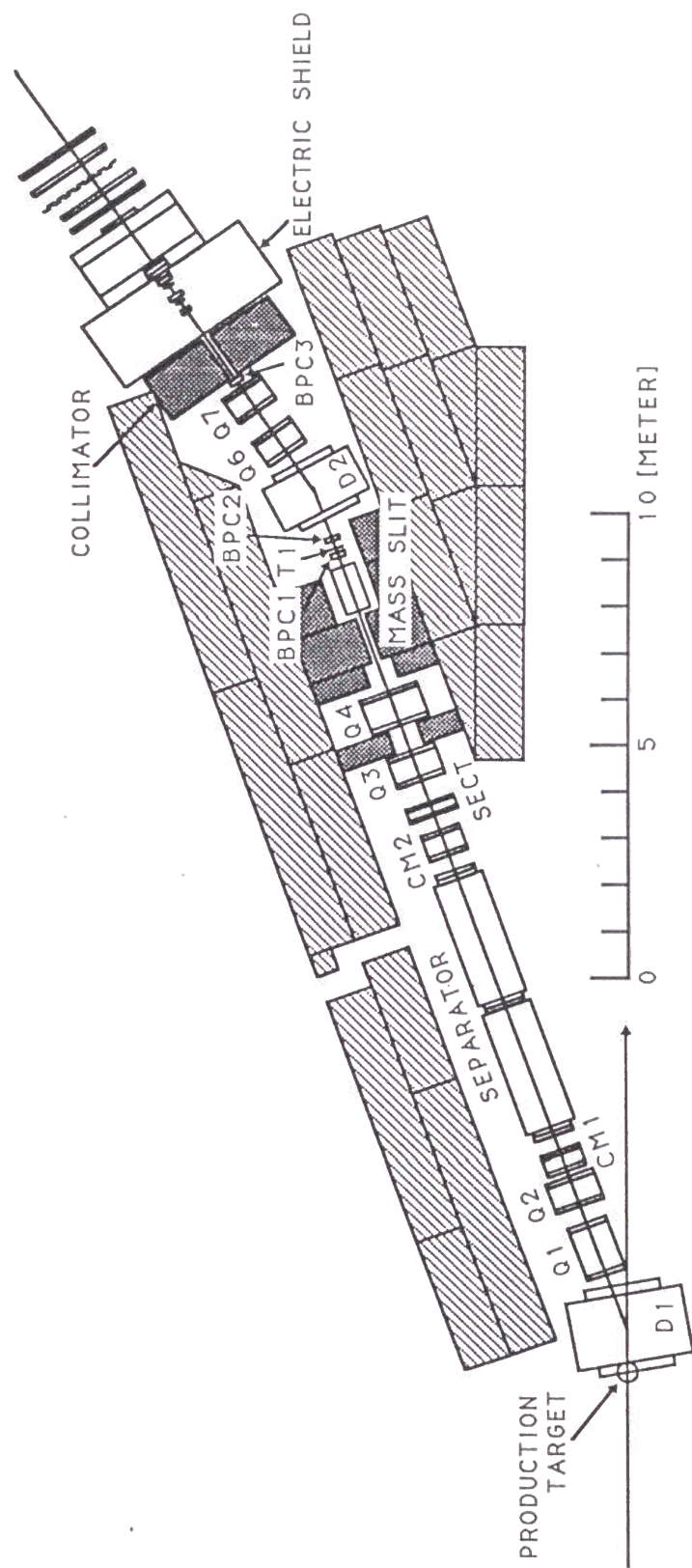


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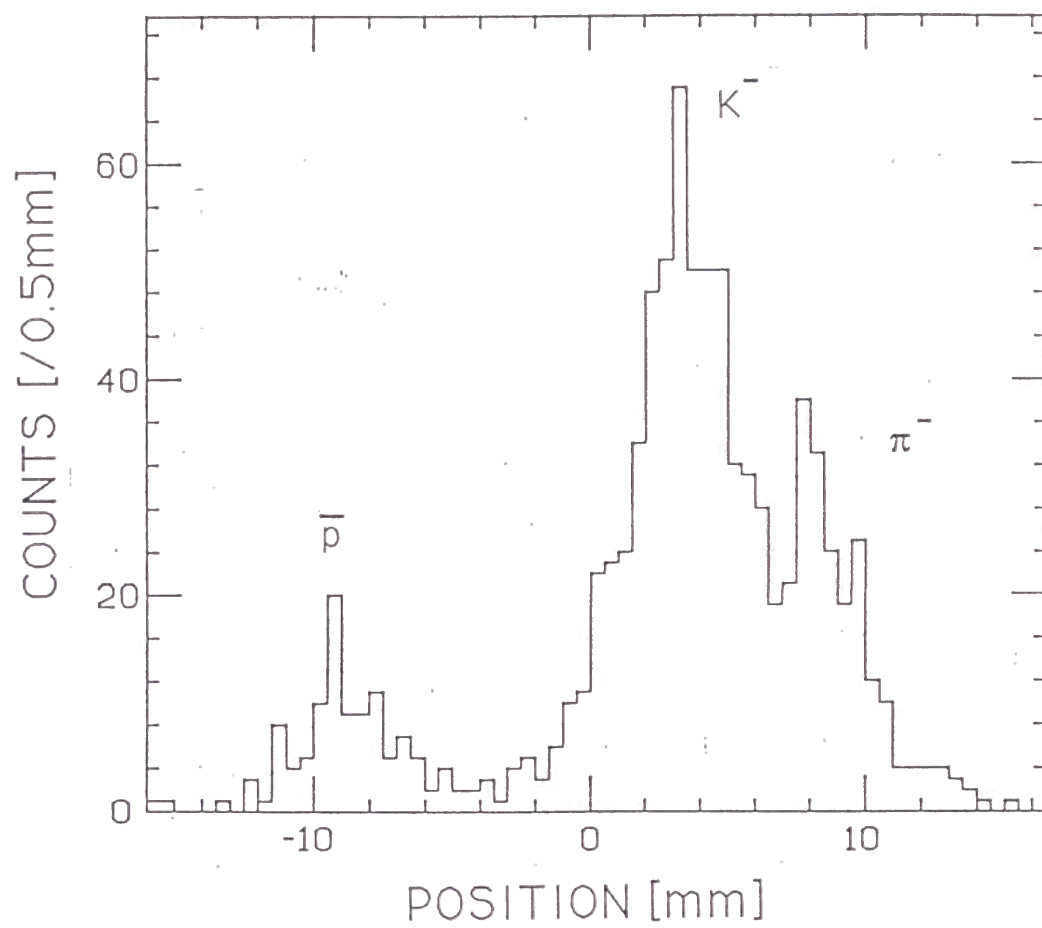


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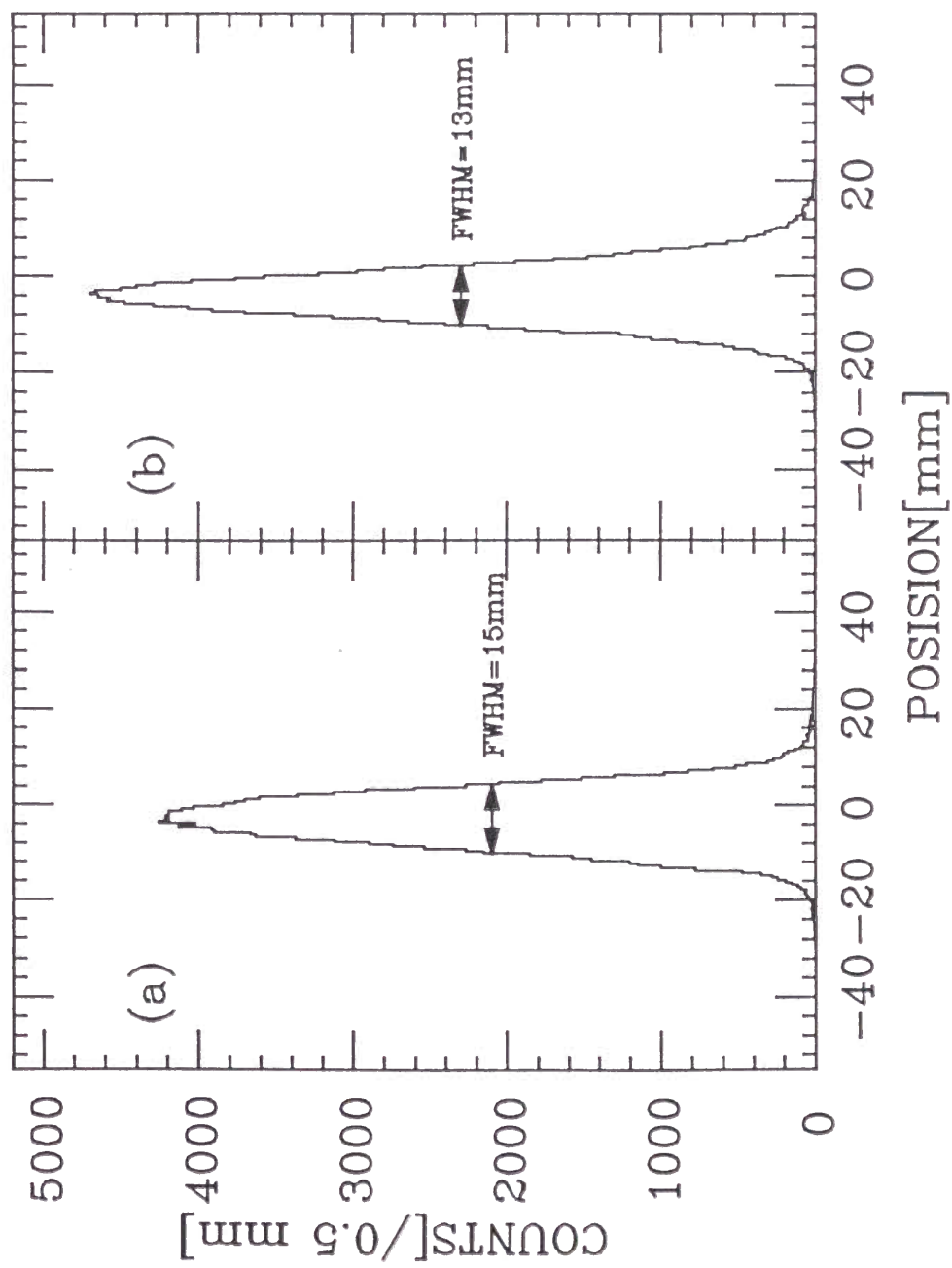


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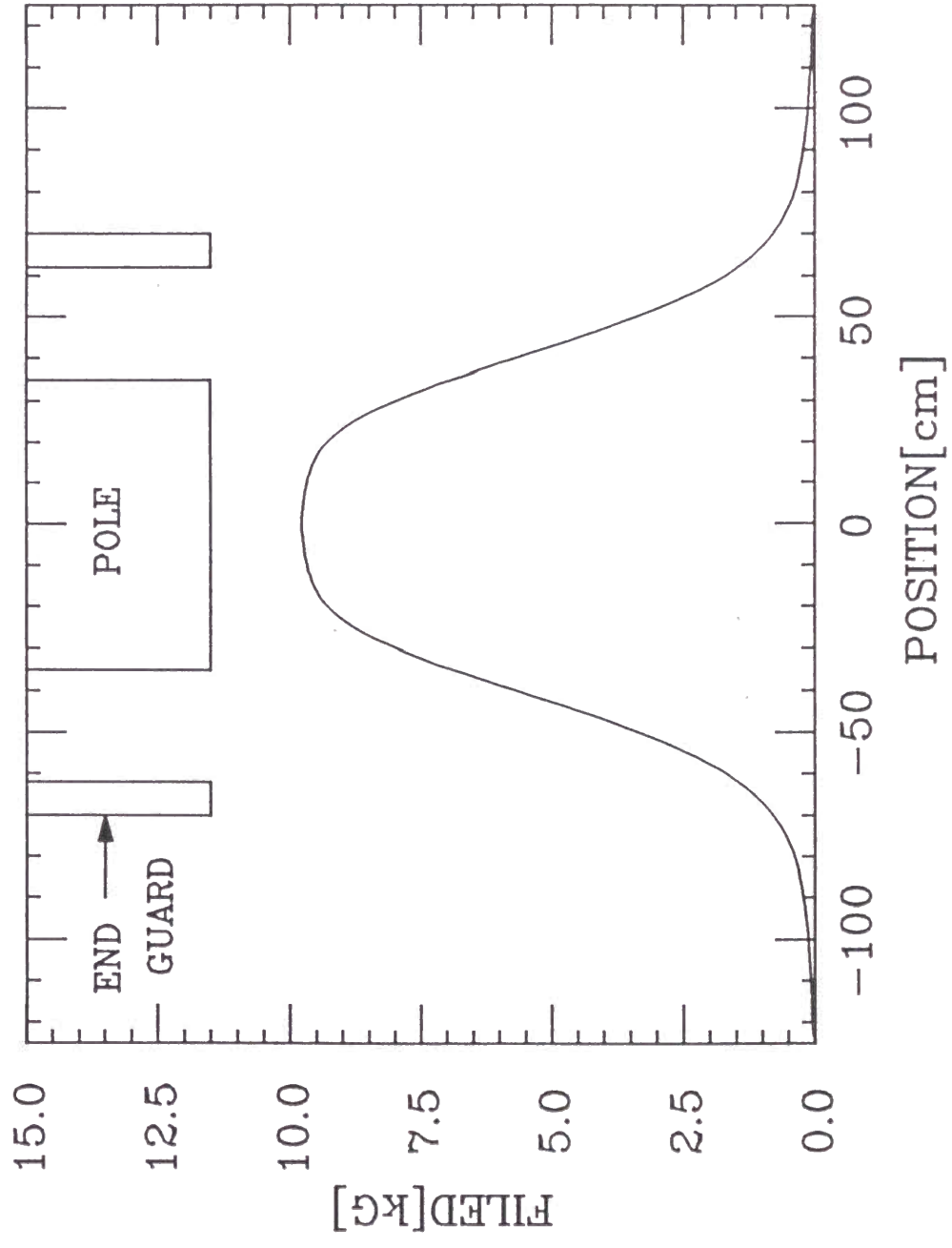
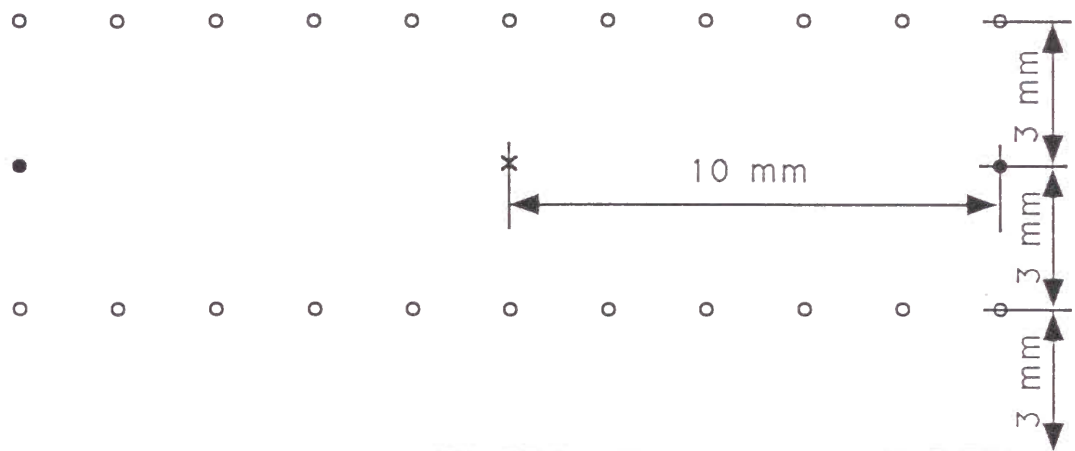


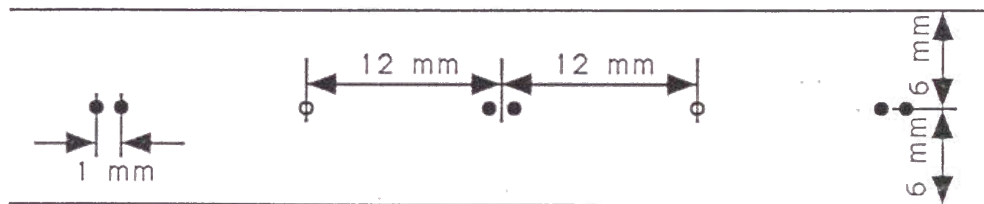
Figure 9

DC 1



× SENSE WIRE ○ FIELD WIRE • POTENTIAL WIRE

DC 2-3



• SENSE WIRE ○ FIELD WIRE

Figure 10

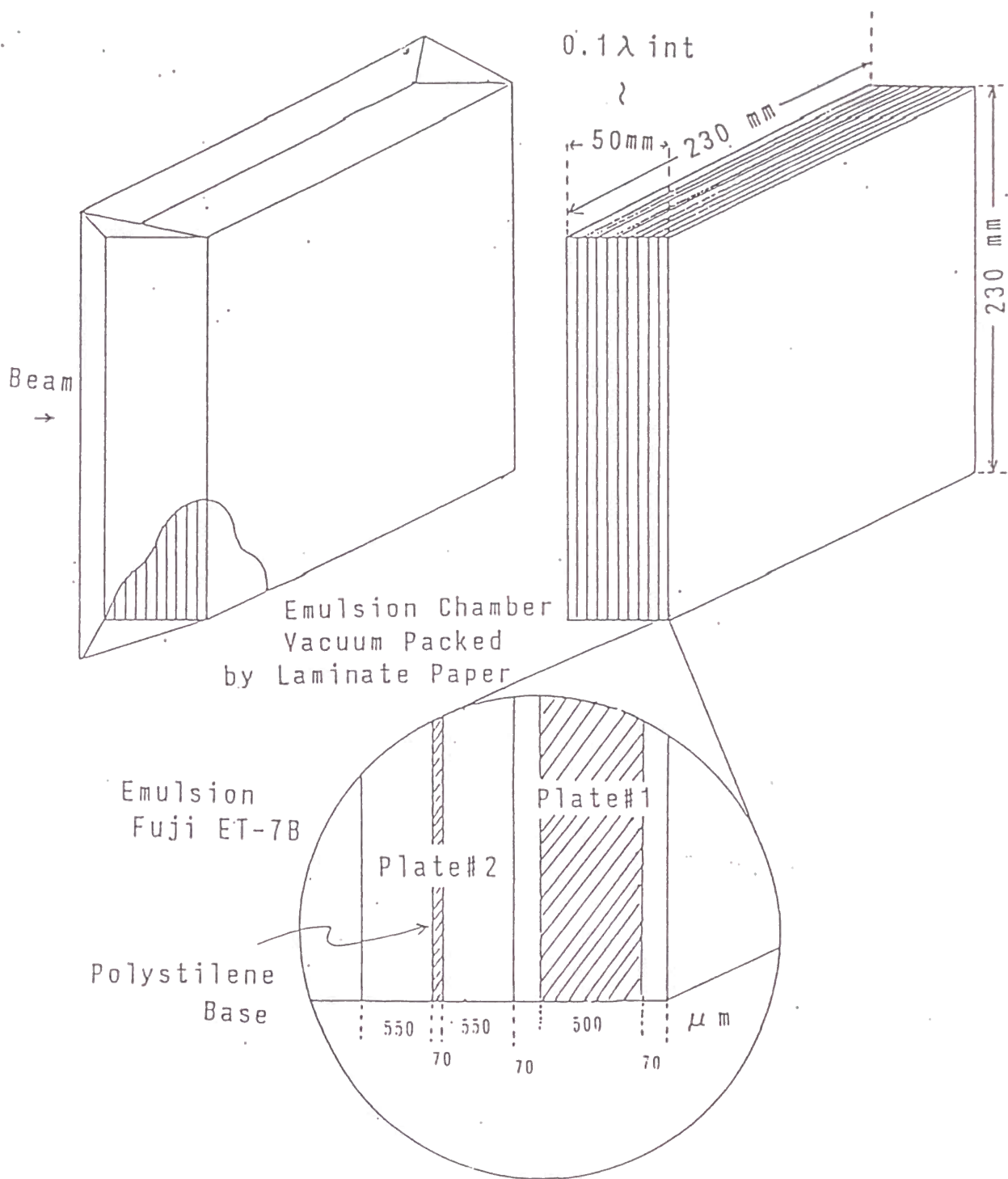


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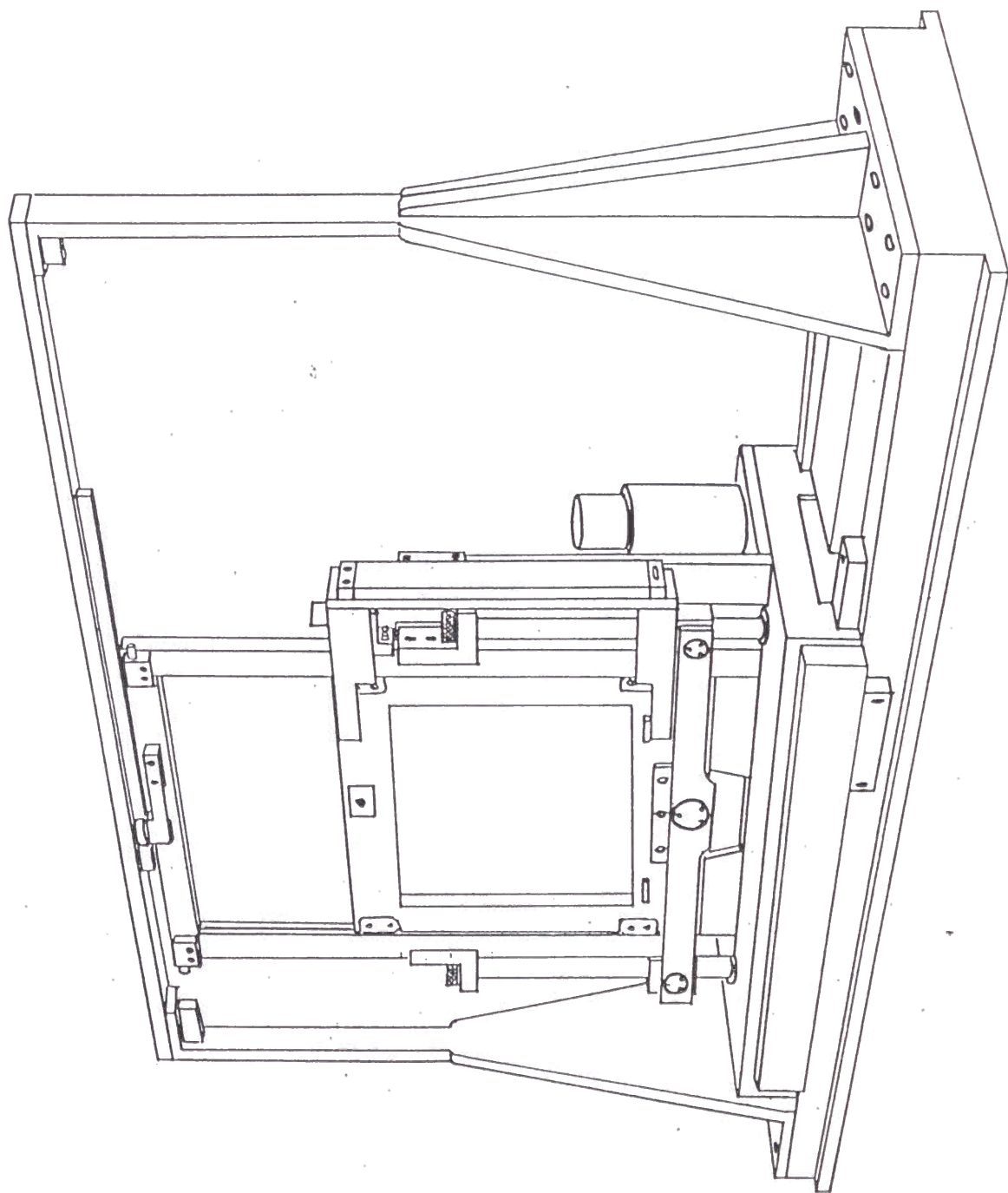


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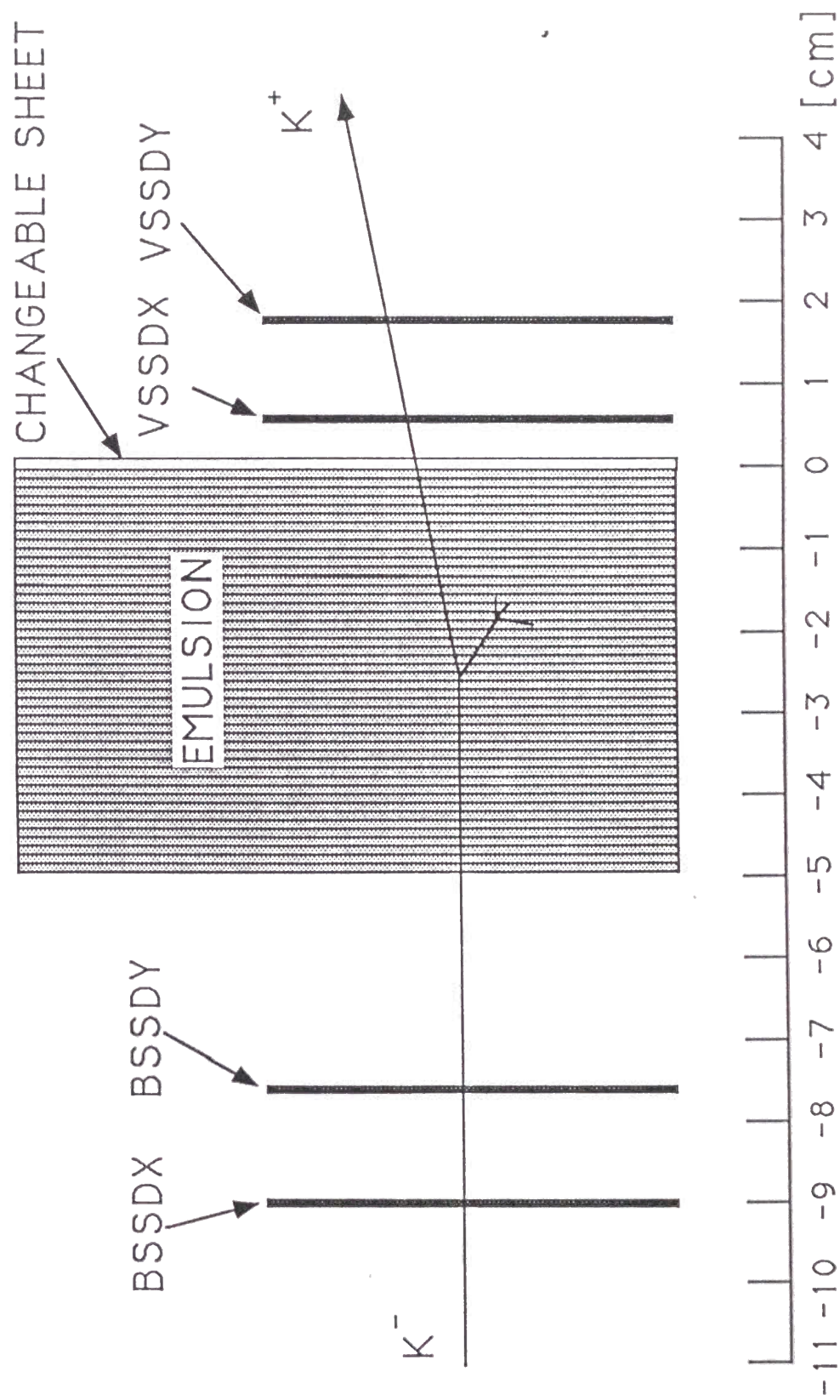


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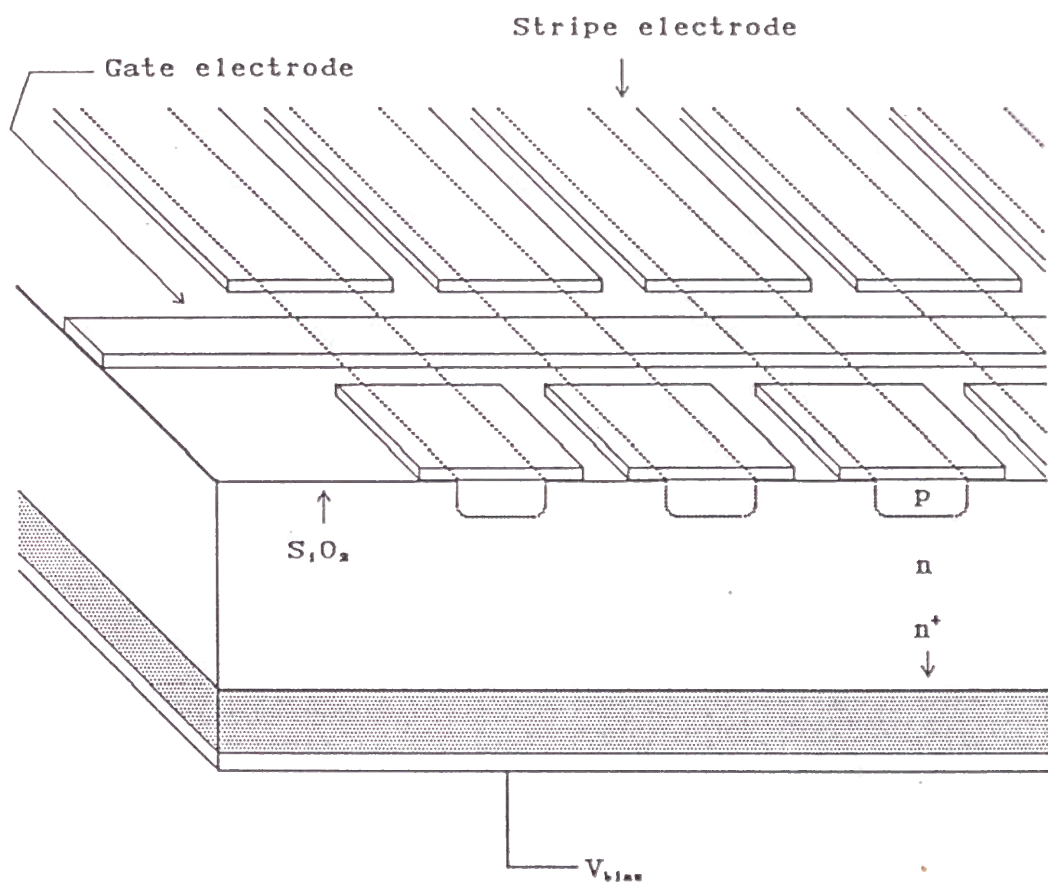


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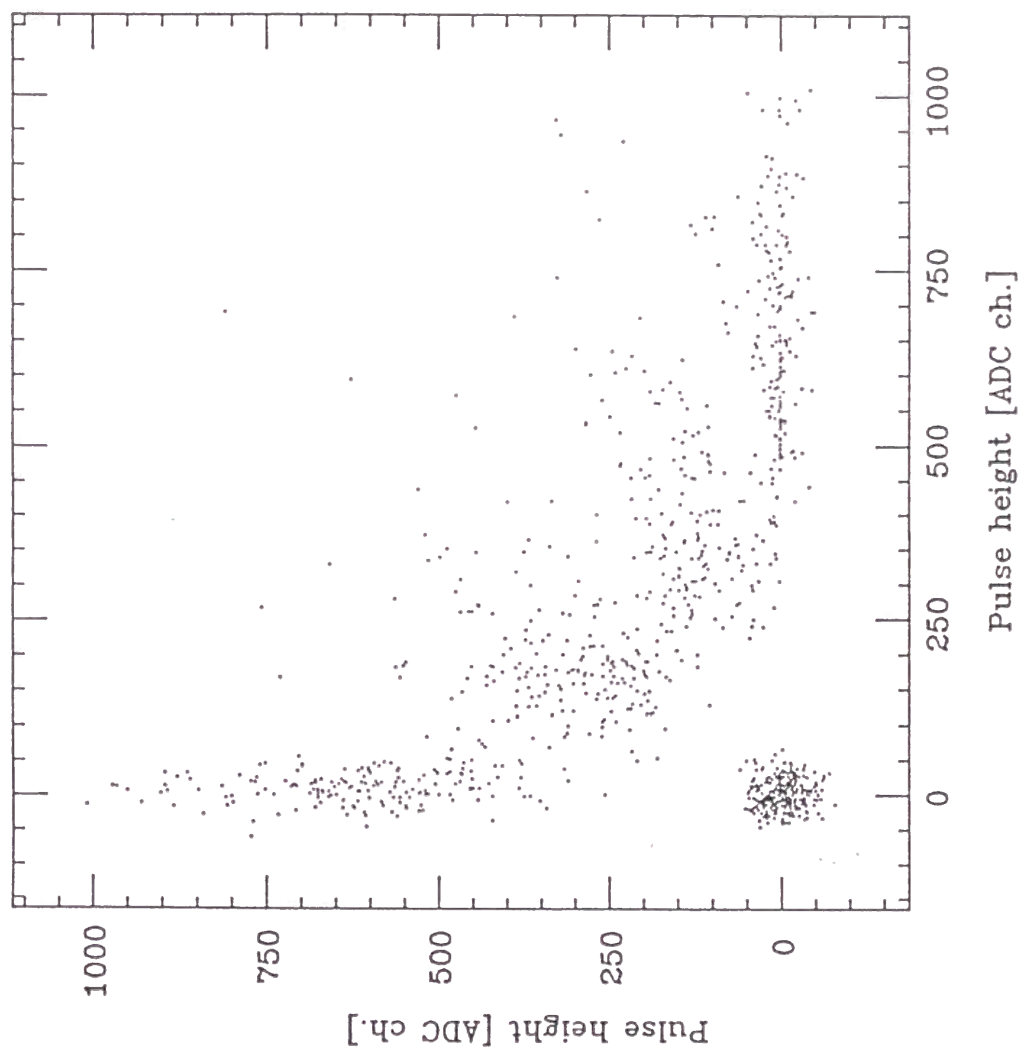


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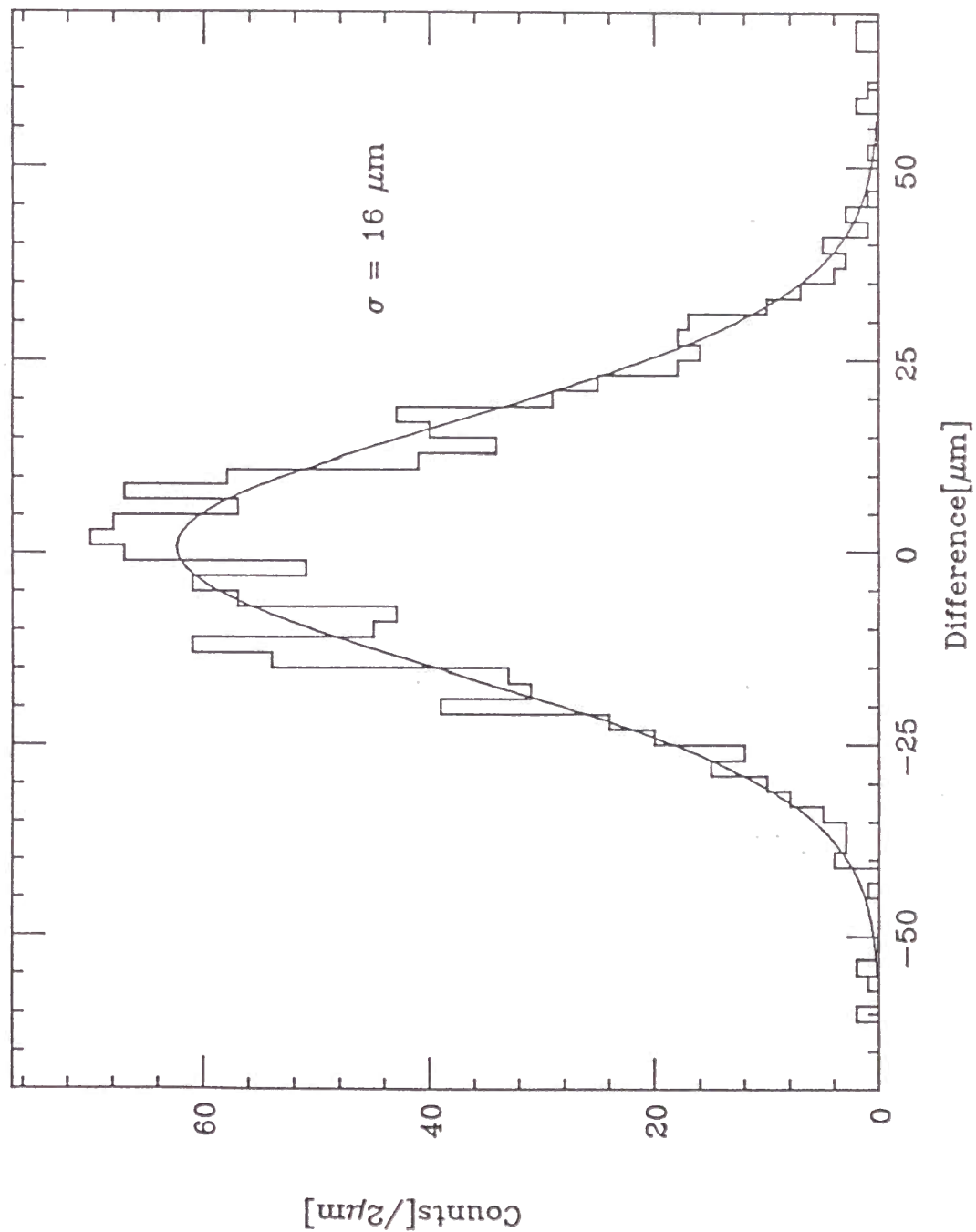


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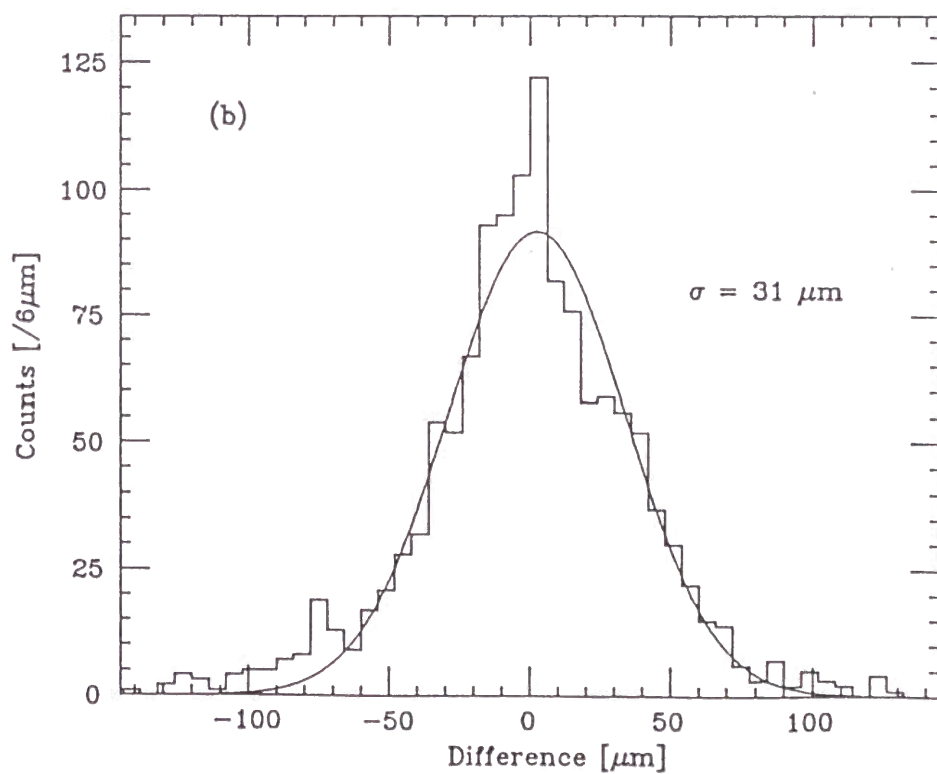
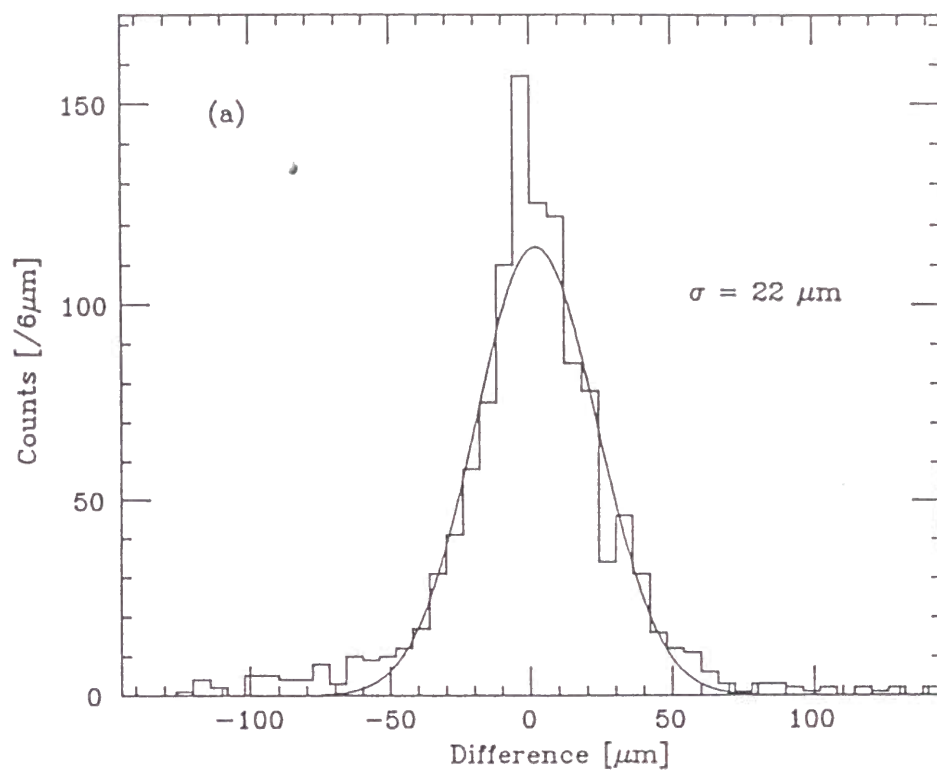


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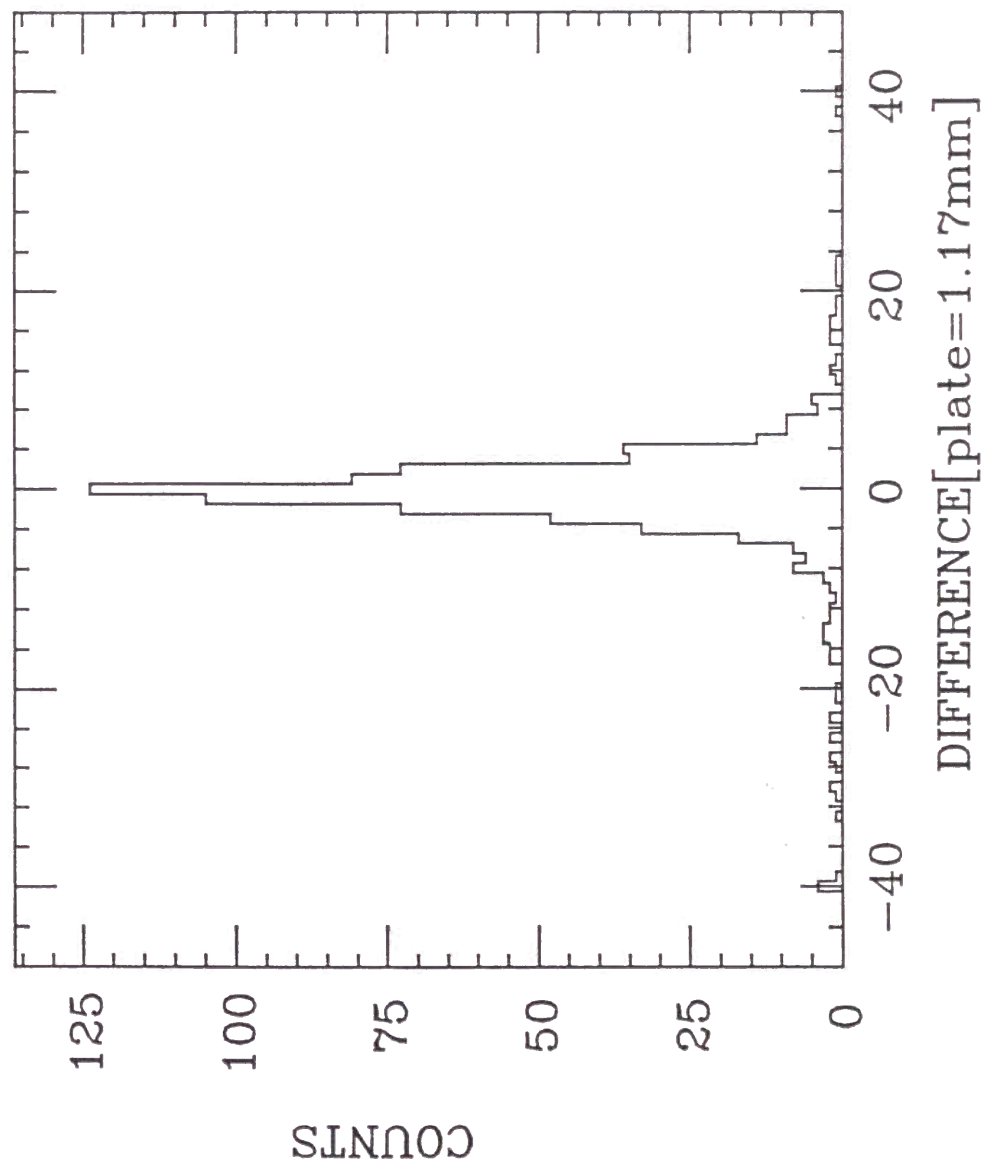


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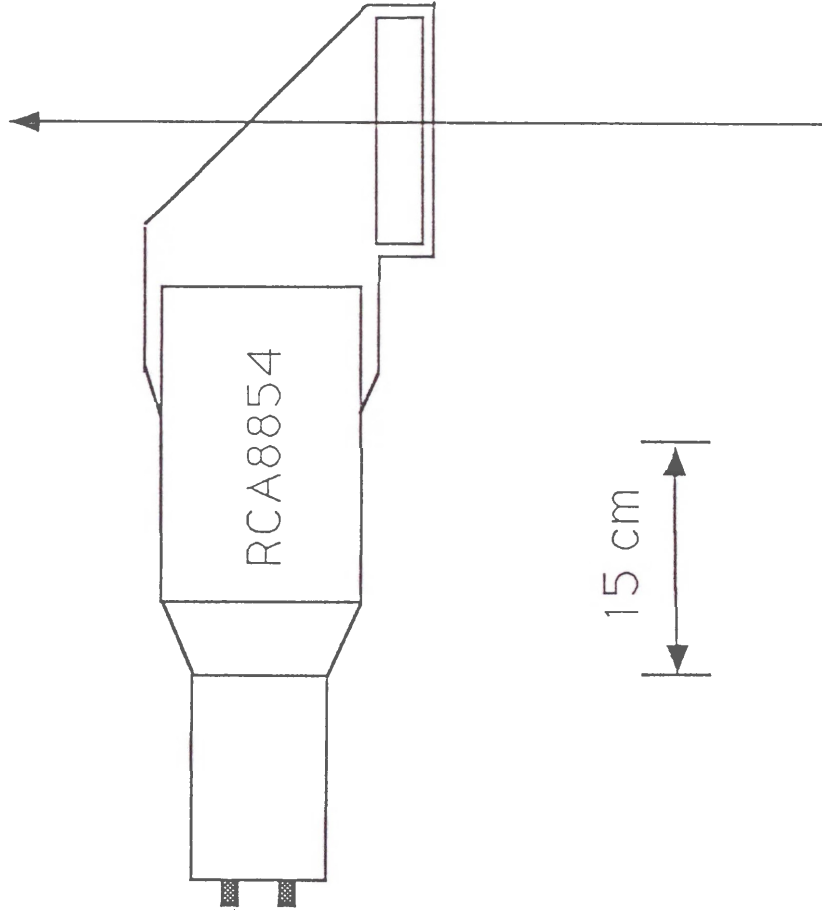


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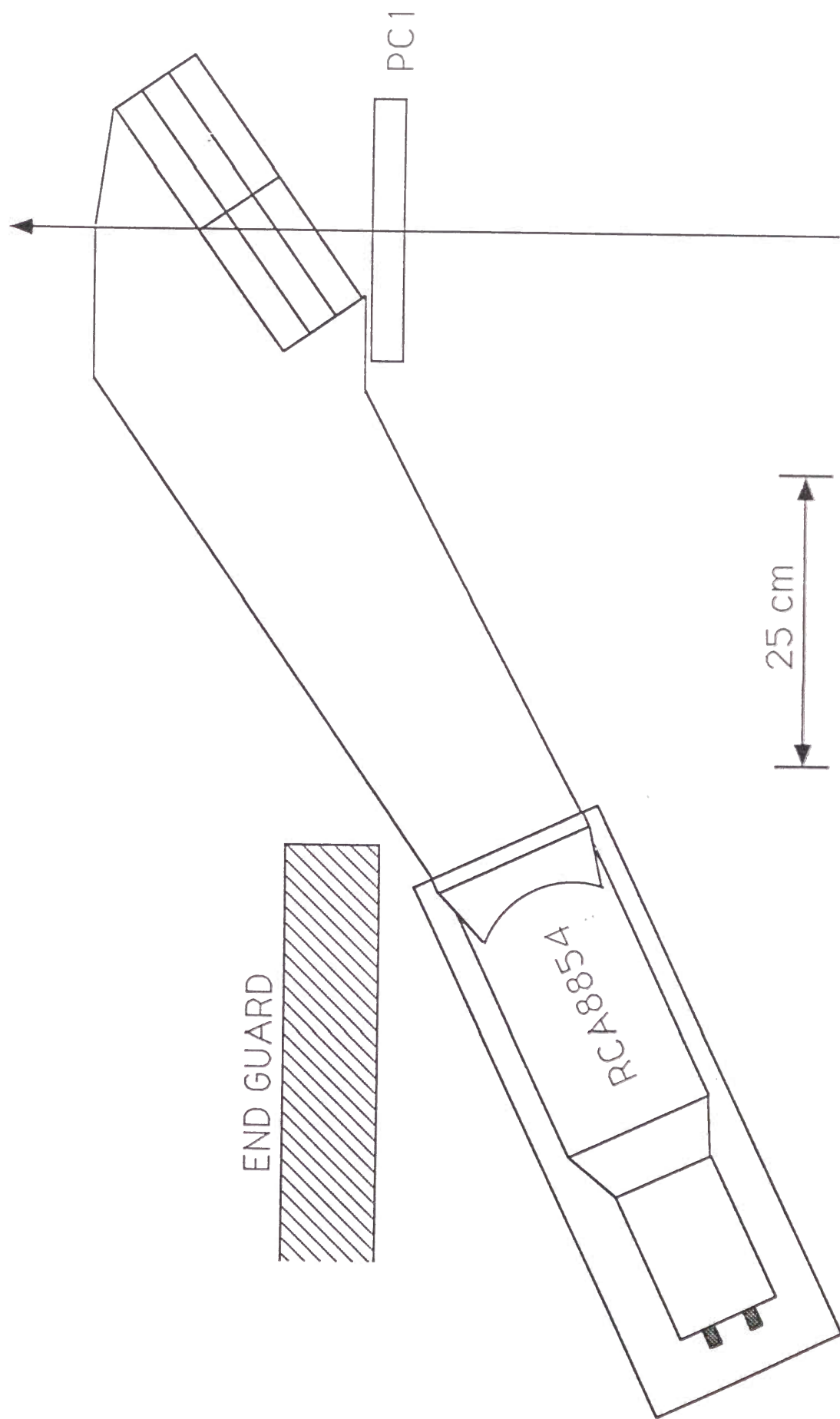


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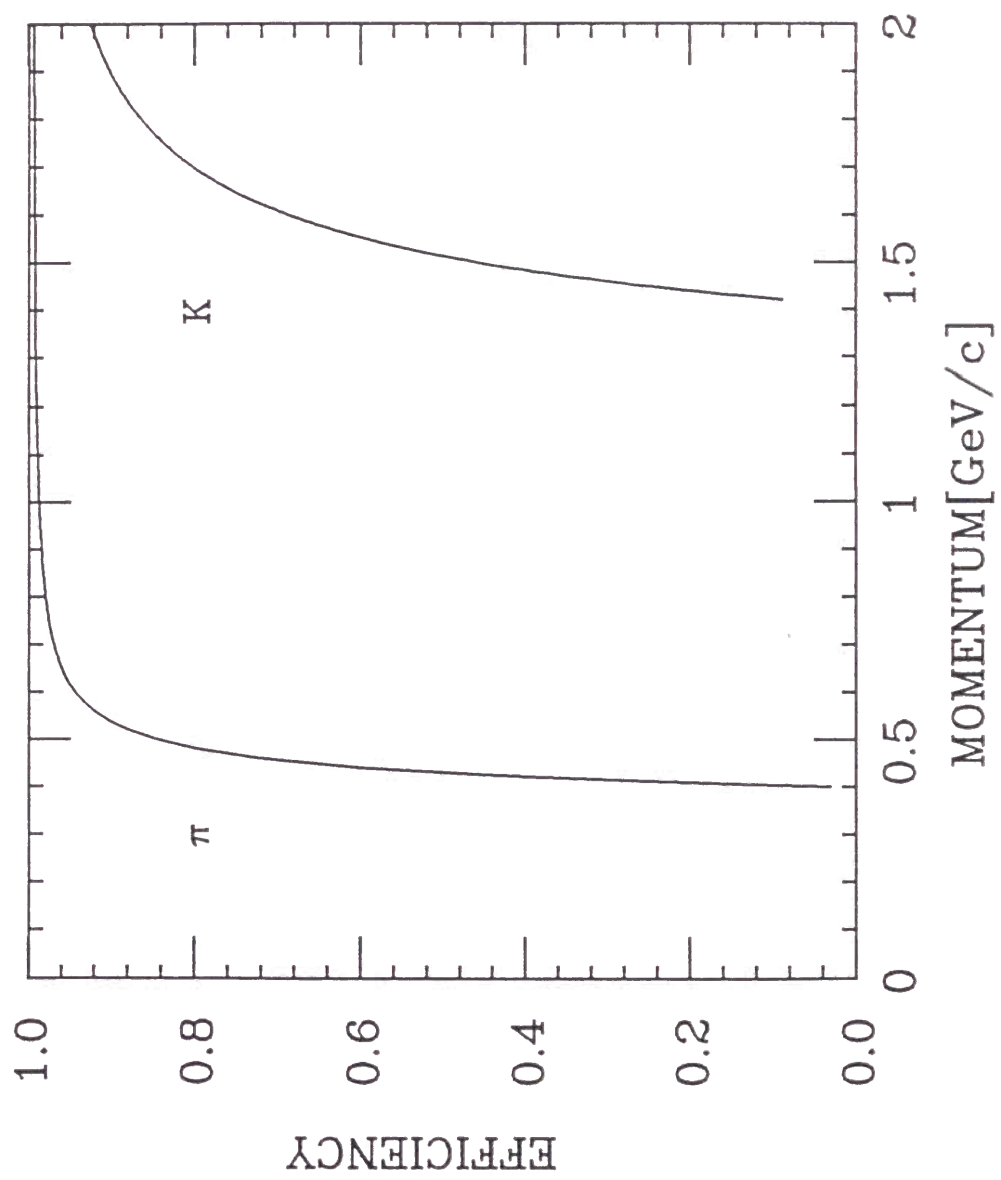


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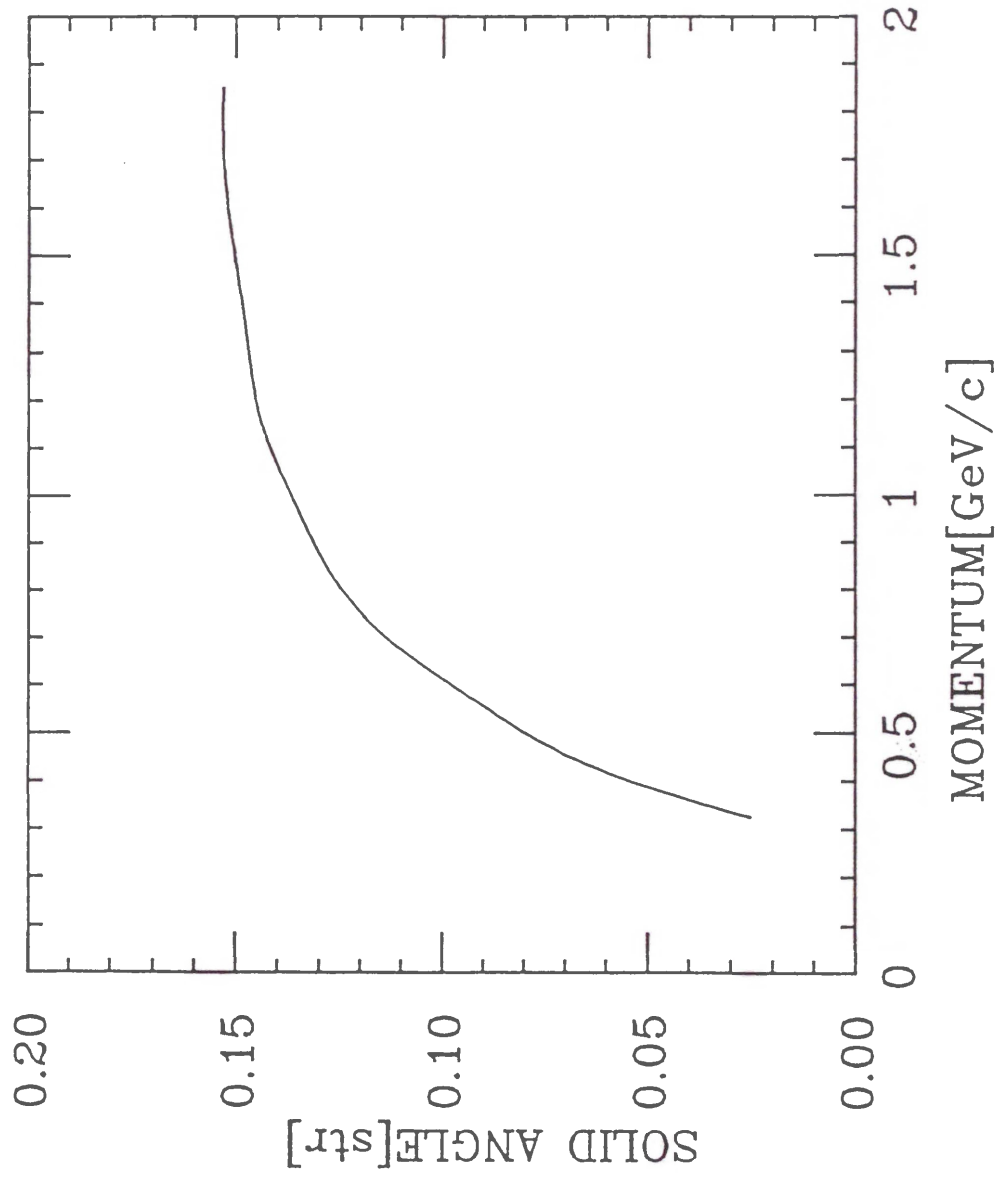


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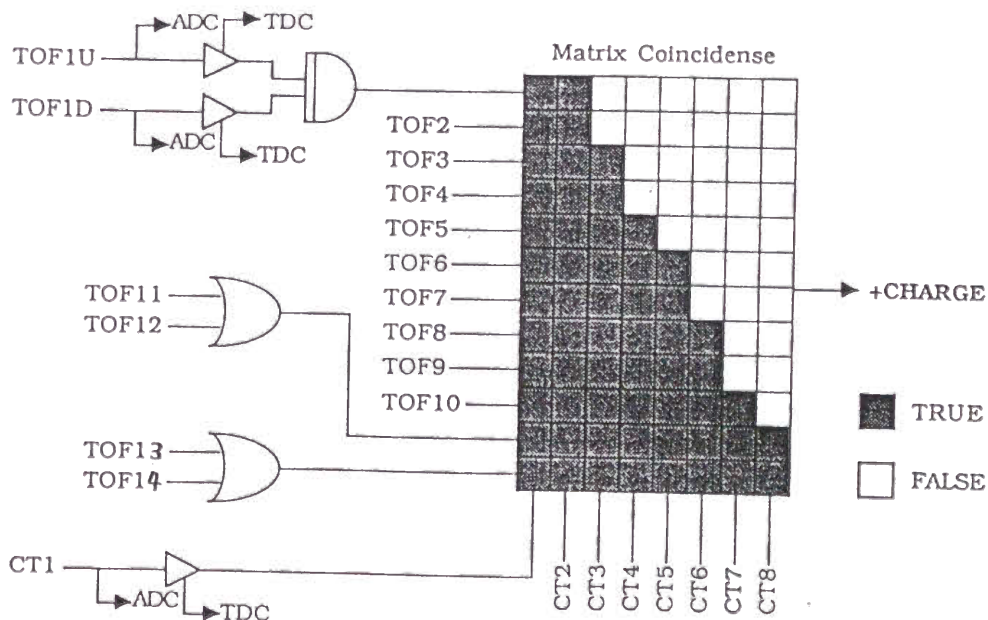
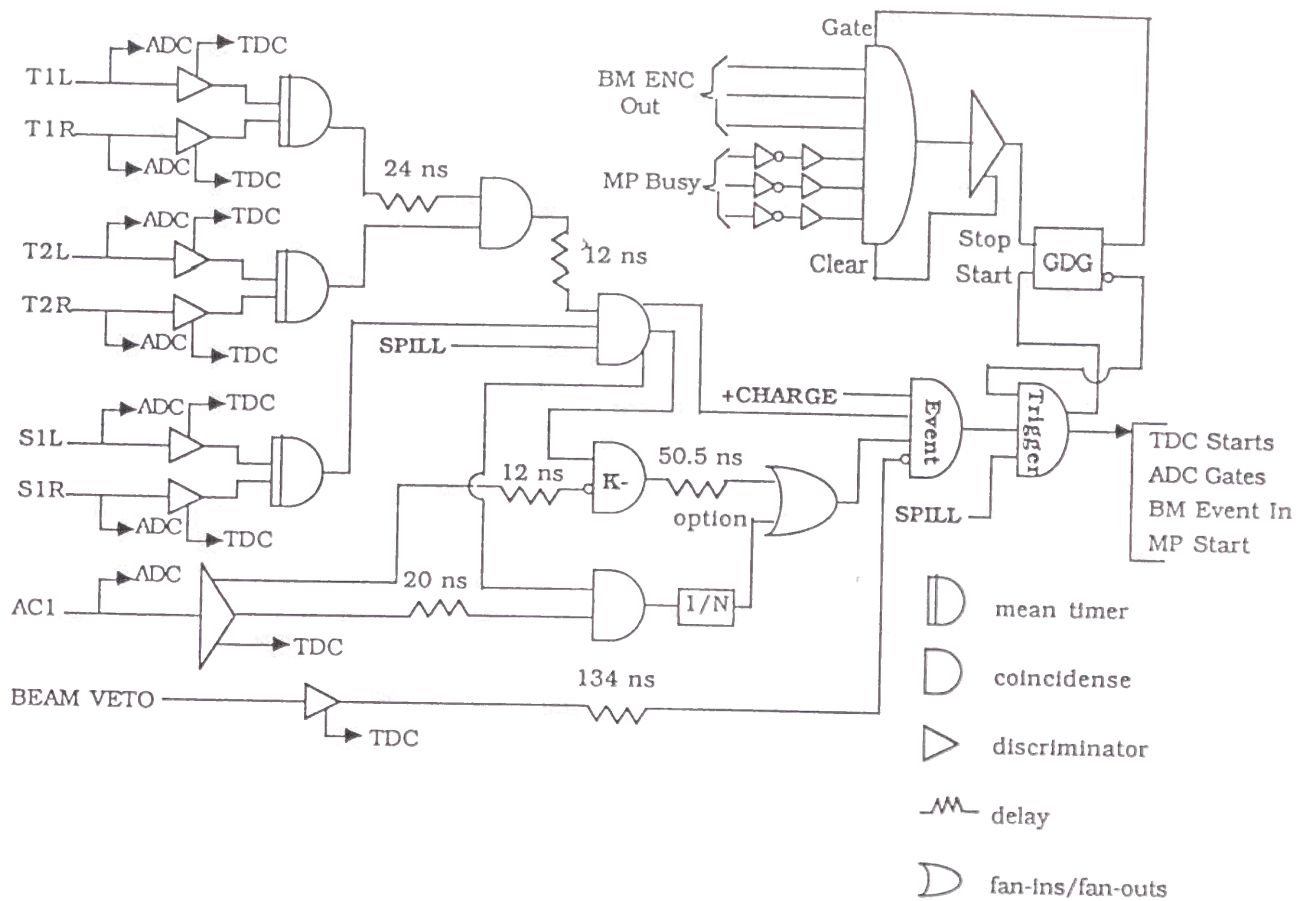


Figure 23

DEC-NET (Ethernet)

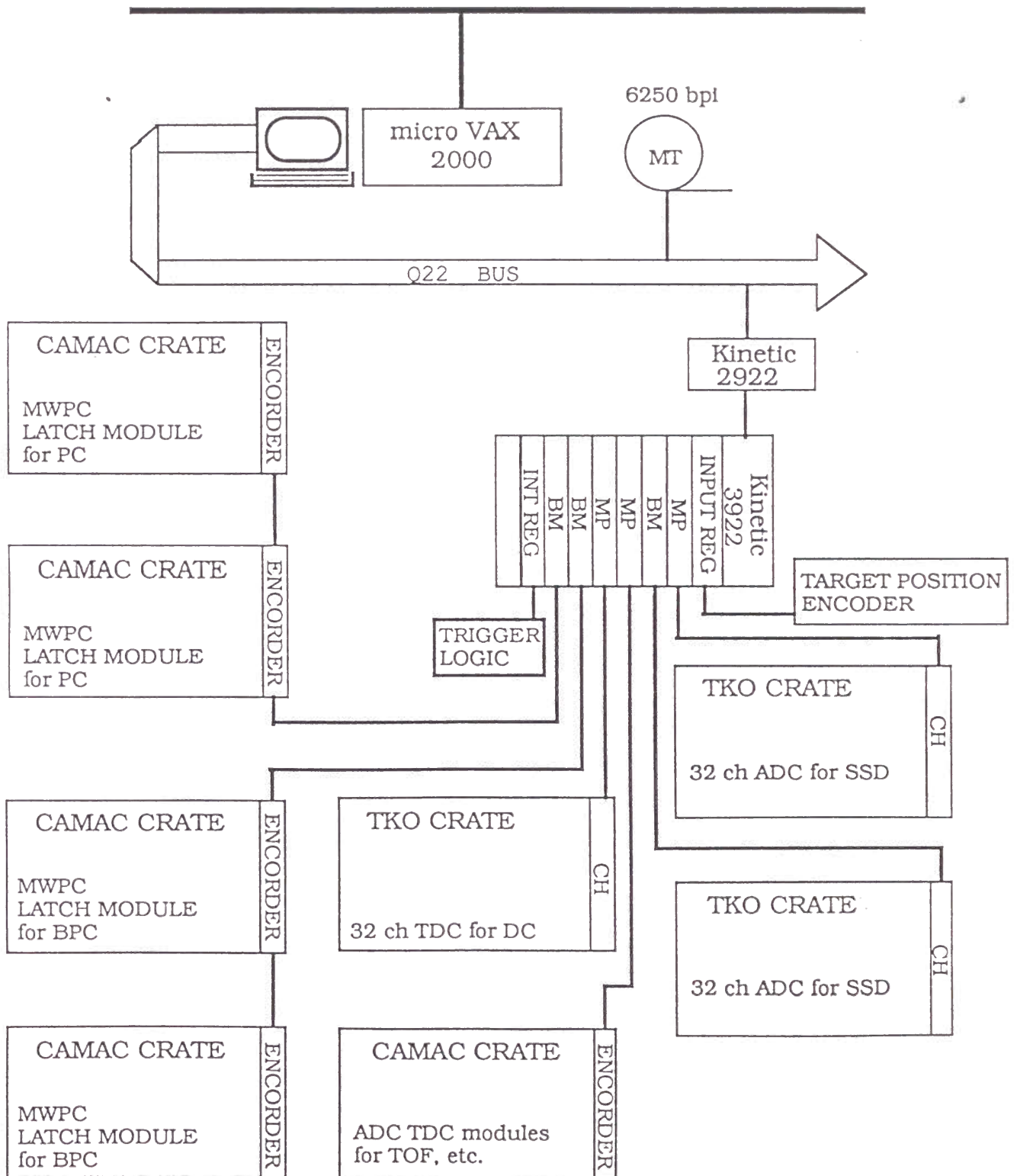


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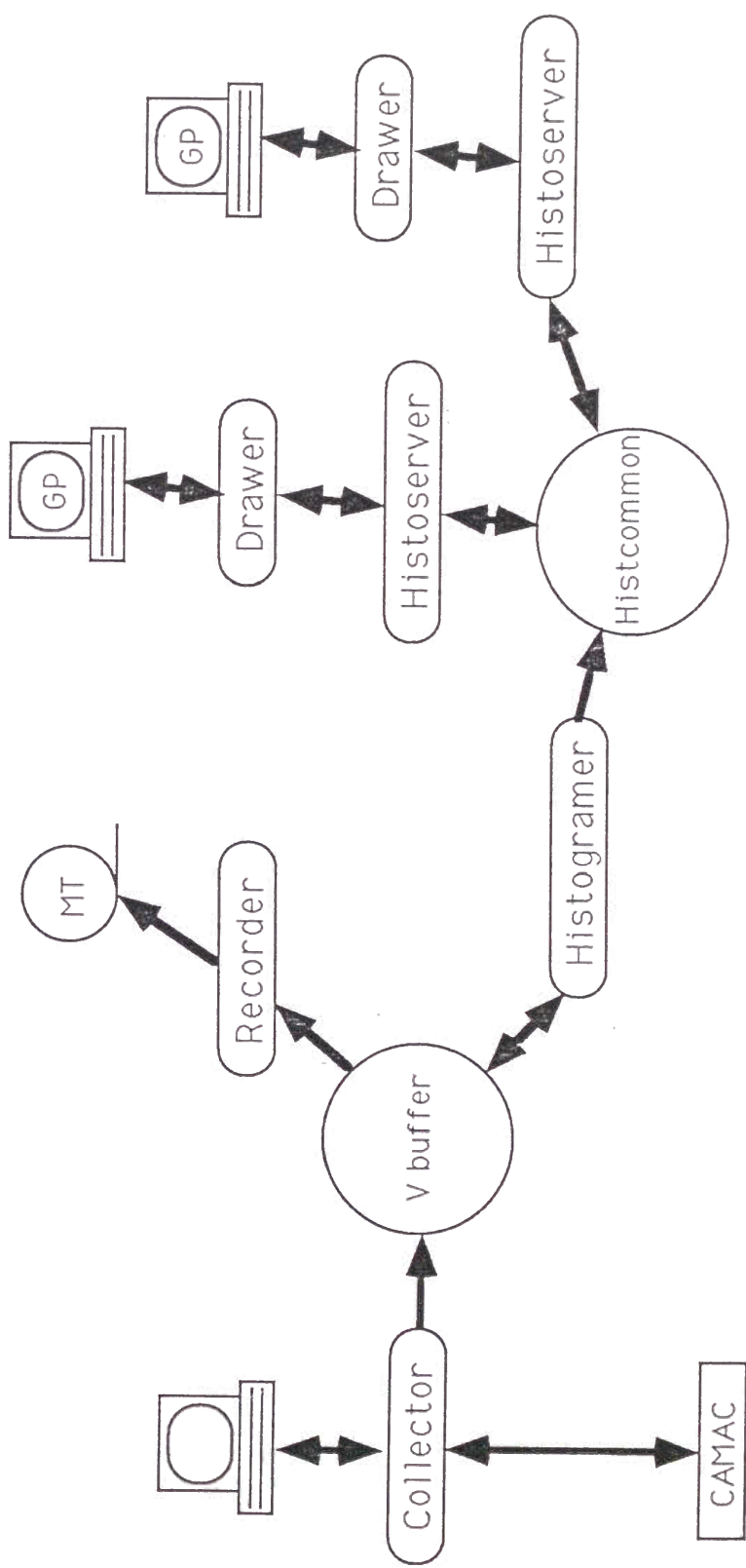


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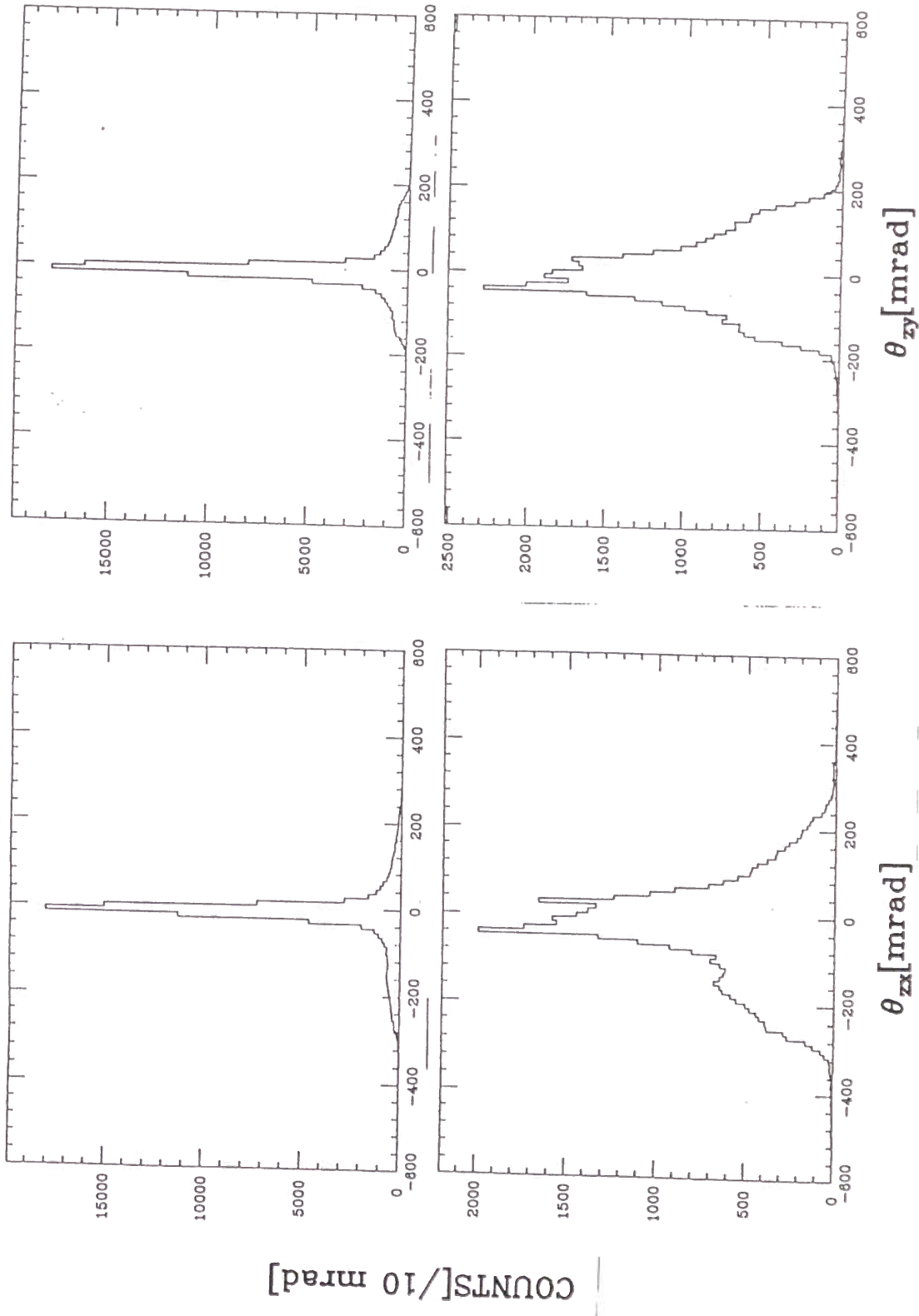


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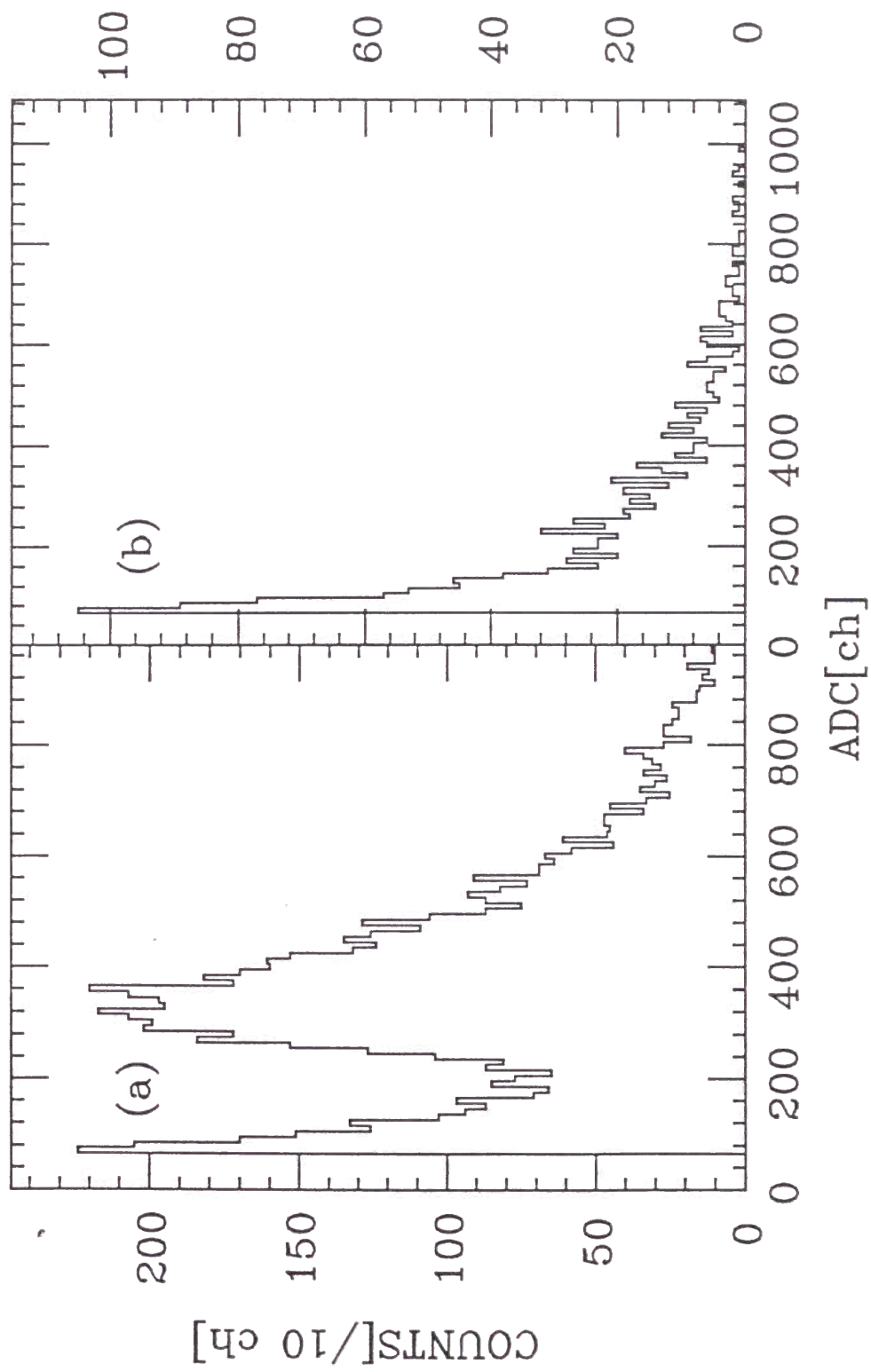


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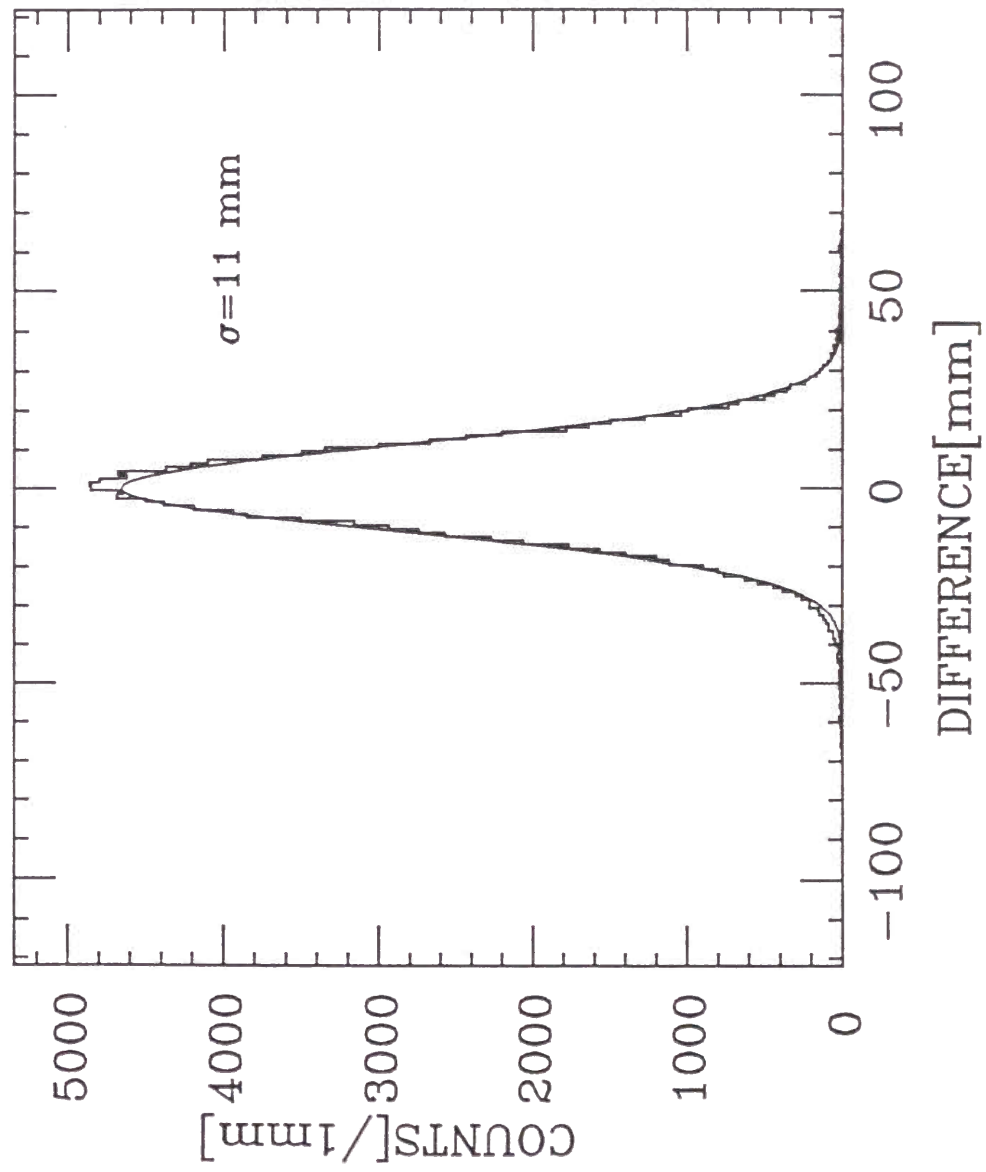


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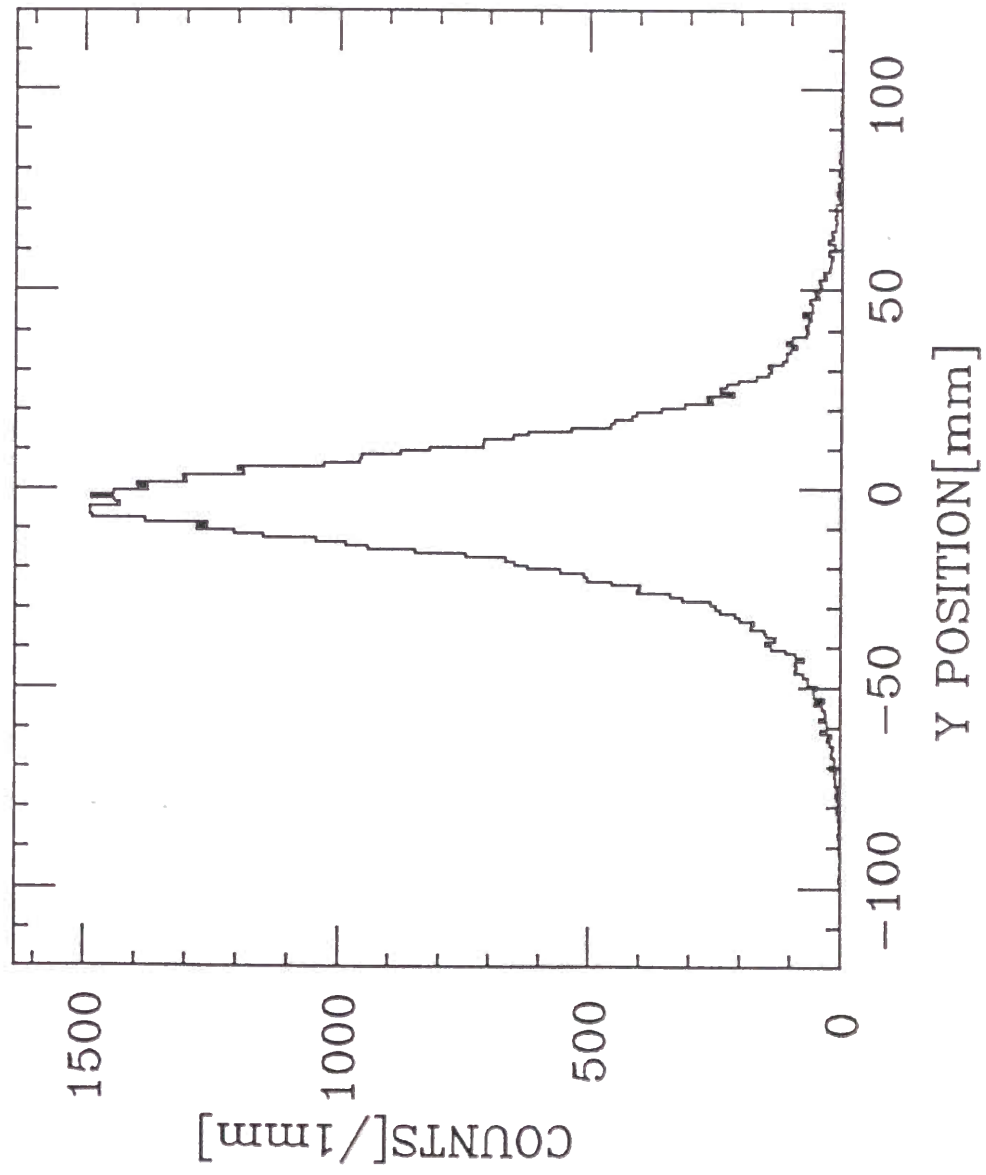


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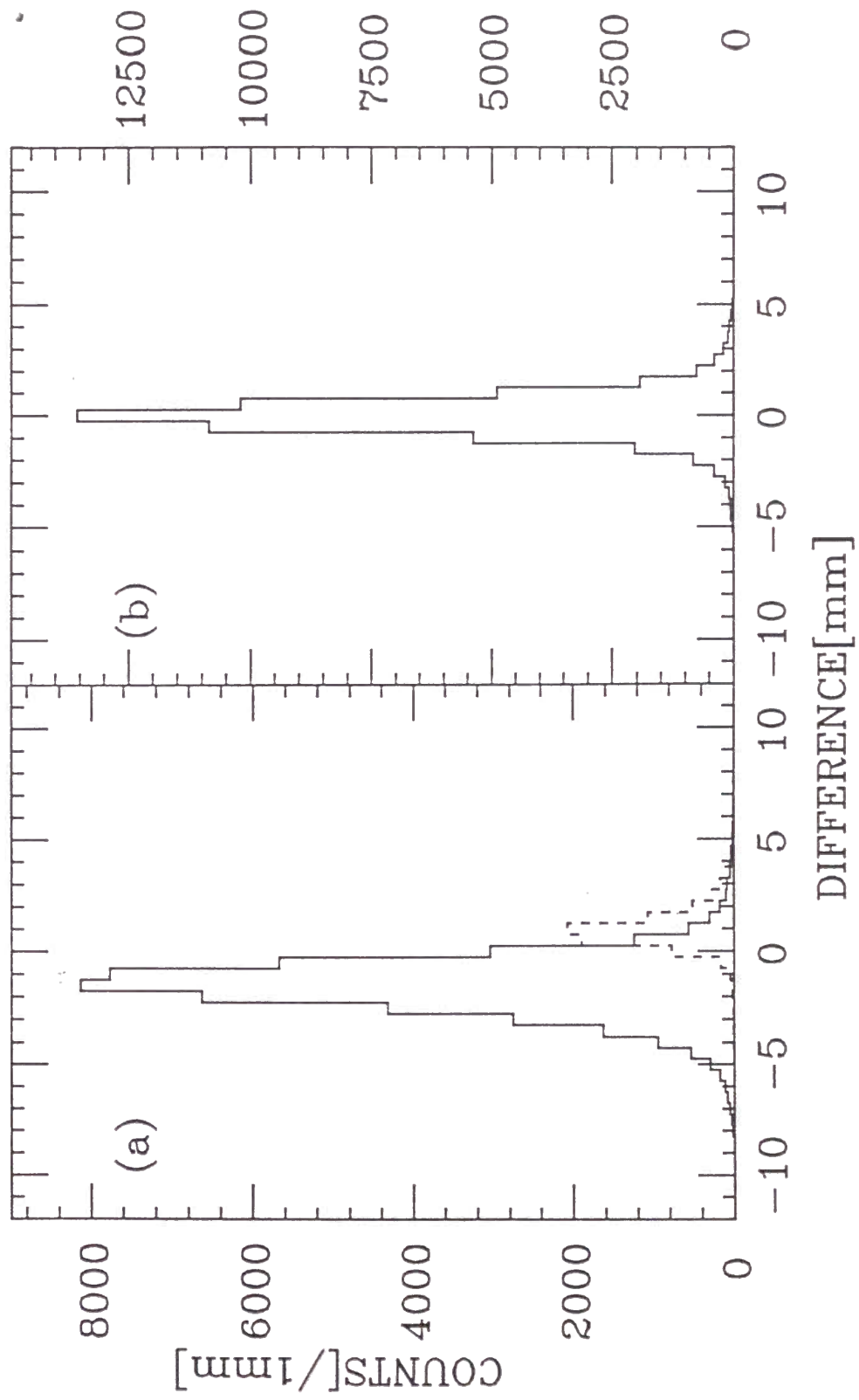


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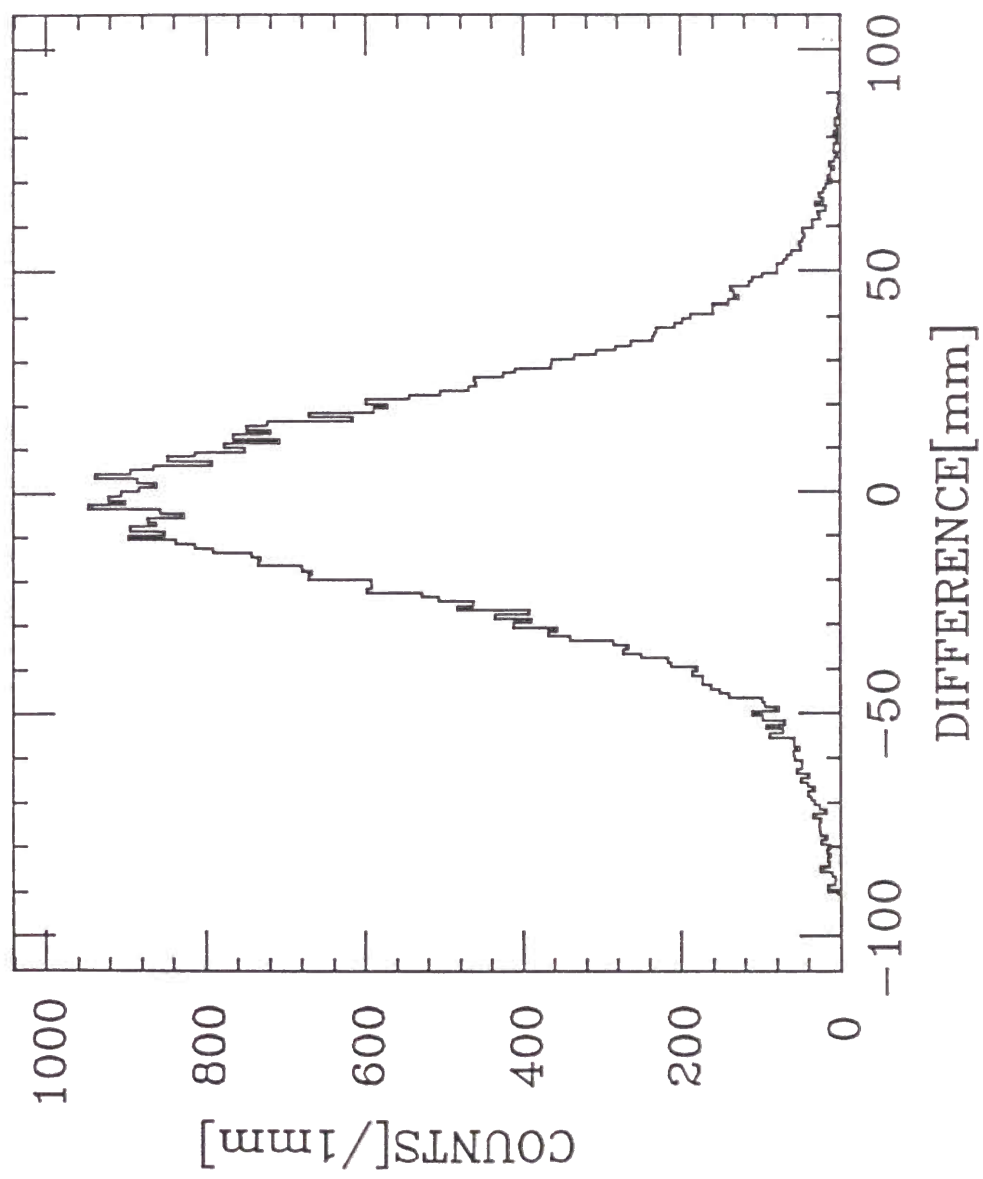


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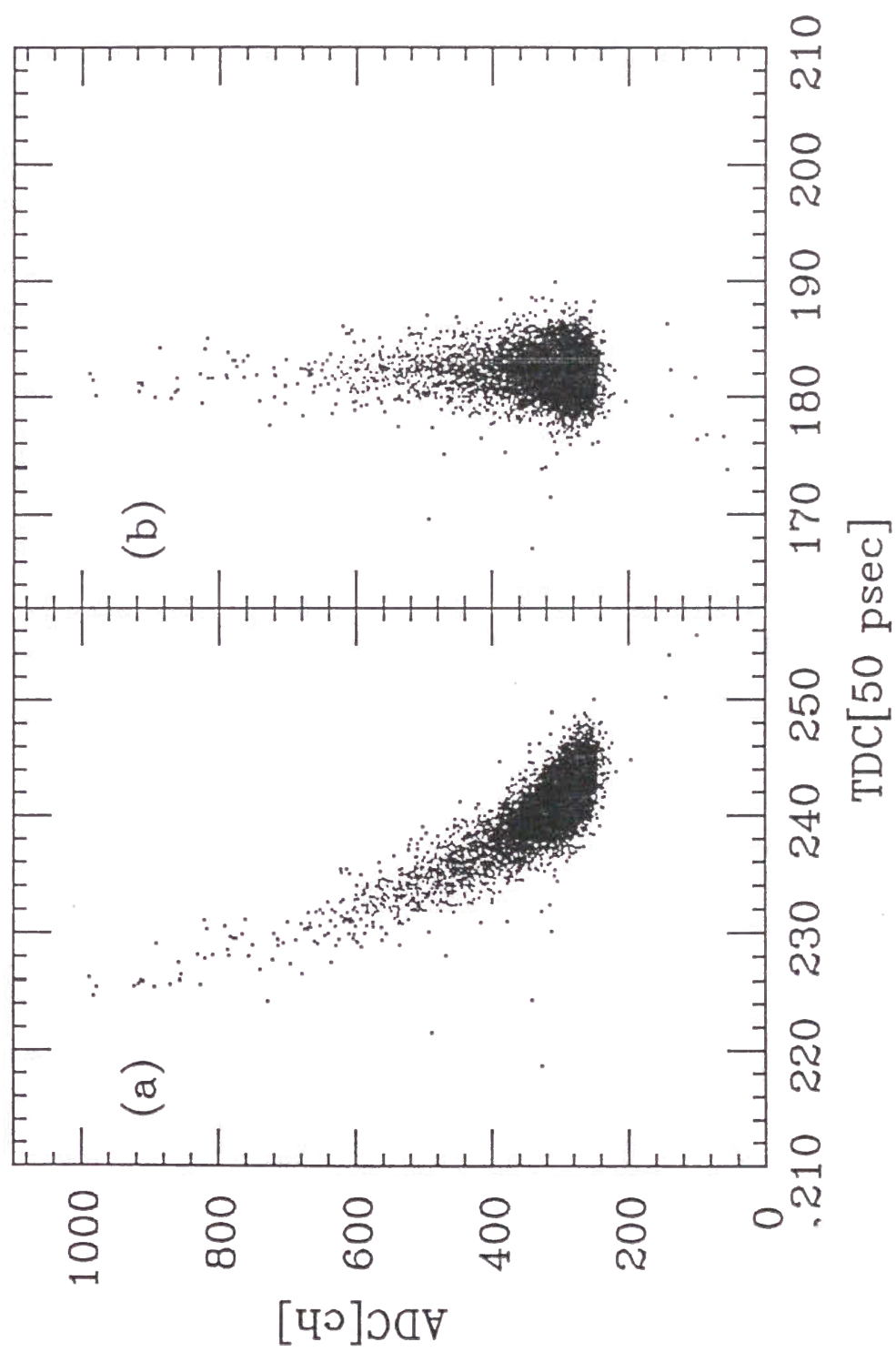


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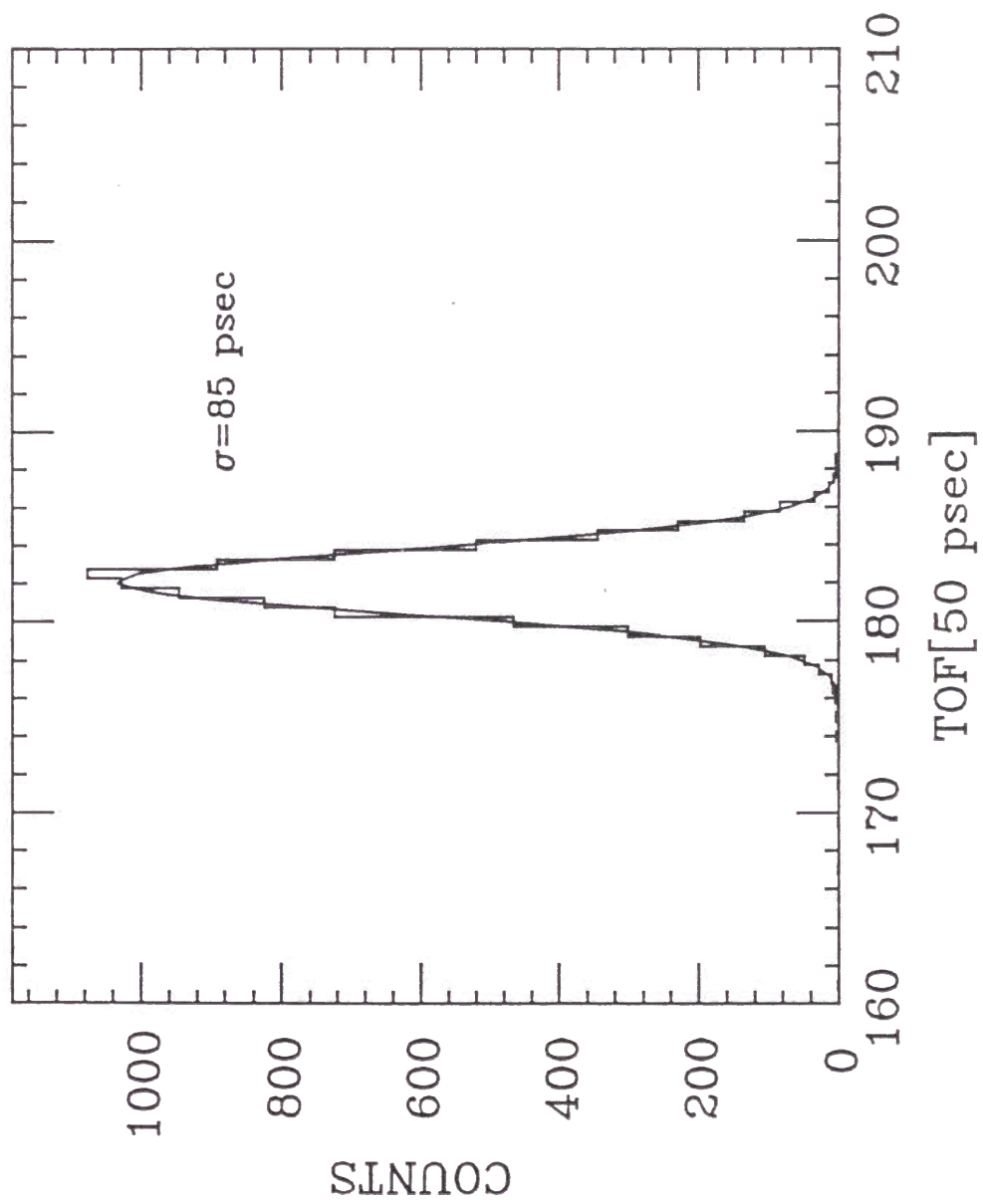


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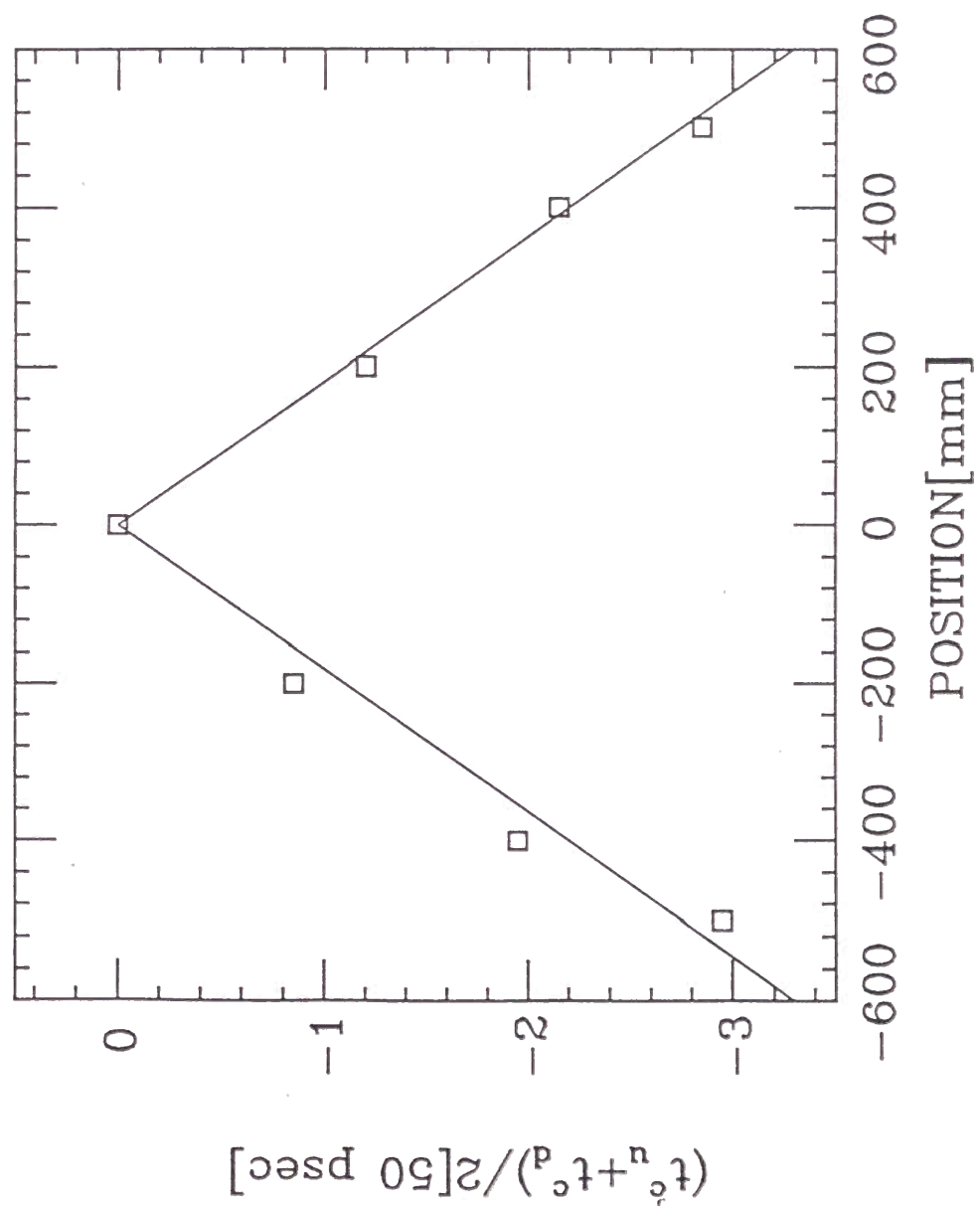


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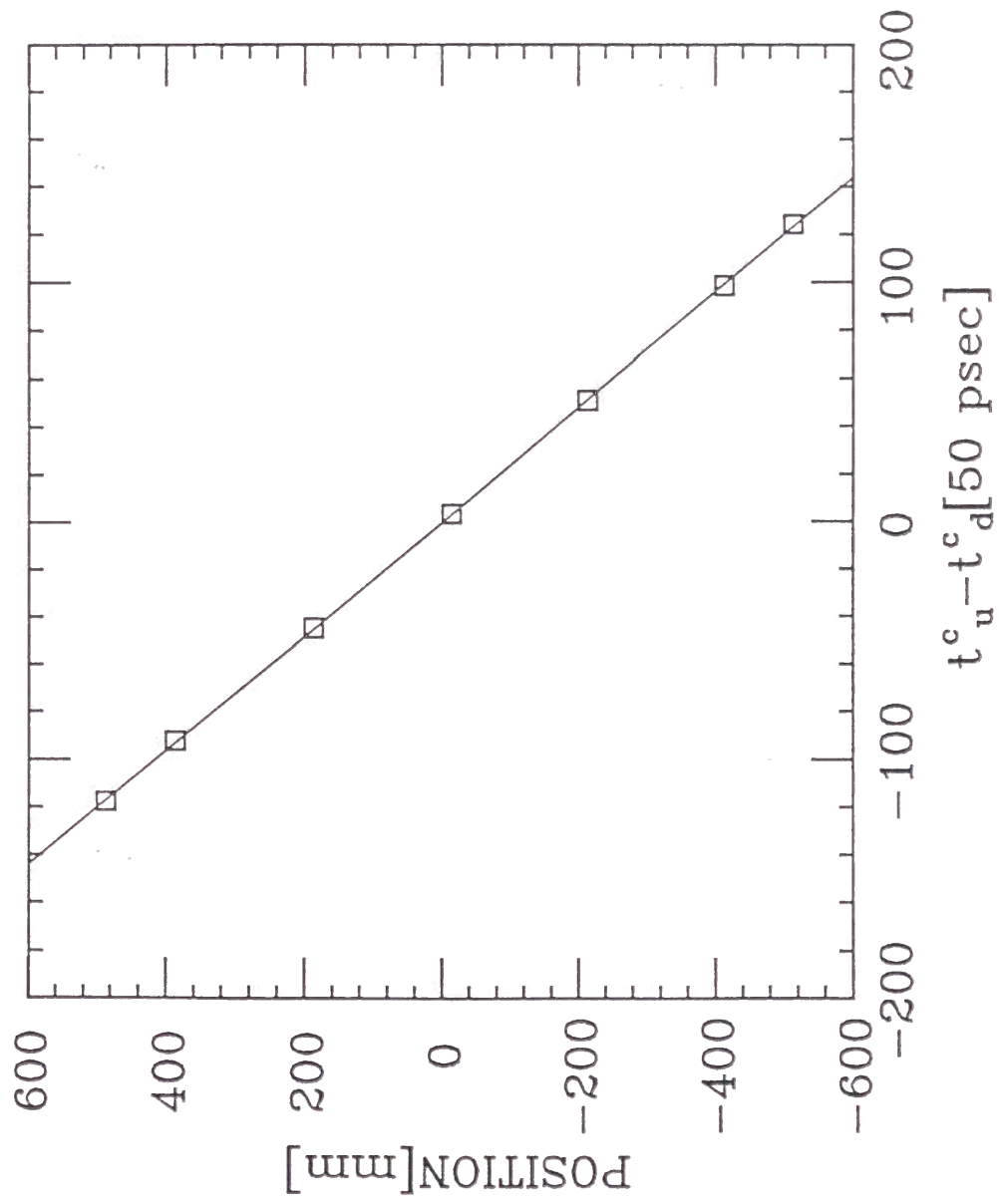


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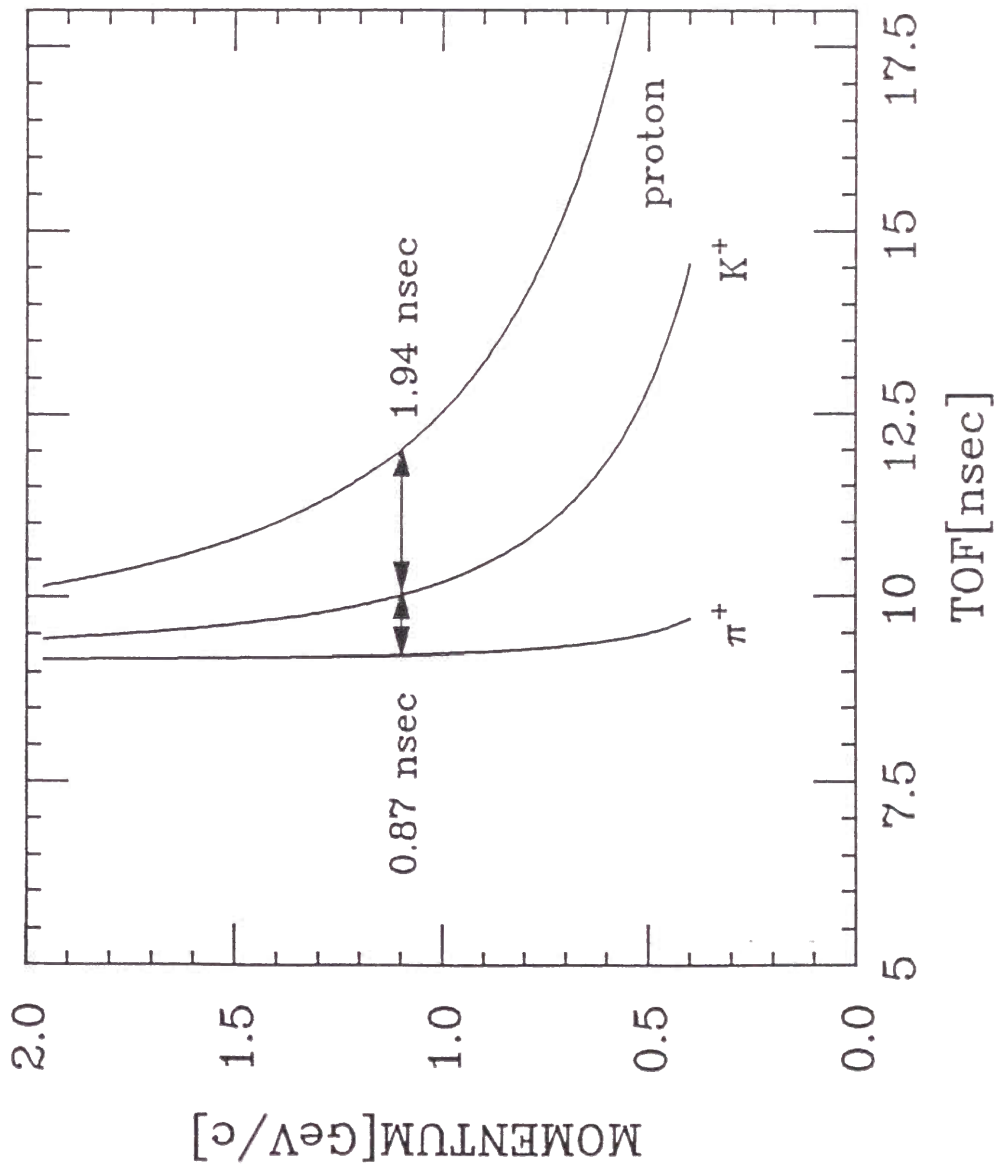


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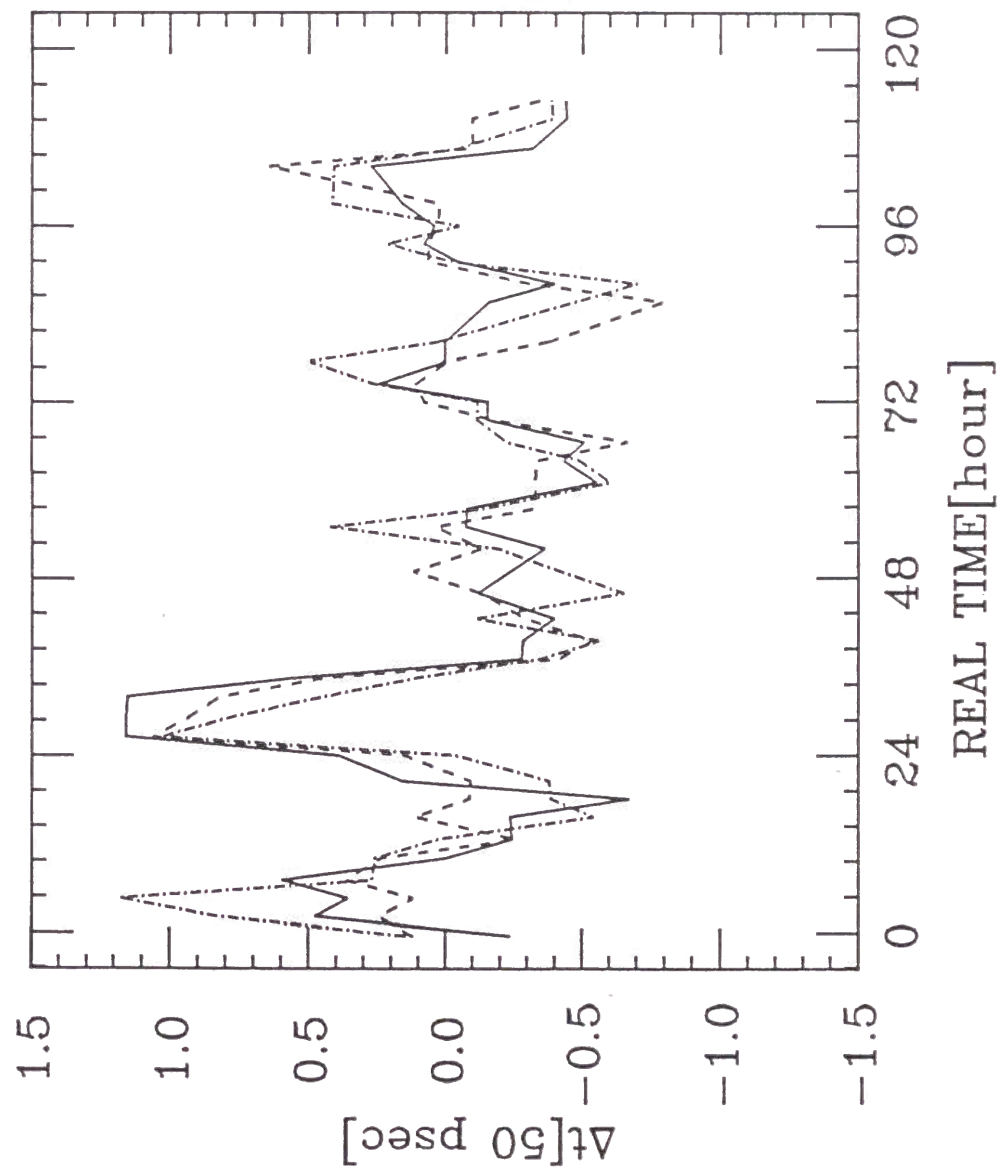


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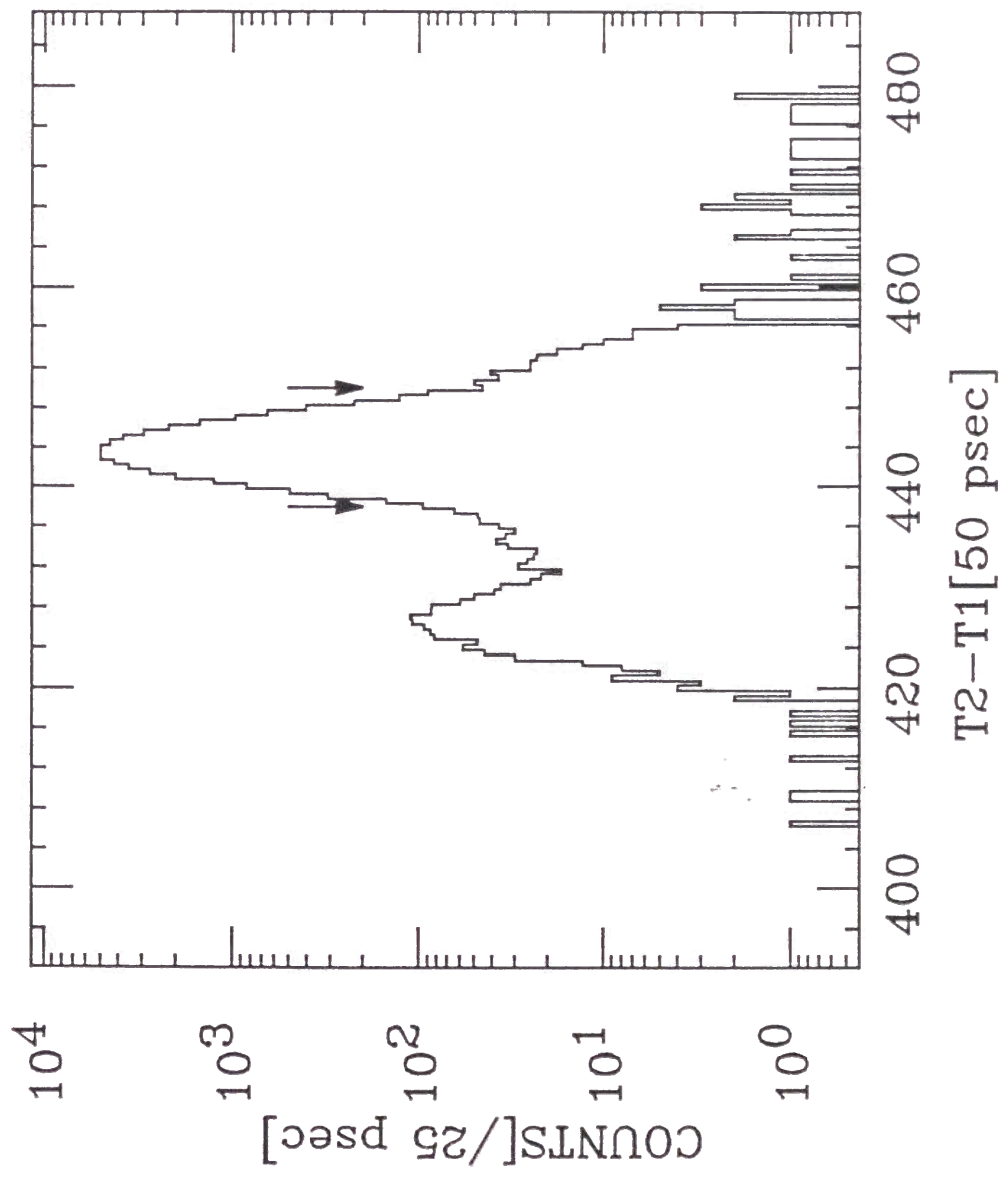


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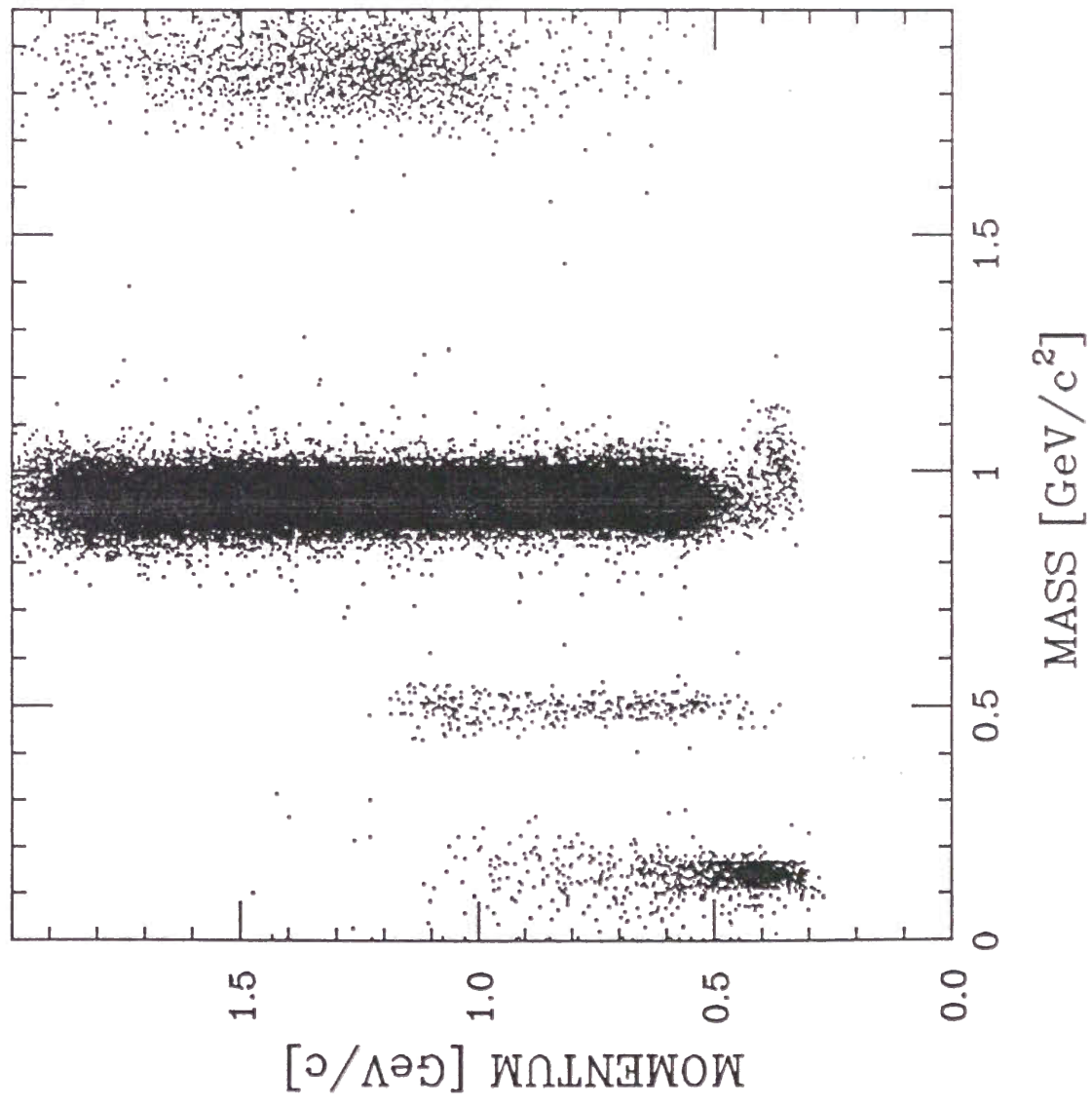


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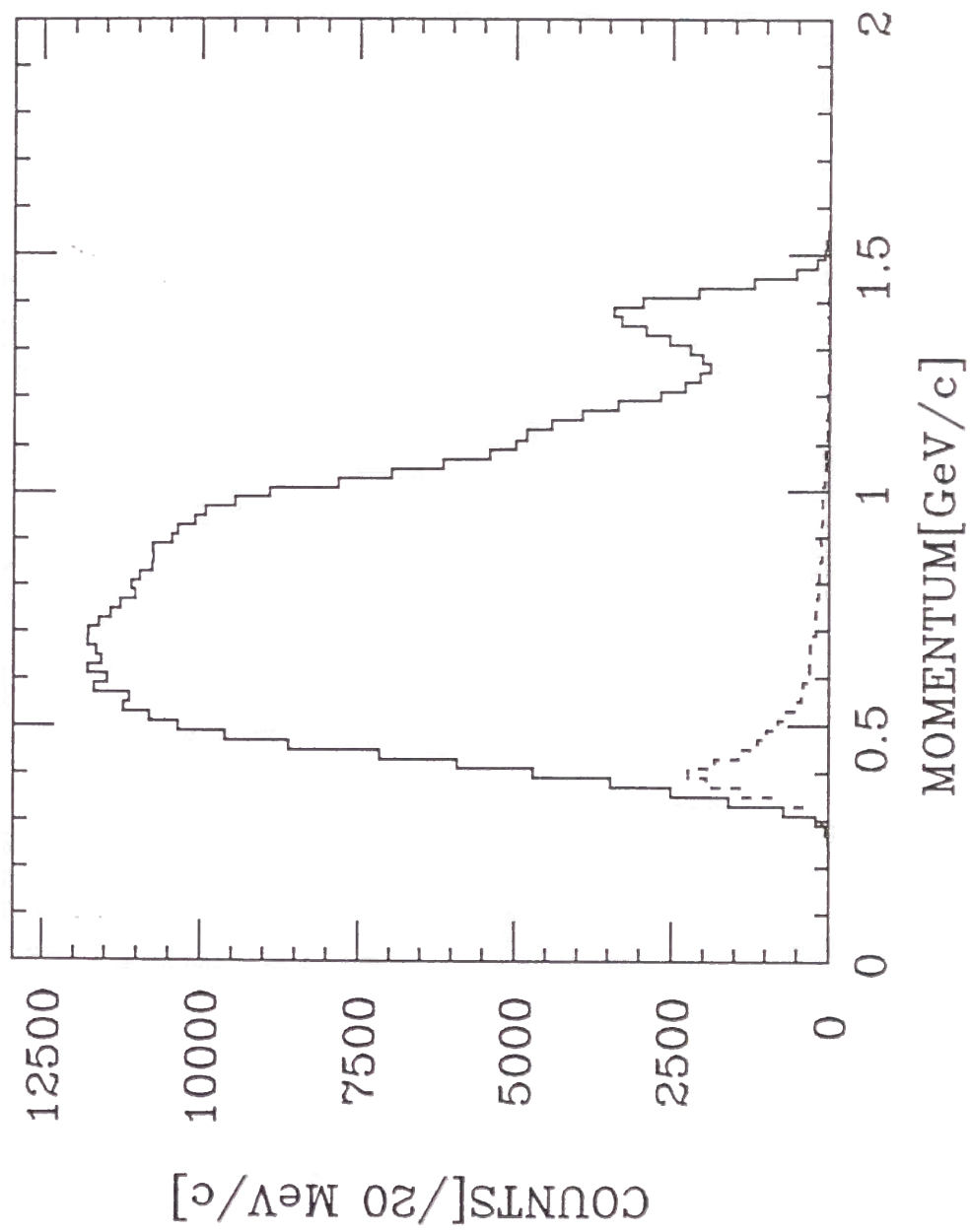


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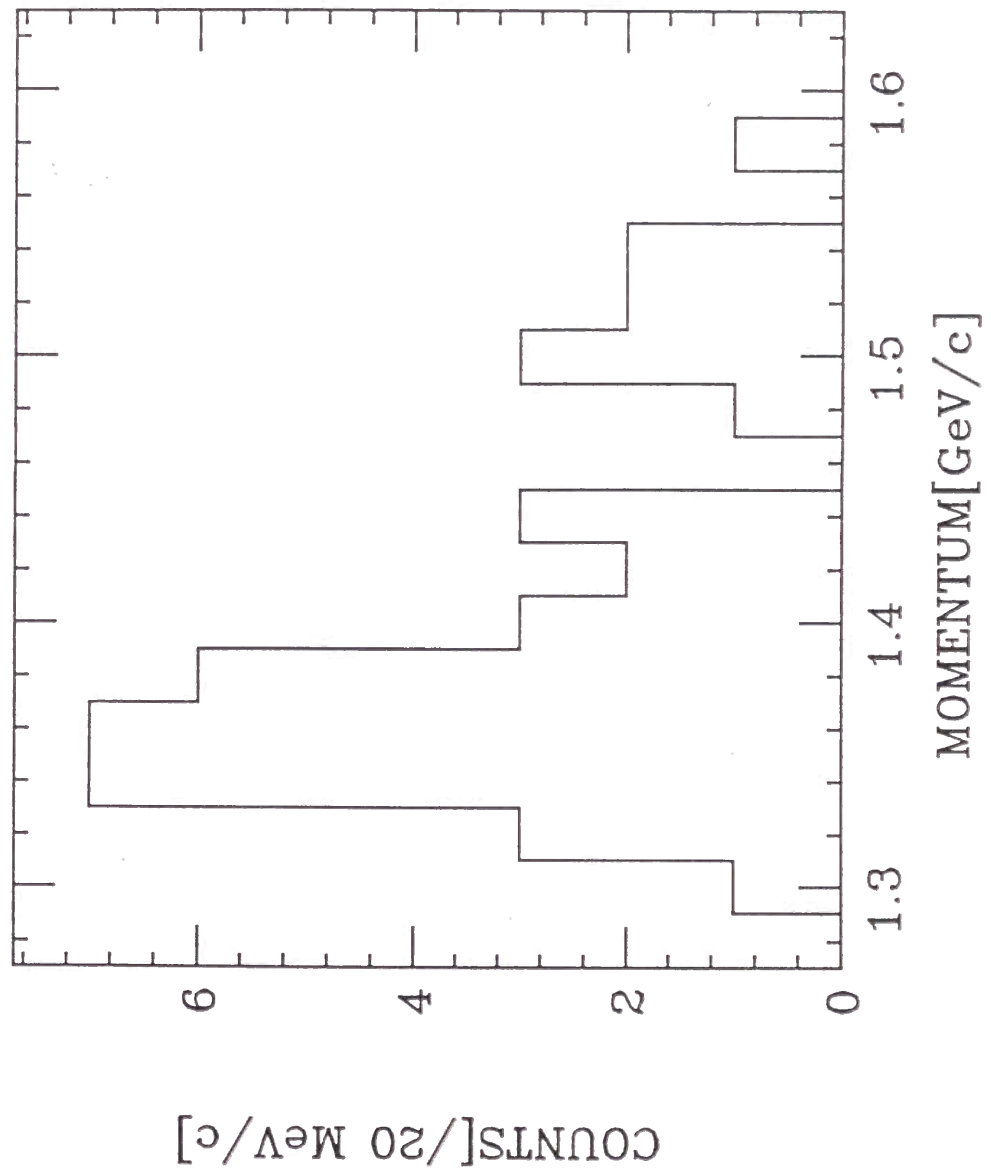


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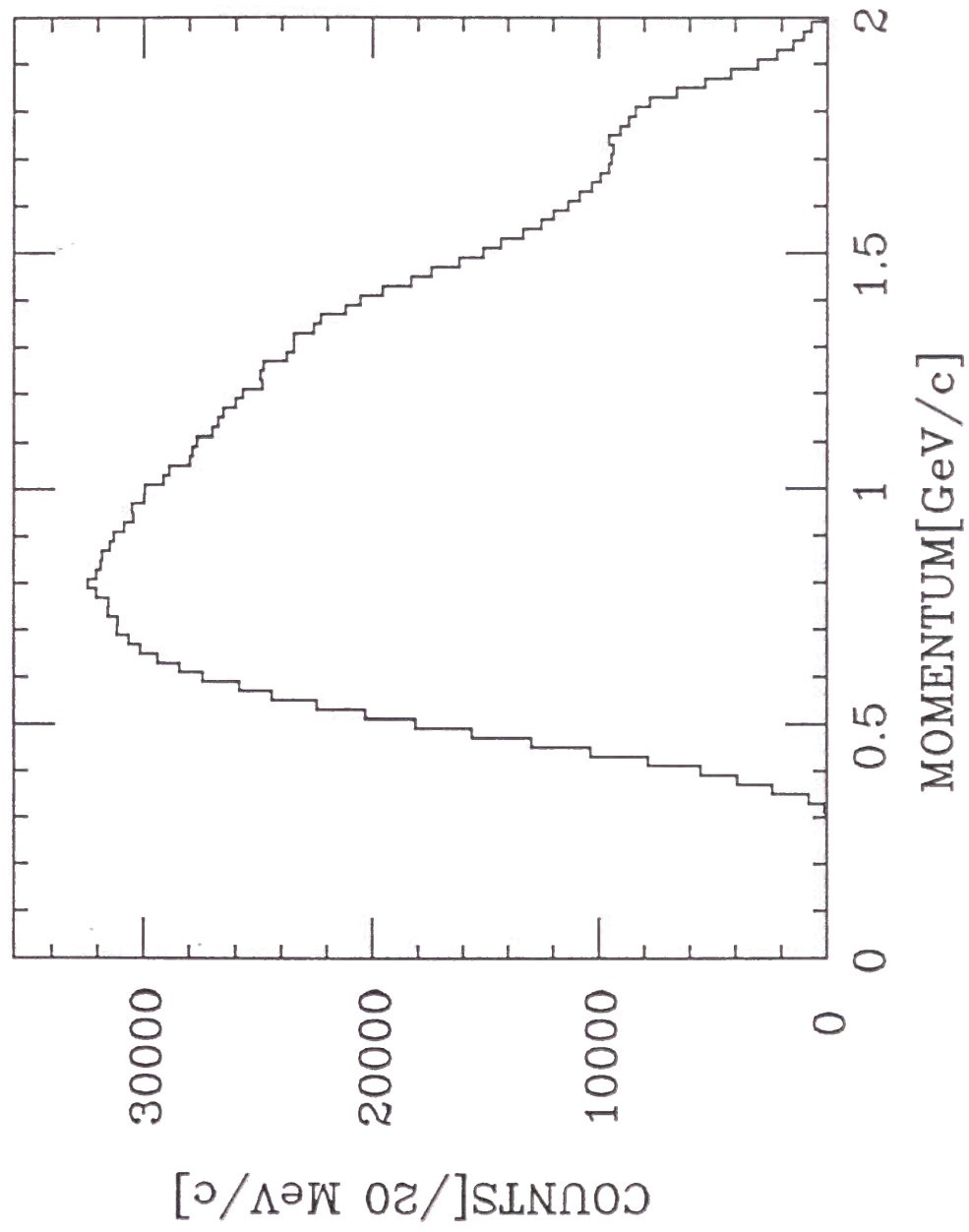


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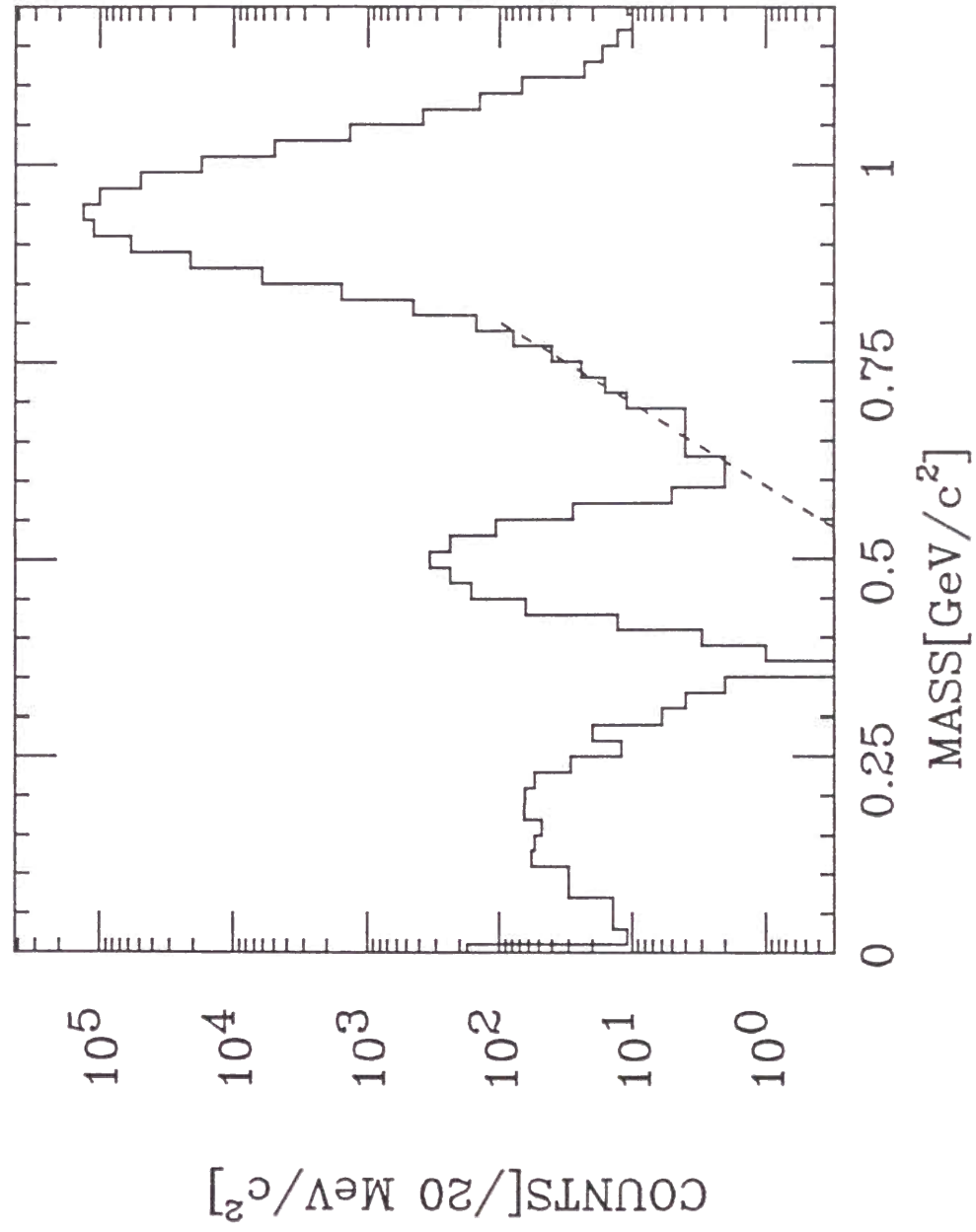


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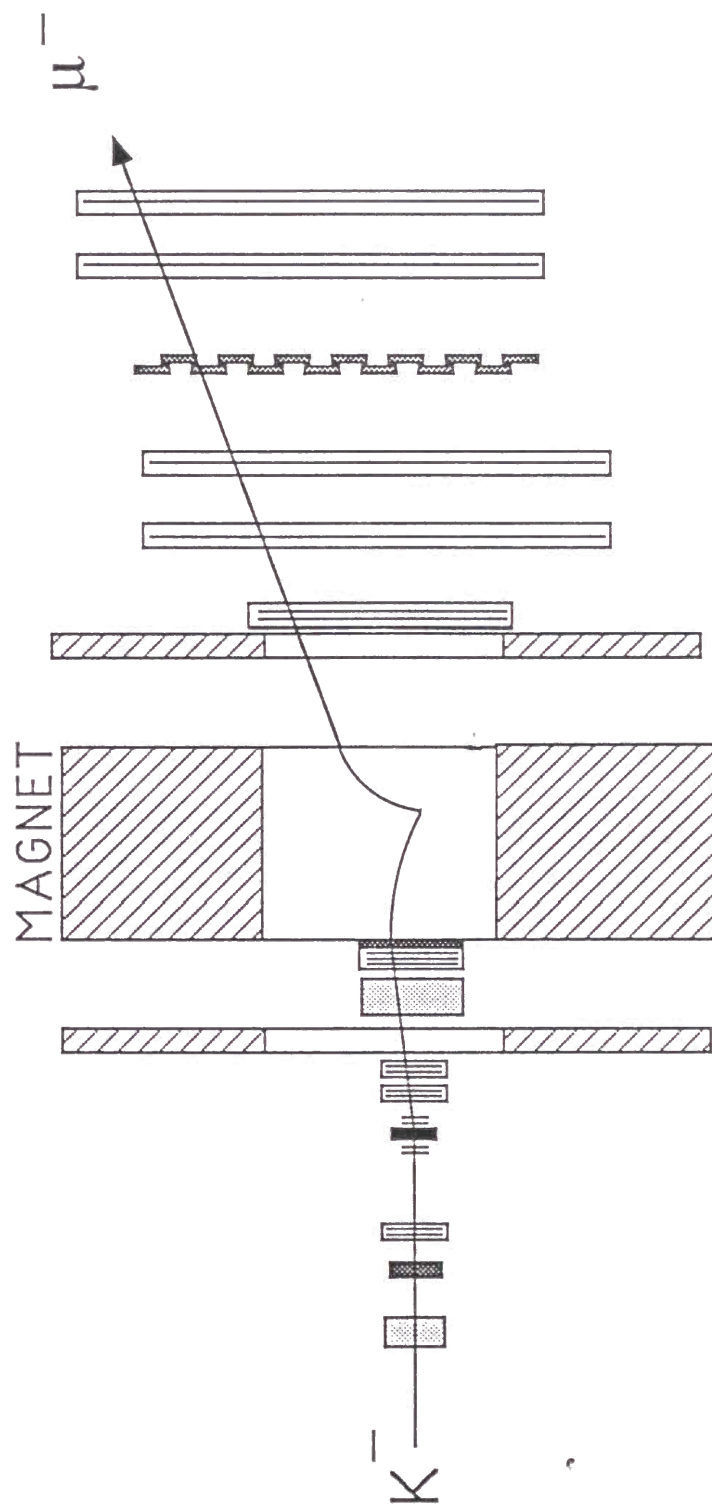


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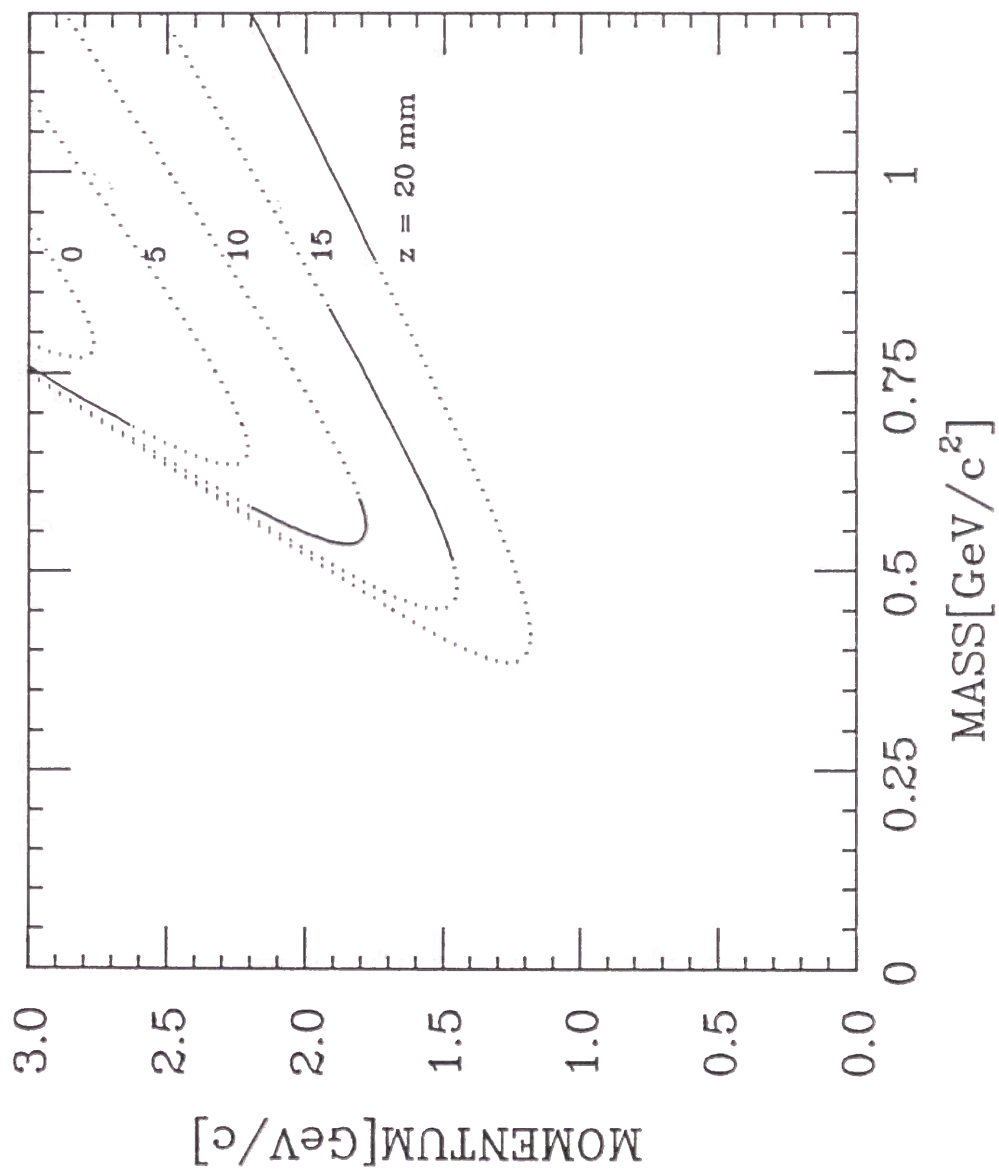


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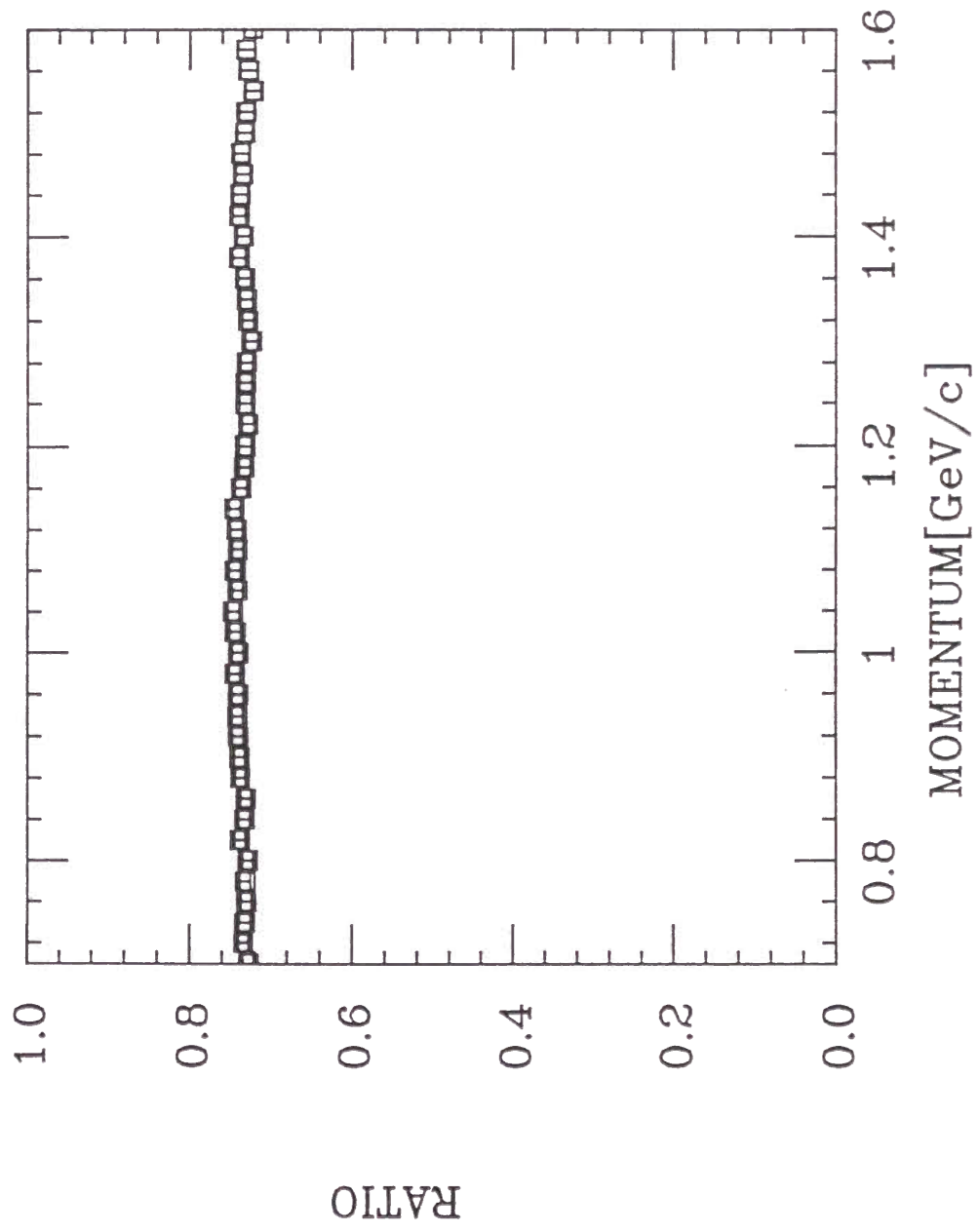


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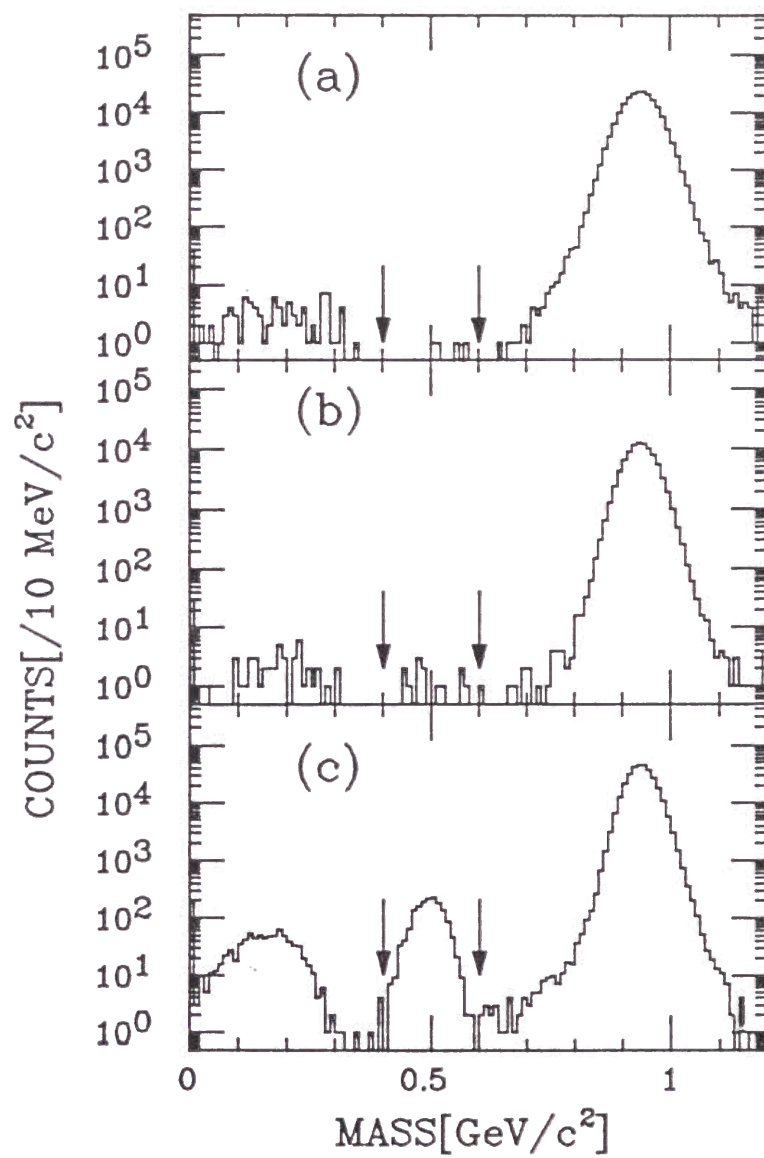


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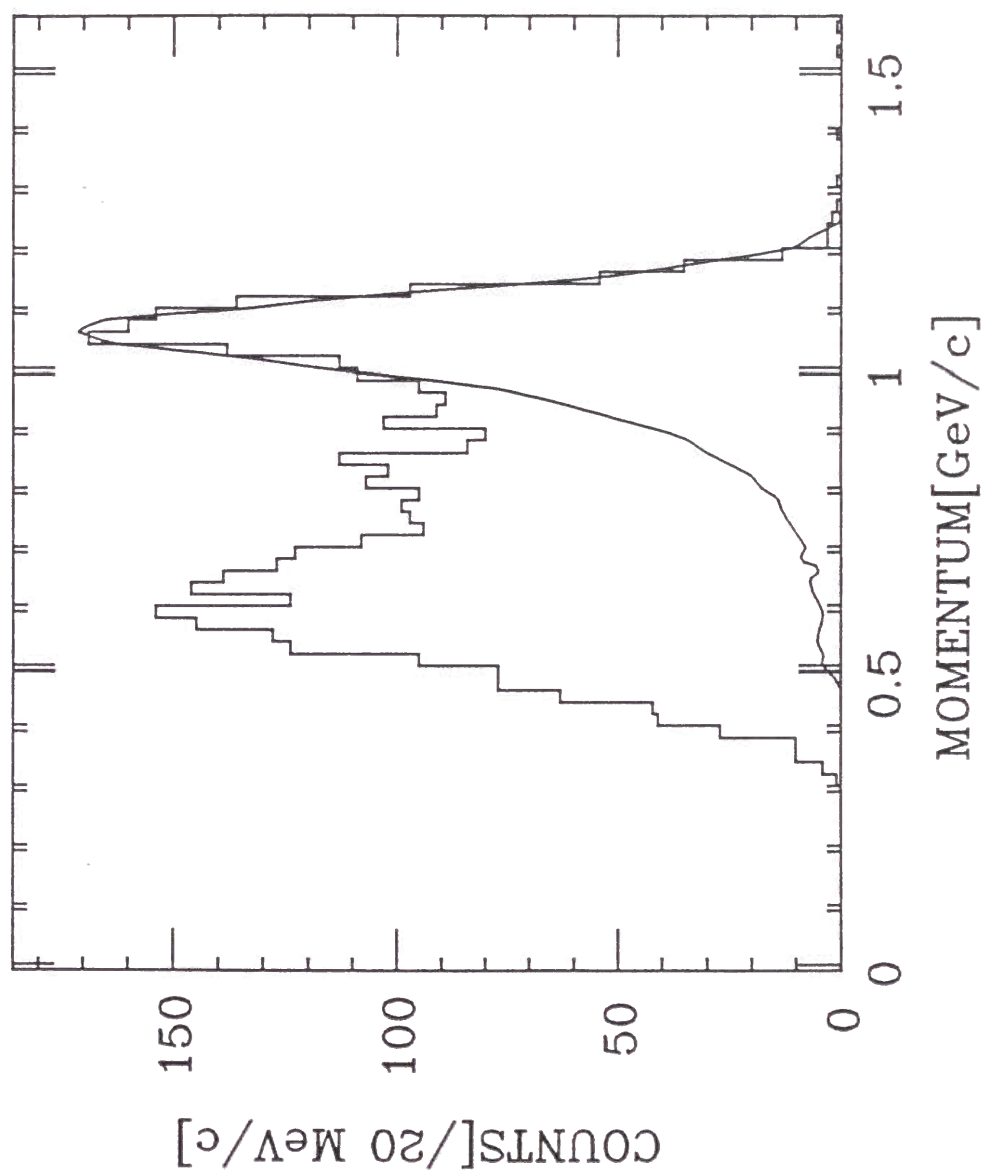


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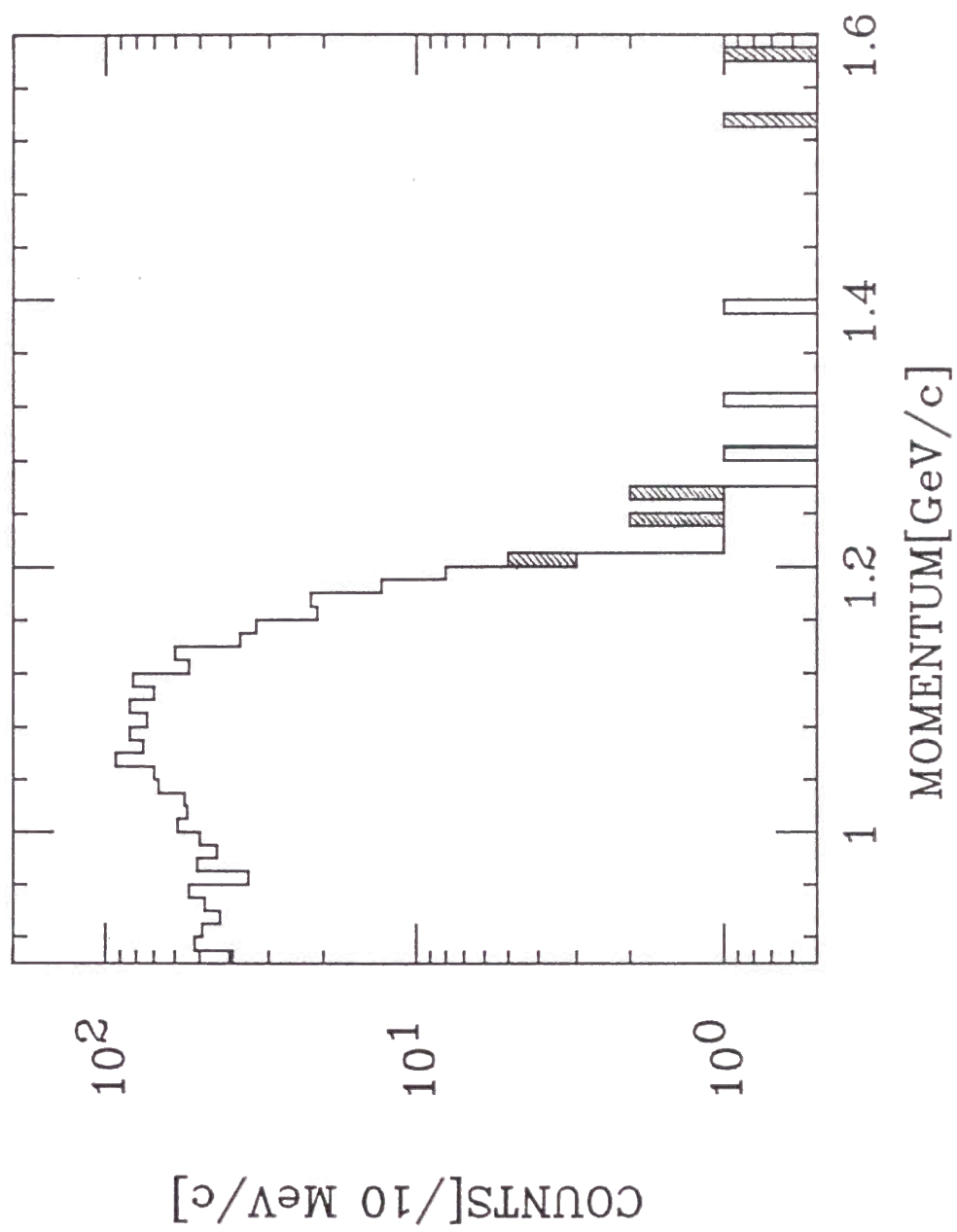


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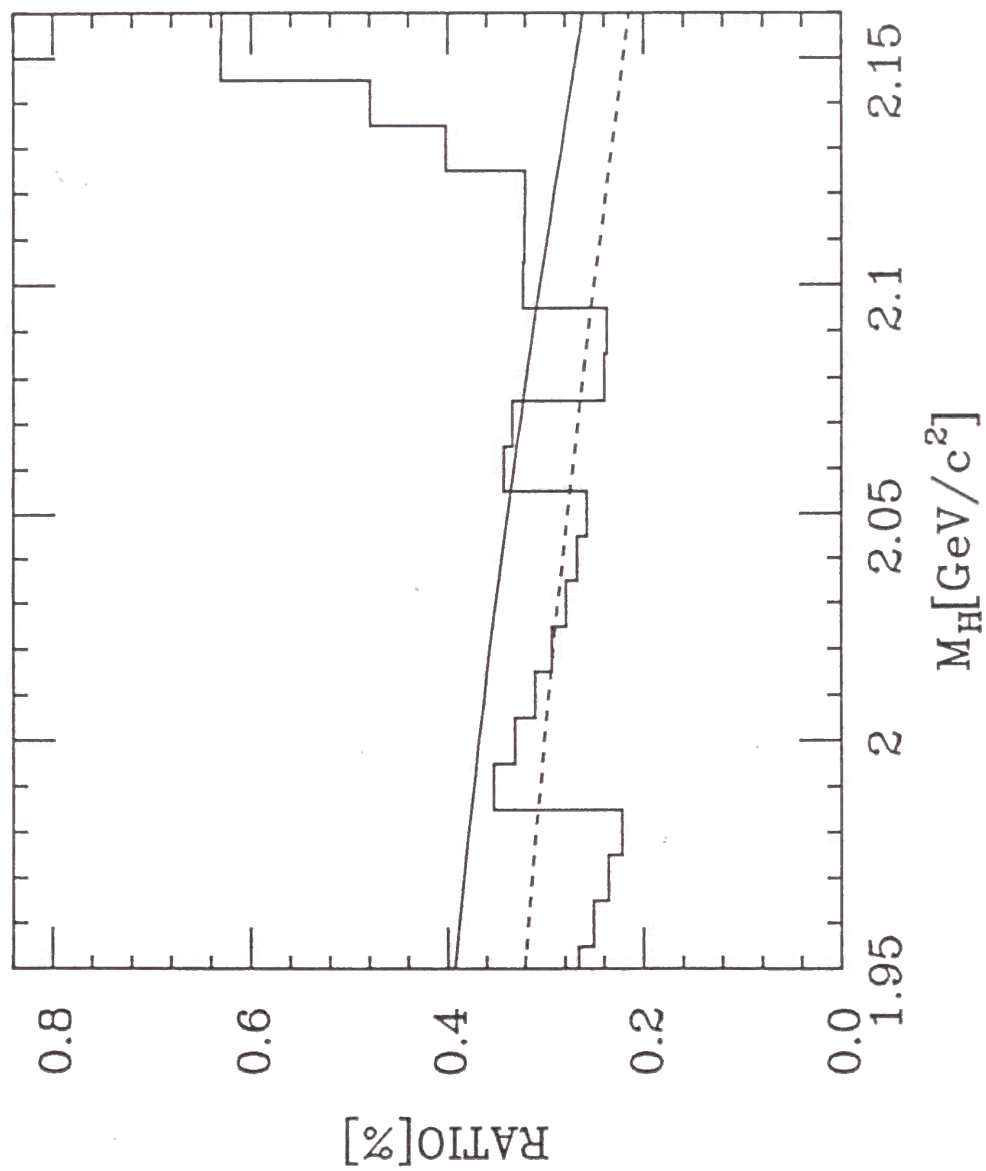


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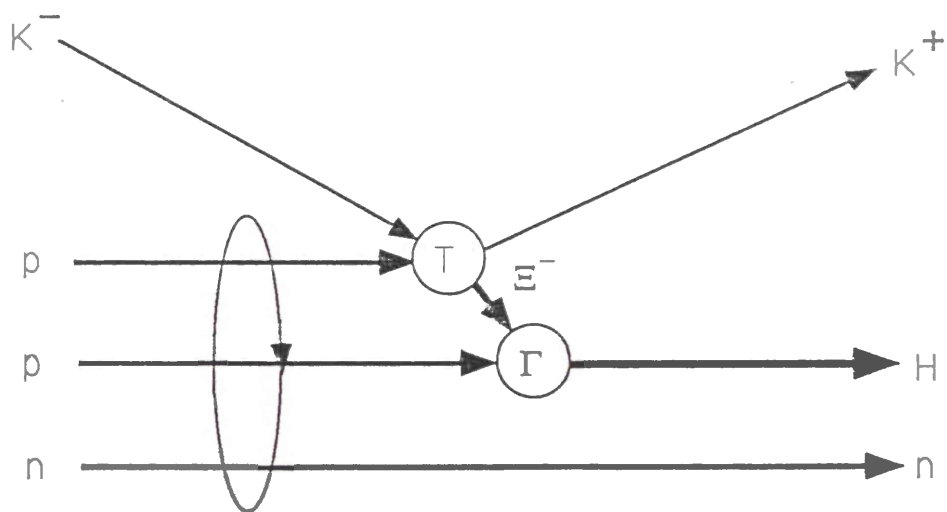


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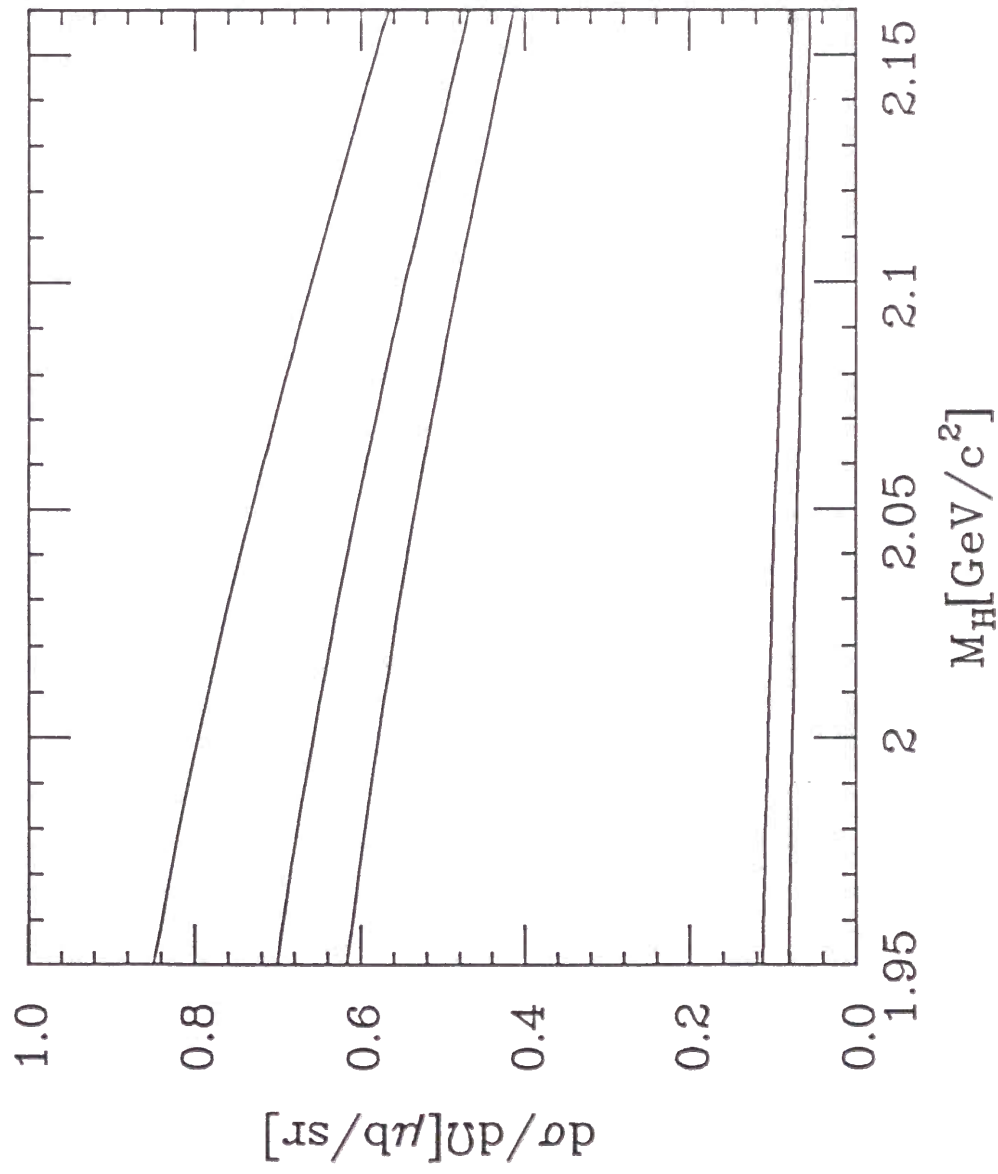


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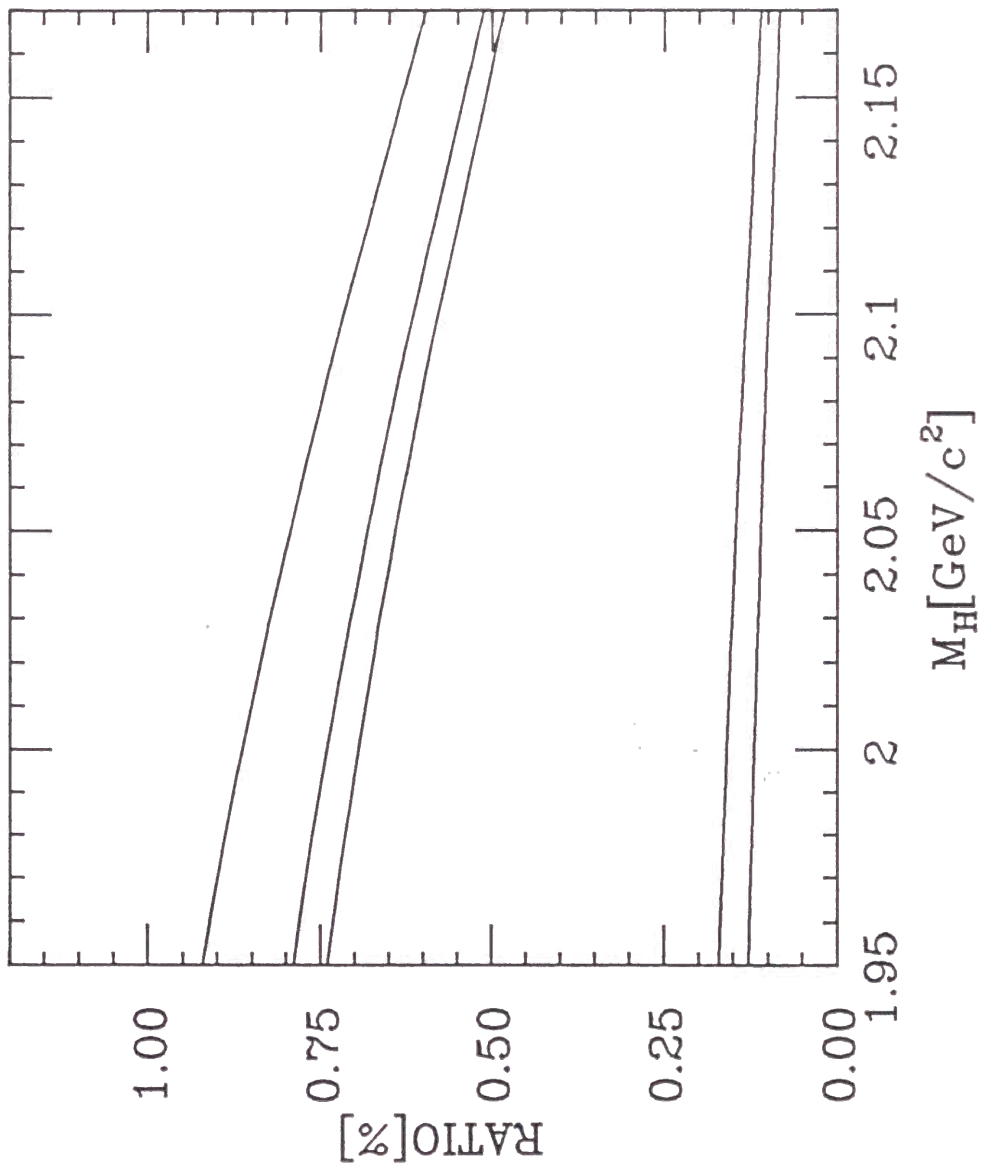


Figure 53