Recent Work at the Bevatron

Second Lecture by Owen Chamberlain
at the
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In reviewing recent work at the Bevatron, I have made choices based upon my own taste and which experiments I thought might be especially interesting to you in terms of your new laboratory.

At the start, let me say that there is one experiment that deserves special mention, even though the results are not new. That is the experiment of Kerth, Clark, and collaborators in which they searched for the reaction

$$K_L \rightarrow \mu^+ + \mu^- \qquad (1)$$

but found that the reaction did not occur at the expected rate. Their result is particularly interesting because they have found that the reaction occurs even at a lower rate than would be expected from the lower limit (calculated) called the "unitarity limit." Since the long-lived K^0 is known to decay to 2 gamma rays, this can be used to calculate what should be the guaranteed rate of reaction (1) by means of the Feynman diagram shown in Fig. 1. This is not strictly a lower bound for the process, since it is still possible for destructive interference to decrease the calculated rate. However, there was not expected to be any process that could lead to destructive interference in this case. In the actual experiment they determined that, with a 90 percent confidence level, the decay branching ratio for reaction (1) is less than 1.6×10^{-9}, while the so-called unitarity limit is 4.8×10^{-9}.

As with all experiments that give startling results, there is the definite possibility that the experiment is wrong. But, I can assure you that the experimenters have worked very hard to make quite sure that their apparatus would be sensitive to reaction (1). There are other explanations of the absence of reaction (1) involving the concept that the long lived K is a superposition of K_1 and K_2. One possibility is that there is destructive interference between the K_1 and K_2 parts. This would mean, however, that the short-lived K would have to decay fairly rapidly into 2 muons.

The same group is now preparing another experiment to determine whether or not the K_S does, in fact, decay rapidly into muon pairs. If not, then the puzzle remains. At the present time the branching ratio of K_S into 2 muons is known to be less than 5×10^{-7}. It will be most interesting whether that branching ratio can be measured to be less than 1×10^{-7}.

I wish to turn, now, to the experiment of Cable, Hildebrand, Pang and Stiening in which they search for the reaction.

$$K^+ \rightarrow \pi^+ + \nu + \bar{\nu} \qquad (2)$$

The experiment, when it was started some time ago, was thought of as a search for neutral currents in the weak interaction. There were many motivations for a search for neutral currents, including the fact that the $|\Delta I| = \frac{1}{2}$ rule that seems to apply to weak strangeness-changing non-leptonic decays indicates that neutral currents must be present. However, the present motivation is different. It is now regarded as a search for second-order weak interactions.

On dimensional grounds one would expect that second order reactions would occur with branching ratios of the order of $(GM_K^2)^2 \approx 10^{-13}$, but since the calculations diverge there is the definite possibility that the second-order processes will be much more abundant than that. In fact, reaction (2) is rather uniquely well suited to a search for second-order weak reactions because it is one of the few reactions that cannot occur through a combination of weak and electromagnetic interactions but can occur through second-order weak interactions.

Since the reaction (2) is not seen, the experimental results must be quoted in terms of hypothetical shapes of the pion spectrum. The authors have chosen to express their results in terms of the spectra that would be expected from various first-order interactions, those of the scalar, vector, and tensor forms. These spectral shapes are shown in Fig. 2, along with the spectra to be expected from the 2-pion and 3-pion decays of the K^+. In Fig. 2 the spectra are expressed in terms of the expected range distributions in a carbon absorber. Also shown, as dotted curves, are the sensitivity curves of the apparatus at various experimental settings, marked I, II, and III. These sensitivity curves will be explained later.

The apparatus is shown in Fig. 3 (XBL 718-4170). Incident K^+ in a beam of momentum 500 MeV/c are stopped at the center of a large cube of lead glass. The glass is obtained from the Ohara Company of Japan, type SF-1. The pieces of lead glass constitute a large Cherenkov counter for the detection of any gamma rays that might be emitted in the decay. Obviously, the authors are looking for K decays that lead to pions but do not show any sign of gamma rays. The central portion of the apparatus is shown in Fig. 4 (XBL 718-4169). The kaons are incident from the right. They are required to count in the counters K1, K2, K3, and K4, but not to count in the Cherenkov counter KC, which is sensitive to pions. The stopping region, at the center, is largely surrounded by counters connected in anticoincidence. Also, all the material labeled B is lead glass used as anticoincidence. The useable pions are those that pass out in the direction of the pion telescope, counters T1 through T8. The detected pions are those that stop in the vicinity of the counters T6 and T7. They can be identified as pions through the observation of their decay to muons and the decay of muons into electrons. This whole chain of events is recorded on film as photographs of four 4-beam oscilloscopes.

The film record of each interesting event shows which of the photomultipliers that are viewing lead glass pieces received signals, the electronically measured lifetime of the kaon, the pulses of the kaon and pion counters K1 to K4 and T1 to T8 (including a required pulse from pi-mu decay), the pulses from T5 through T8 on a slower sweep where the mu-e decay can be seen, and various incidental pieces of information such as frame number and a number indicating the state of the absorbers in the apparatus.

By adjusting the absorber placed in the pion telescope, it is possible to arrange that pions of various ranges stop in the vicinity of T6 and T7 where the pion identification is made. The range sensitivity of the apparatus for 3 particular absorber values is shown as I, II, and III in Fig. 2. The absorber II is used to detect the 2-π decay of the kaon, which is used as a calibration for the apparatus. The settings I and III are used to detect the sought-for $\pi\nu\nu$ decay.

Their results, to the present time and expressed in terms of the branching ratio for reaction (2) at 90 percent confidence level are:

For scalar spectrum: less than 2.1×10^{-6};
For vector spectrum: less than 7.5×10^{-7};
For tensor spectrum: less than 1.4×10^{-6}.

The experiment is being continued to improve these results.

The same authors have searched in the same apparatus for the process

$$K^+ \rightarrow \mu^+ + \nu + \bar{\nu} + \nu \tag{3}$$

They find the branching ratio, with 90 percent confidence level, is less than 7×10^{-6}. In this case they see 7 events that are consistent with the kaon decaying into muon without the emission of any gamma rays. For this process, reaction (3), there is the difficulty of a background from the process $K^+ \rightarrow \mu^+ + \nu + \gamma$ in which the energy of the gamma ray is very small, therefore is easily missed by the lead glass Cherenkov counters. The authors have decided that it would be dangerous to make assumptions on the origin of these 7 events. While they are consistent with reasonable estimates of the background rate, there is difficulty in evaluating accurately the real background rate. The authors have preferred to quote their result on the basis that these 7 events might be real events of the type (3). They do not have any present plans for trying to improve on the quoted result for reaction (3).

Next I wish to discuss an experiment in which I have a direct interest. Other experimenters involved are Shannon, Nelson, Kenney, Steiner, Shapiro, Dahl, and Pripstein. This is an experiment to determine the asymmetry in the reaction

$$\pi^- + p \rightarrow \pi^0 + n$$

when the initial protons are polarized. The motivation for this experiment is better determination of the pion-nucleon scattering amplitudes. It is expected that the results from this experiment should be important for determining whether there are ambiguities in current phase-shift solutions and in increasing the precision of the current solutions by adding a new type of measurement to the data already available.

A plan view of the apparatus is shown in Fig. 5. There are 20 neutron counters in all. The optical spark chambers are used to search for events with 2 gamma-induced showers. The spark chambers have plates whose thickness is 0.2 radiation lengths and a total thickness of 7 to 9 radiation lengths. The spark chambers are triggered when an incident pion leads to a neutral final state providing one neutron counter counts.

The polarized target operates at 1° Kelvin with a sample of propane-diol in which the hydrogen is about 50% polarized. A ^{3}He cooling system is being designed for use in future experiments, to give higher target polarization, but it is not yet constructed.

The incident pion beam is run at an intensity of about 500,000 particles per 1.3-second beam burst. This gives rise to about 2 events per pulse. At this time about 10^4 events at each of the beam momenta 1250 MeV/c and 1580 MeV/c have been recorded. The next momentum to be measured will be 1030 MeV/c. About 30% of the events photographed show 2 showers.

The events are analyzed by selecting those 2-shower events that fit satisfactorily to the process $\pi^- + p \rightarrow \gamma + \gamma + n$ and then picking out the events in which the gamma-gamma mass is consistent with that of the neutral pion. This analysis indicates that the events thus selected contain 18% background events in which the desired process occurs, but occurs on bound protons within the heavy nuclei of the polarized target rather than on free protons.

Very preliminary results are shown in Figs. 6 (XBL727-1241) and 7 (XBL727-1242). The results at 1250 MeV/c represent about half the data taken (Fig. 6). For Fig. 7 (1580 MeV/c) only one quarter of the events have been analyzed. Notice that in each set of results there appear to be inconsistencies. Careful work is needed to determine the origin and cure of these inconsistencies. It must be emphasized that these results are preliminary.

As a last item, I want to discuss the observations on K mesic atoms, work by Dr. Clyde Wiegand and Gary Godfrey and Jeff Gallup. Using modern solid-state detectors, they observe the X rays emitted as K^- mesons stop in various materials and fall through successive atomic states, finally being absorbed by the nucleus.

Their apparatus is shown in Fig. 8 (XBL708-3573). A low-momentum separated K^- beam is incident from the left. Counts in the scintillators S_2, S_3, and S_4 without any count in S_5 indicate that a K^- has probably stopped in the vicinity of the target. If the stopping particle is a K, there should be no count in the water Cherenkov counter. The solid-state detectors are used to observe the atomic X rays. The work has been very materially helped by excellent development of the solid-state detectors and allied circuitry by Goulding, Pehl, Walton, and Landis. They have not only made very good detectors, but have, as well, made significant developments in the circuits to make them very little susceptible to error even at high counting rates. Among other things, they have shown how the early stages of amplification following the solid-state detector may be d.c. connected. Accumulated charges are occasionally discharged by photodiode action while the counting circuit is disabled for a short time.

The phenomena occurring when a K^- stops are fairly complicated. They have not been fully studied, as yet. As the K stops, it is probable that molecular effects may determine which atom the K is captured in. As the K gets closer to a nucleus it is expected that the K loses energy mainly by Auger-electron emission, at first, involving the understanding of atomic physics. As the K gets closer to the nucleus it should lose energy mainly by X-ray emission. Finally, nuclear effects determine what atomic state the K is captured from.

Fig. 9 (XBL717-3915) shows the pulse-height spectrum they have obtained from K^- stopping in helium. Because the X rays are low in energy, it has taken special care to get this spectrum. The observed peaks are marked to indicate the element in which the K stopped and the initial and final n values of the transition. (The angular-momentum quantum number ℓ cannot be determined from the observed X-ray energy in these hydrogen-like spectra.) Notice that transitions to n=2 states are observed, but transitions to n=1 states are absent in the helium spectrum. This means either that the K is being absorbed from the n=2 state, or that the n=1 state is so much broadened by nuclear effects that it is not recognizable as a well-defined energy level.

Fig. 10 (XBL7112-4915) shows their results in chlorine and sulfur. Notice the very good resolution: 600 eV FWHM (full width at half maximum). There is evidence for Σ^- hyperonic atoms resulting from the stopping of Σ particles that are made when kaons are absorbed. In the Cl spectrum there is evidence for a nuclear gamma ray from ^{32}P, and in the S spectrum there is evidence for a nuclear gamma ray from ^{19}F. In sulfur, there is a broadening of the line for the 4-to-3 transition, indicating that the n=3 level is broadened by rapid absorption of the K from that energy level. Fig. 11 (XBL723-2664) shows this broadening in more detail. For comparison with the 4-to-3 transition, another nearby line has been moved to this region of X-ray energy. This broadening gives a sensitive measure of the rate of absorption on the nucleus.

An example of the puzzling results that are sometimes obtained is shown in Fig. 12 (XBL723-2663), the spectrum from K absorption in ^{55}Mn. There is a prominent line at the energy where both the 9 to 6 transition and a nuclear gamma ray from Mn fall. The line is more intense than one would expect from looking at the 9-to-6 transition in nearby elements by a factor of 20. It is hard to discover any mechanism that would lead to such a large number of excited states of Mn. Thus, the high intensity of that line remains a mystery.

I will conclude with that. I have chosen experiments that I would expect to be of interest to you in terms of your new laboratory. Many of these problems will remain of interest for some time to come.

Figure Captions

Fig. 1. Feynman diagram for calculating the "unitarity limit" for the μ-μ decay of K_L.

Fig. 2. Pion range spectra for K^+ decay.

Fig. 3. Apparatus for studying K^+ decay. The large pieces of lead glass are used to veto decays in which gamma rays are emitted.

Fig. 4. Central portion of the apparatus.

Fig. 5. Apparatus for studying negative pion charge exchange on polarized protons. Many anticoincidence counters are not shown.

Fig. 6. Asymmetry in negative pion charge exchange scattering on polarized protons. These are very preliminary results.

Fig. 7. Asymmetry in negative pion charge exchange scattering on polarized protons. These are very preliminary results.

Fig. 8. Apparatus for studying K^--mesic atoms.

Fig. 9. X-ray spectrum from K^- stopping in helium.

Fig. 10. Results in chlorine and sulfur.

Fig. 11. Broadened line compared to normal line.

Fig. 12. Spectrum from K absorption in ^{55}Mn.

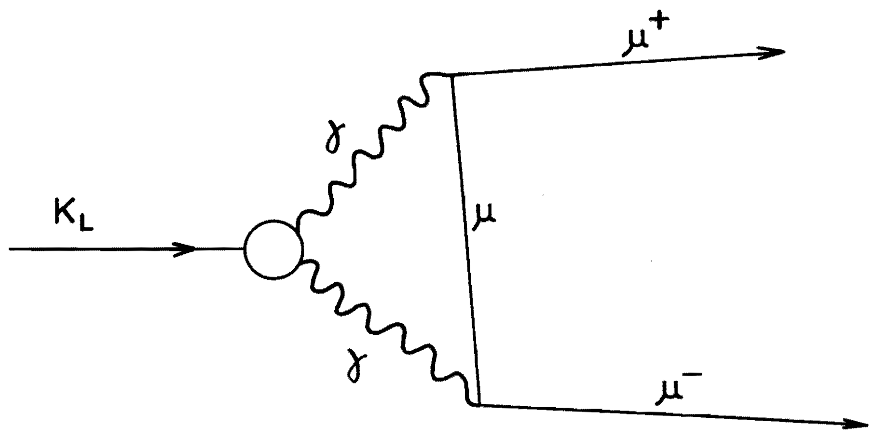


Fig. I Feynman diagram for calculating the "unitarity limit" for the mu–mu decay of K_L.

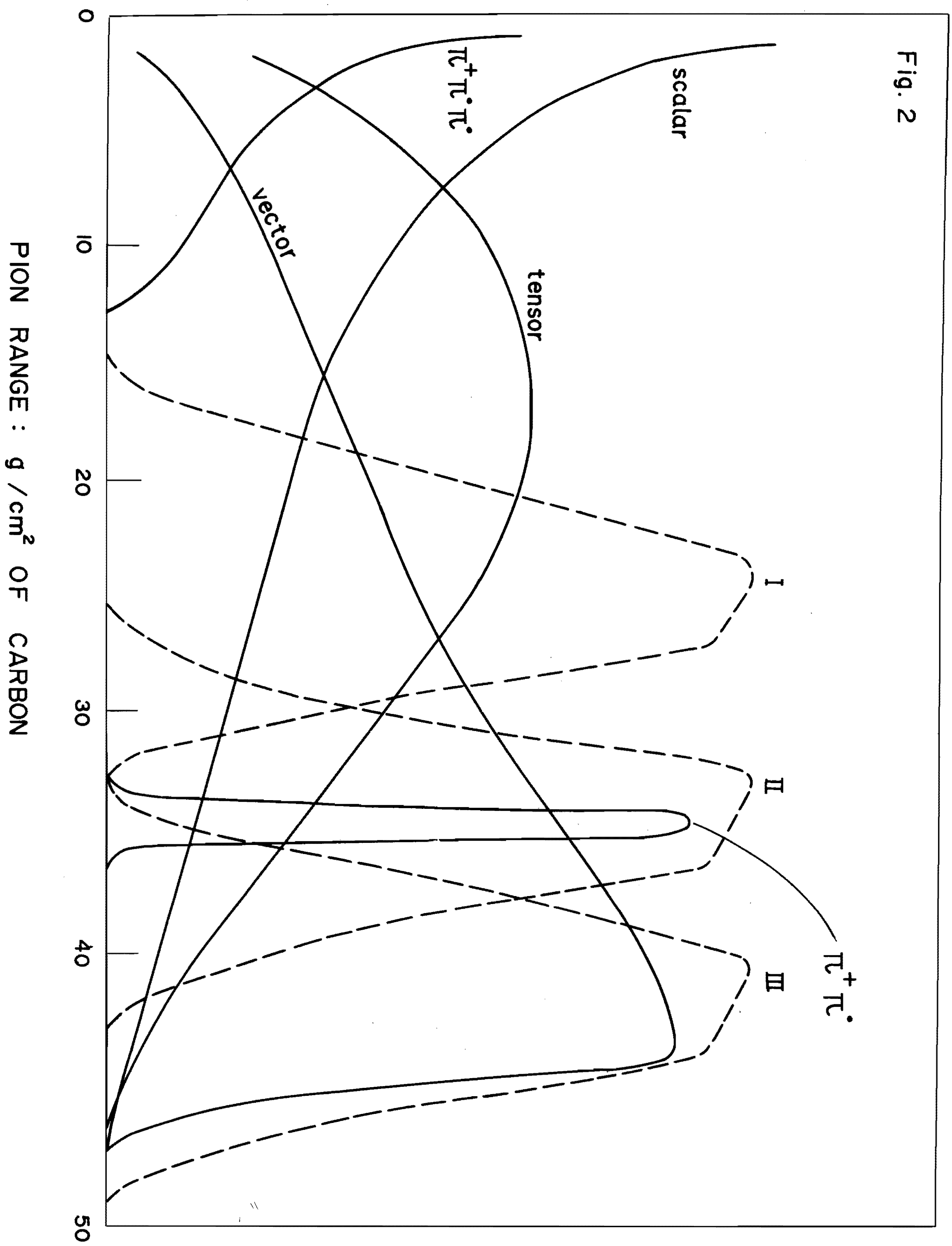

scalar
$\pi^+\pi^0\pi^0$
vector
tensor
I
II
III
$\pi^+\pi^0$
0
10
20
30
40
50
PION RANGE : g / cm² OF CARBON

Fig. 2

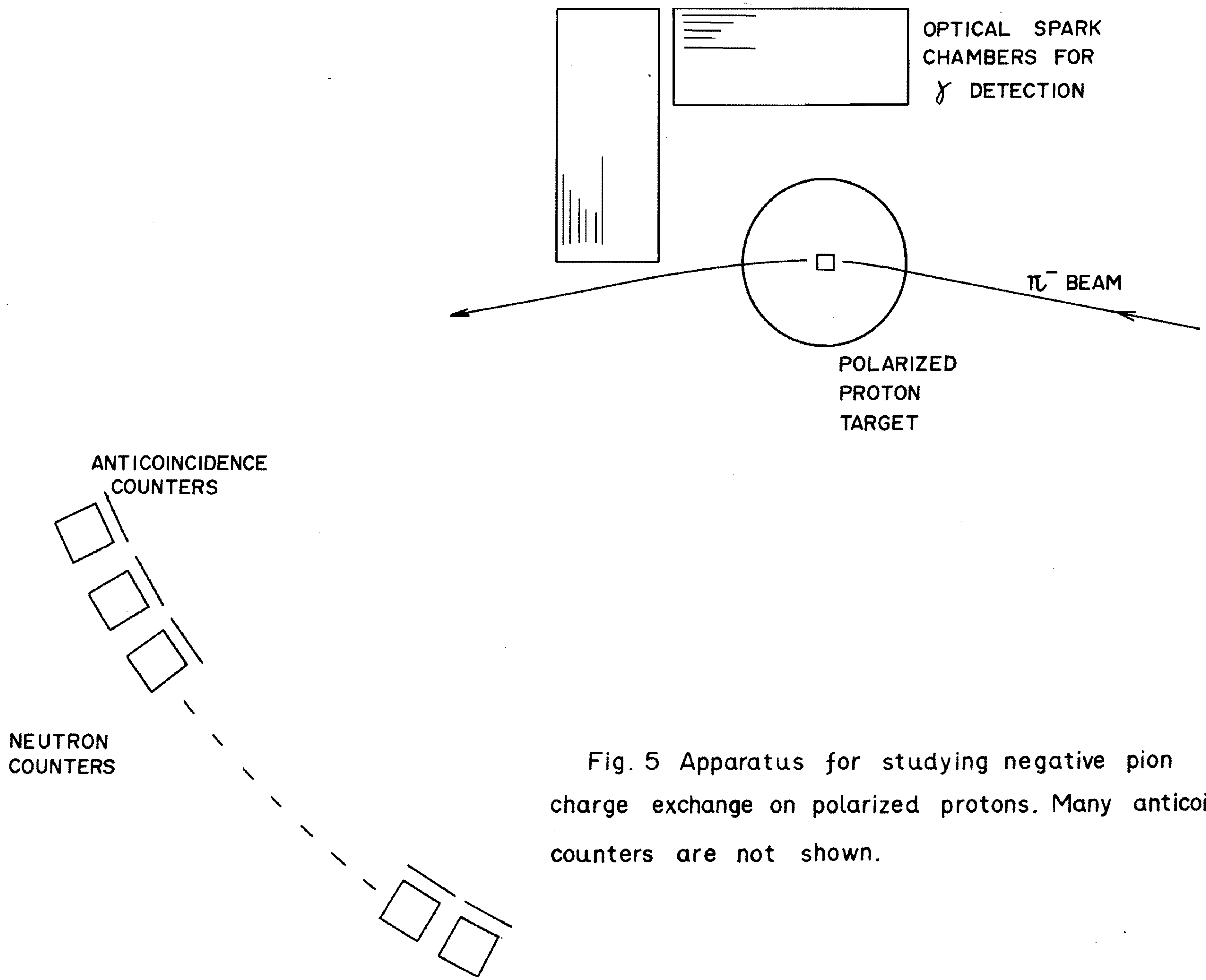
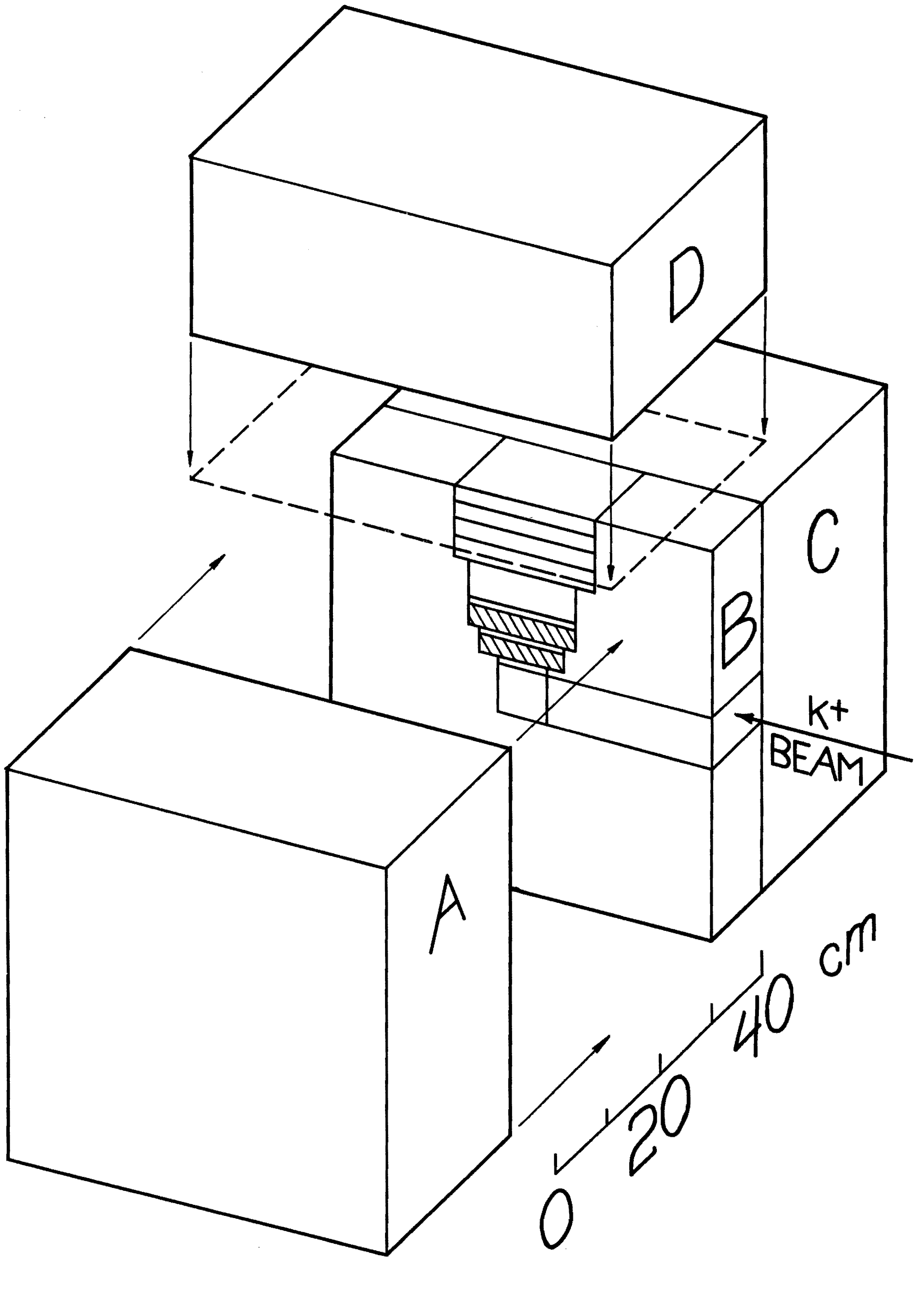
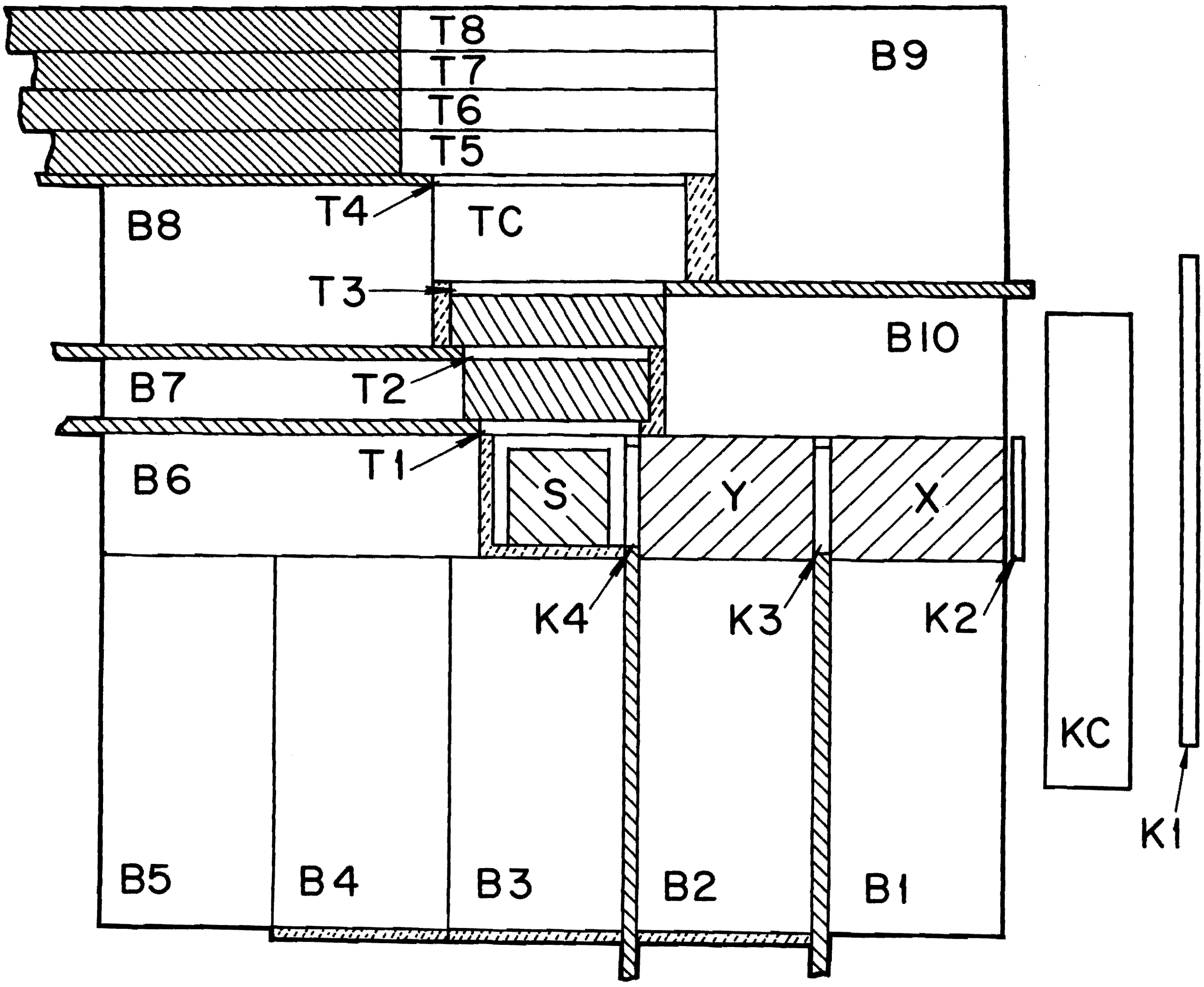


Fig. 5 Apparatus for studying negative pion charge exchange on polarized protons. Many anticoincidence counters are not shown.

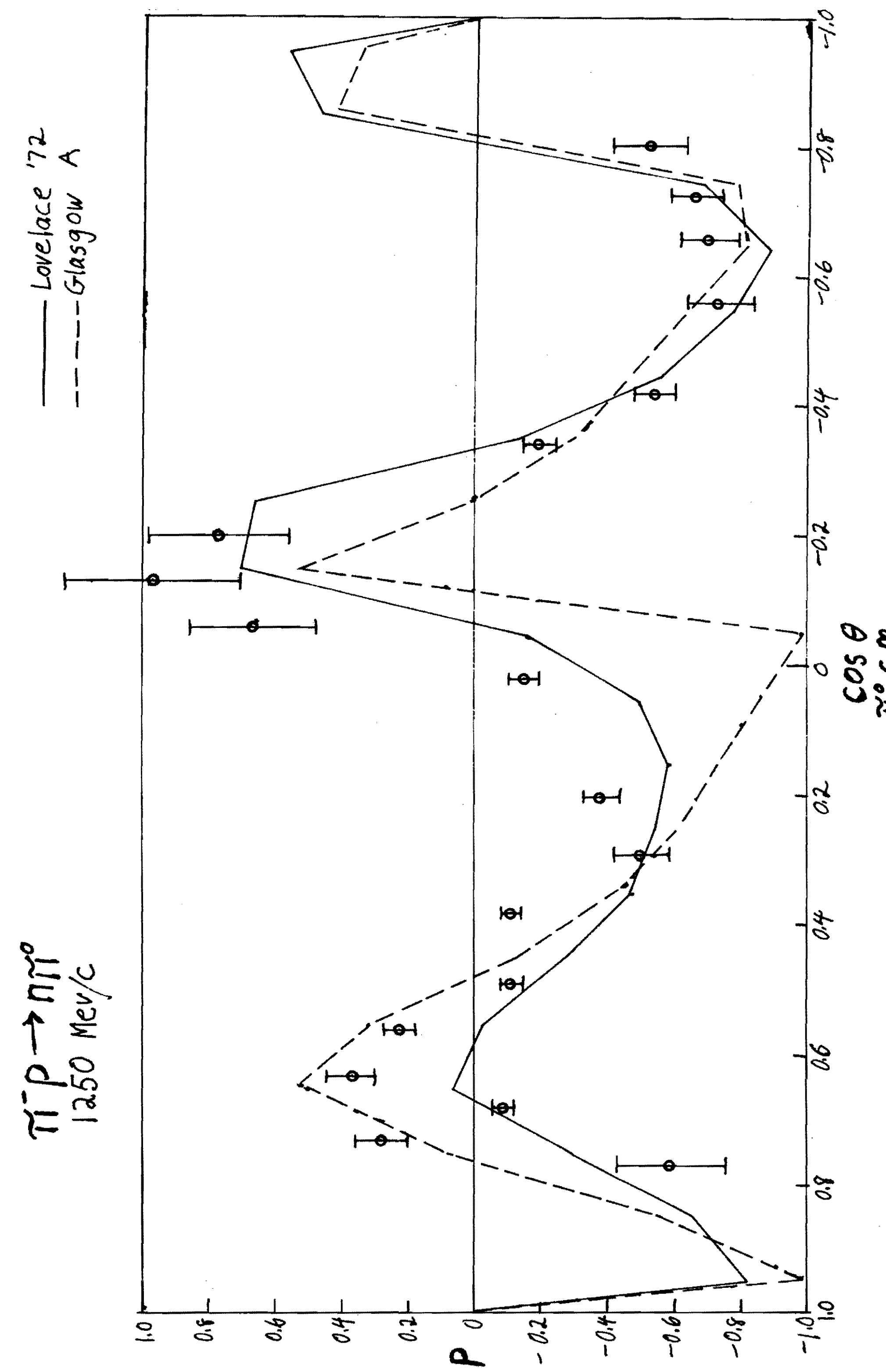


XBL718-4170

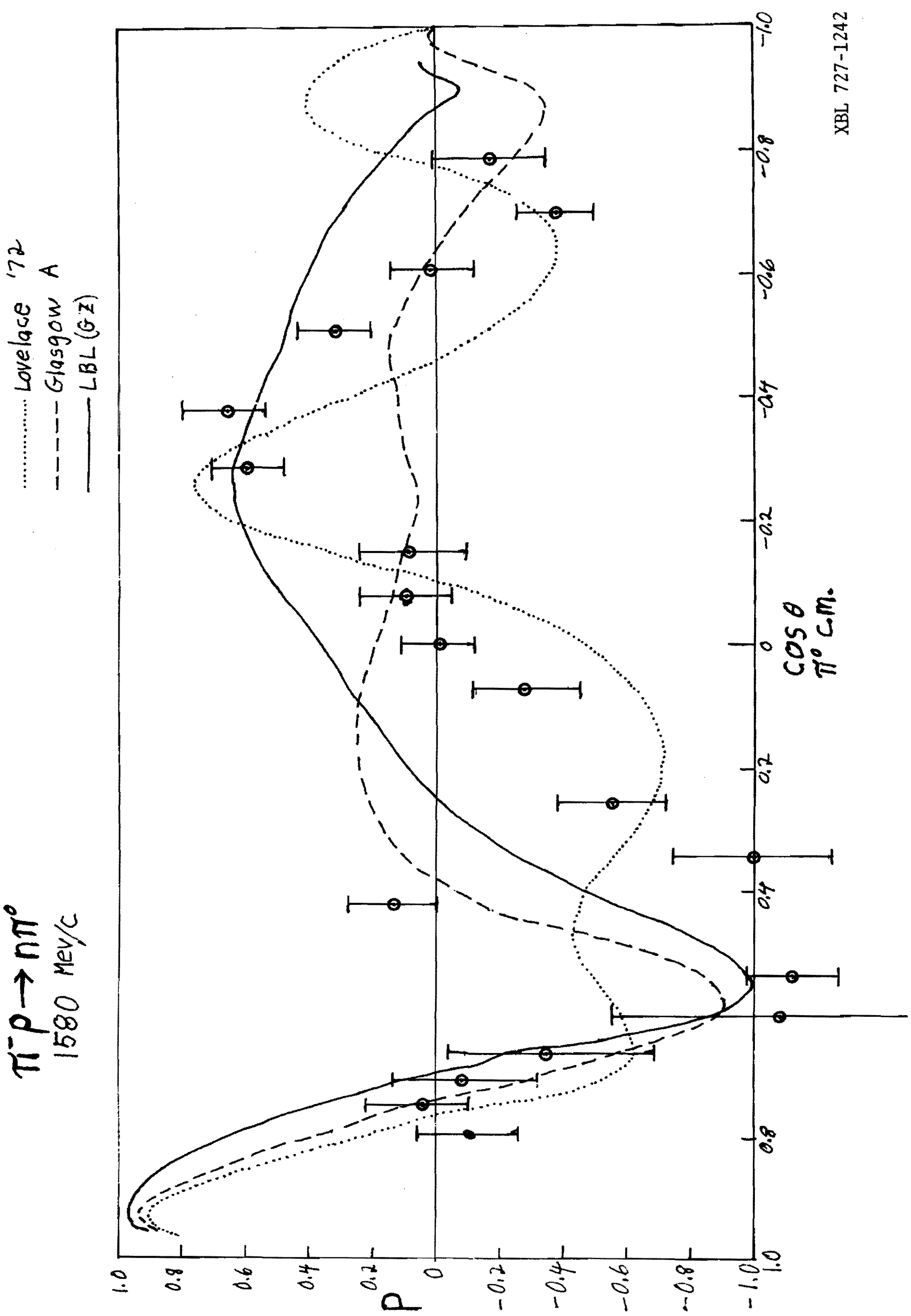


(legend box)	μ^+, π^+ Degrader
(legend box)	K^+ Degrader - γ Converter
(legend box)	Scint. coupled to Pb-glass
(legend box)	Light pipe
(legend box)	K^+ Stopper

XBL 718-4169

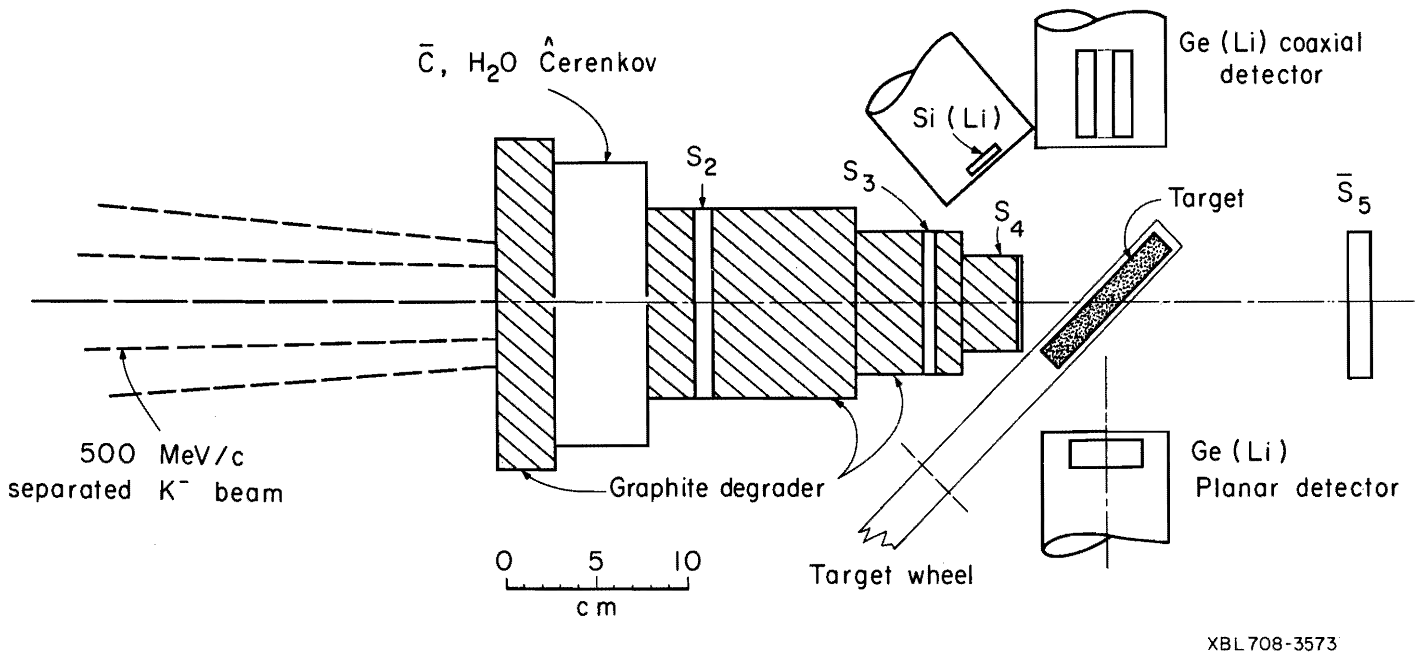


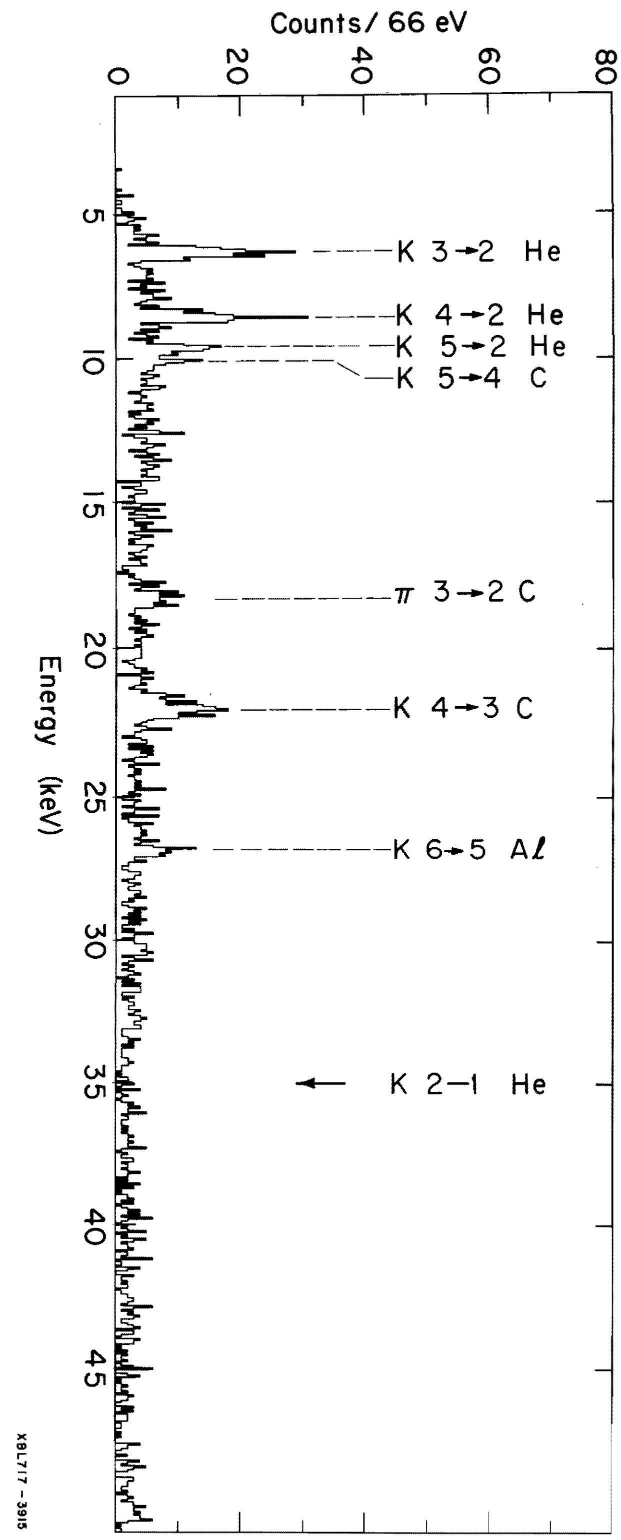
XBL 727-1241

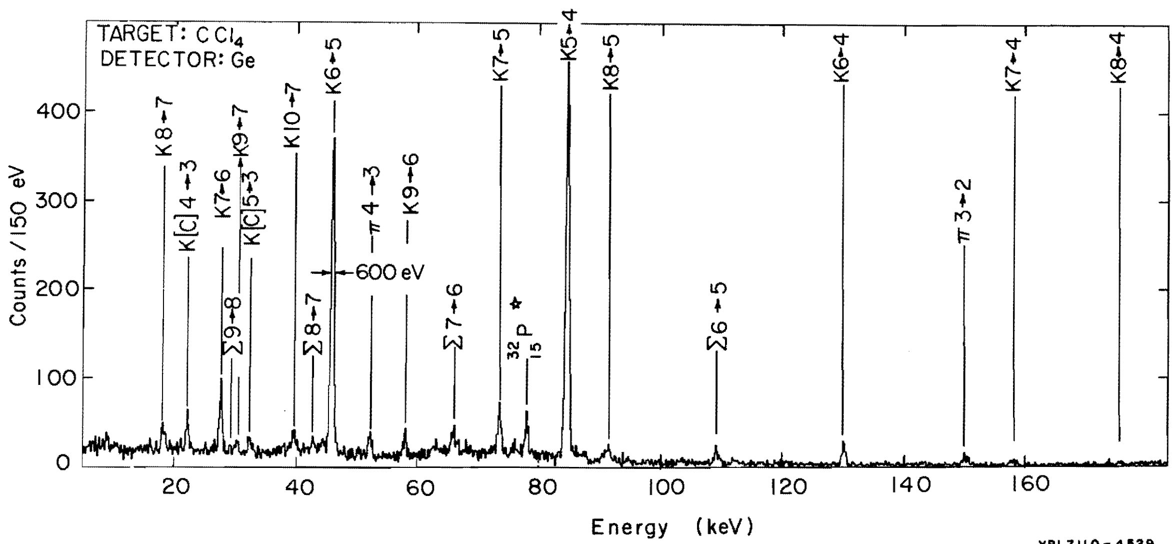


$\pi^- p \to n\pi^0$
1580 MeV/c
Lovelace '72
Glasgow A
LBL (GZ)
P
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
cos θ
π° c.m.
1.0
0.8
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0

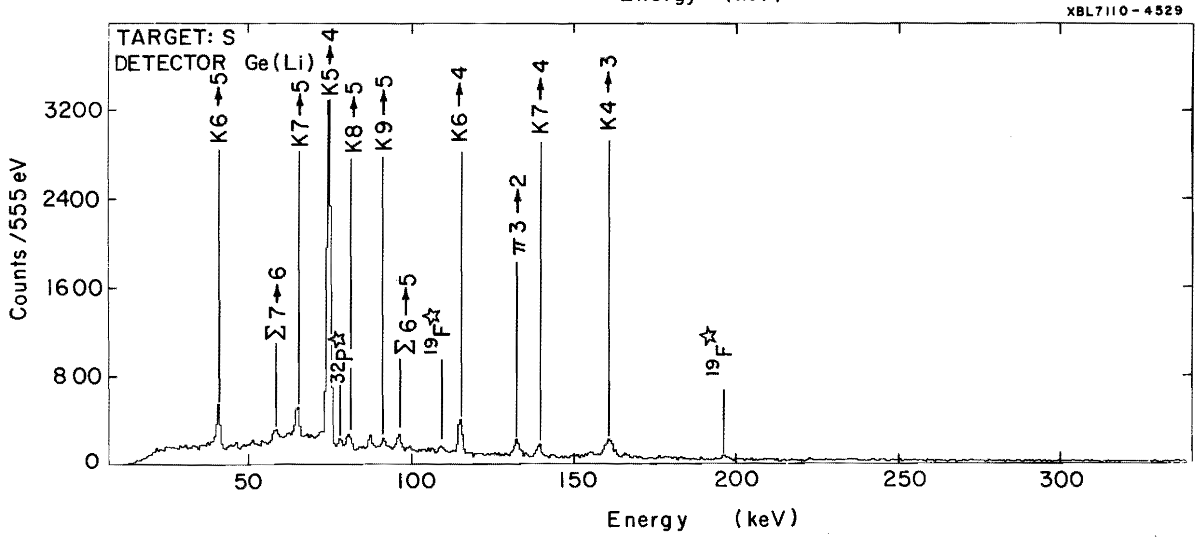
XBL 727-1242


C̄, H_2O Ĉerenkov
Ge (Li) coaxial detector
Si (Li)
S_2
S_3
S_4
Target
$\bar{S}_5$
500 MeV/c separated K^- beam
Graphite degrader
Ge (Li) Planar detector
Target wheel
0 5 10
cm
XBL 708-3573

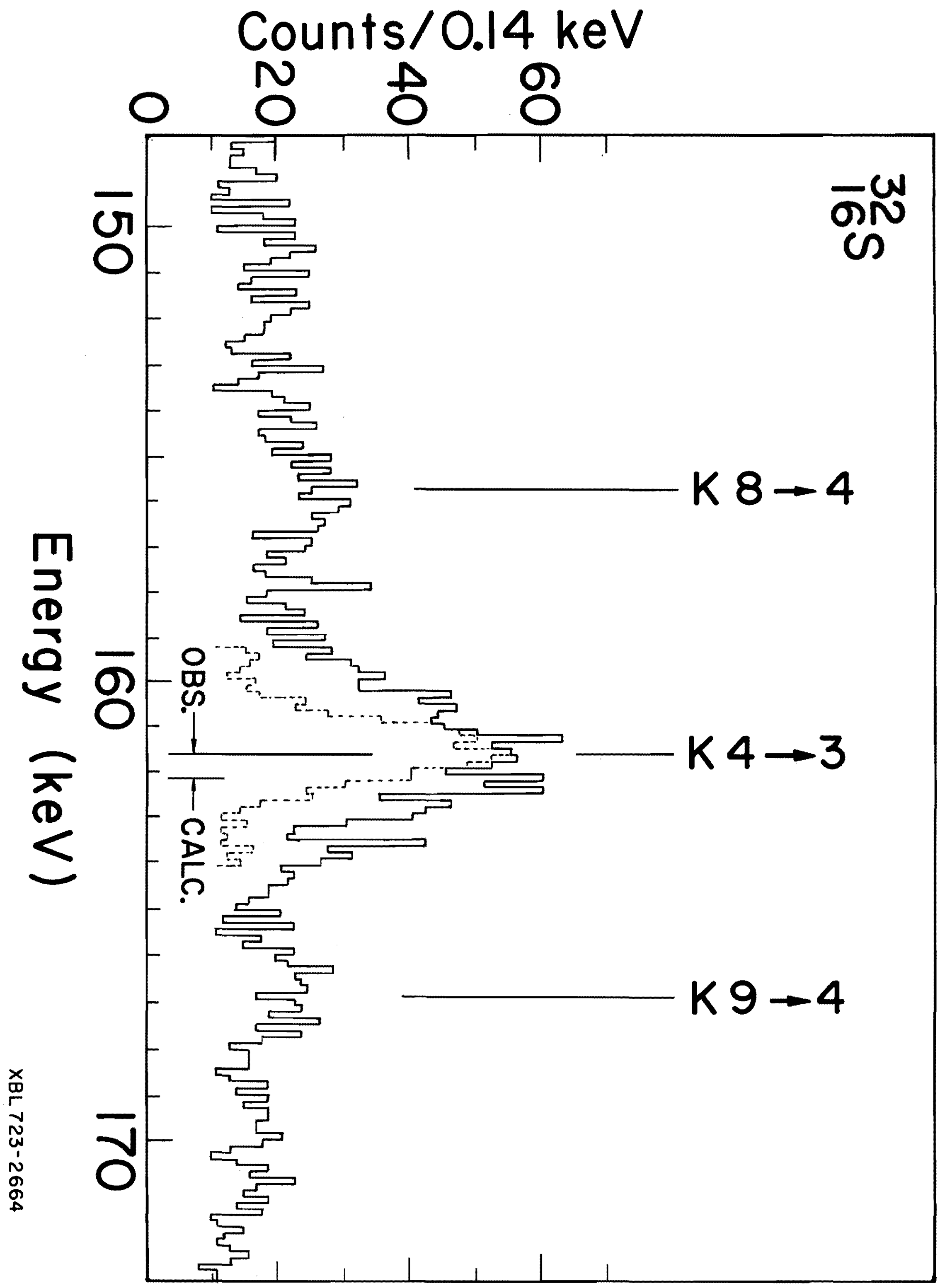

Counts/ 66 eV
0
20
40
60
80
Energy (keV)
5
10
15
20
25
30
35
40
45
K 3→2 He
K 4→2 He
K 5→2 He
K 5→4 C
π 3→2 C
K 4→3 C
K 6→5 Aℓ
K 2—1 He
XBL717 - 3915



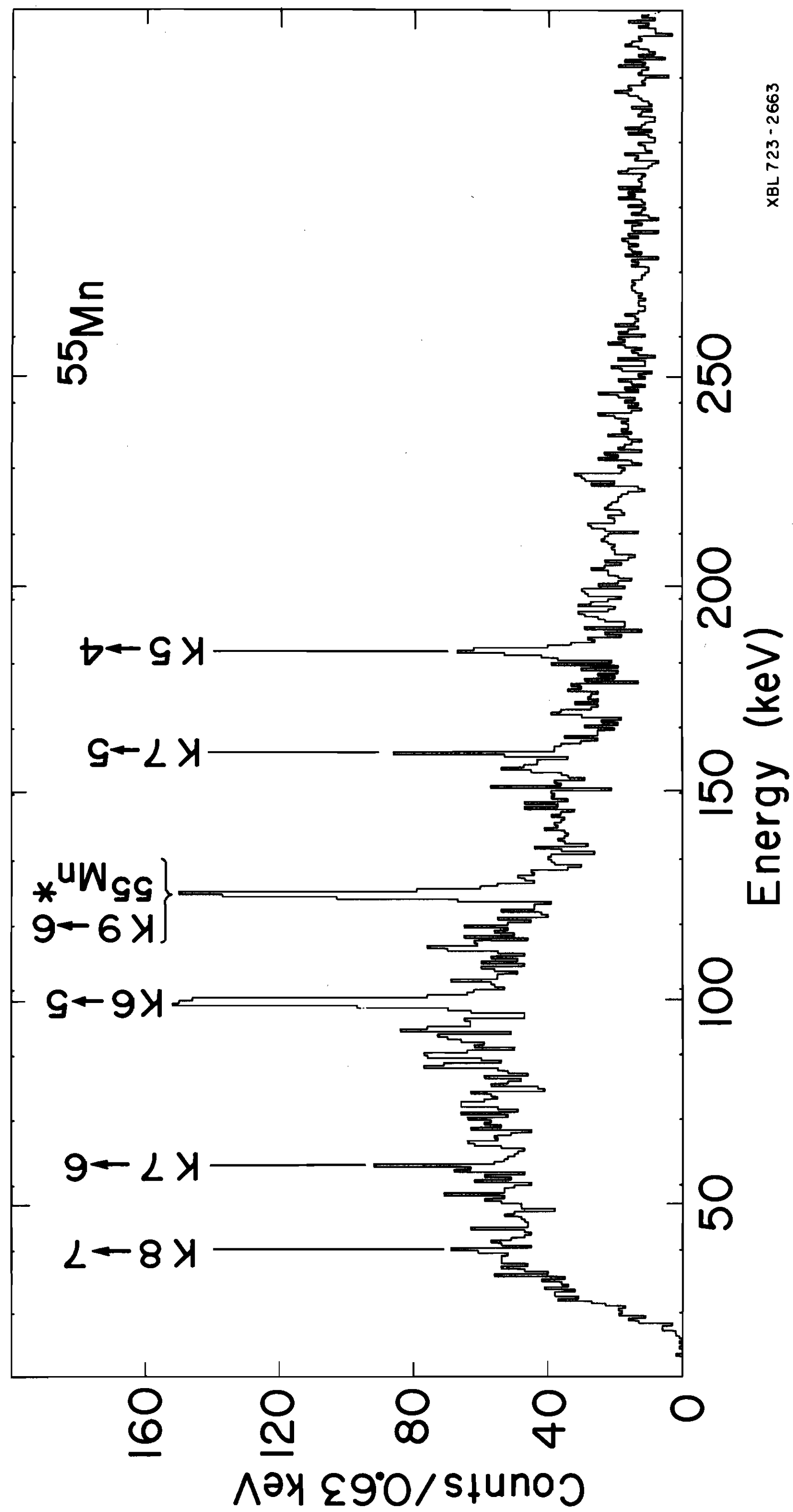
XBL7110-4529



XBL7112-4915



Counts/0.14 keV
0
20
40
60
$^{32}_{16}S$
150
160
170
Energy (keV)
OBS.
CALC.
K 8→4
K 4→3
K 9→4
XBL 723-2664



55Mn
K 8→7
K 7→6
K6→5
K 9→6
55Mn*
K 7→5
K 5→4
Counts/0.63 keV
0
40
80
120
160
50
100
150
200
250
Energy (keV)
XBL 723-2663