A. J. HERZ

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH

PH III-67/20
18 April 1967

~~Rec. but not~~
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After Measday
Walschek in proton hall
50 shifts recomm.
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PHYSICS III COMMITTEE

PROPOSAL FOR AN INVESTIGATION OF THE SPECTRUM OF CHARGED PARTICLES ARISING FROM THE BOMBARDMENT OF LIGHT NUCLEI WITH POSITIVE PIONS

by

B.W. Allardyce, D.T. Chivers, J.J. Domingo,
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The total cross-sections for various reactions of medium-energy pions with light nuclei have been measured, as a function of incident-pion energy, by detecting the residual activities. The results of these investigations are discussed in a preliminary manner in the attached report. We propose to investigate two particular features of these results in greater detail by the more selective method of magnetic spectrometry. Further we propose to use the same spectrometer system to investigate the magnitude of high momentum components in nuclear wave functions.

The activation measurements of the $(\pi,\pi N)$ reactions on self-conjugate nuclei showed that the 3-3 resonance dominates the shape of the excitation function, but that the π^+ and π^- cross-sections are very nearly equal. This deviation from the simple quasi-elastic scattering predictions can be understood if one supposes that the reaction proceeds via (π,π') excitation of virtual nuclear states of reasonably small width. Since the cross-sections are quite large, presumably the states involved have a strong collective character and may be closely related to the giant dipole state observed in photo disintegration. Perhaps the most interesting

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questions are the form the J = 1, T = 1 giant dipole resonance will take when excited through the (π,π') reaction and the possible existence of other collective states not excited by the electromagnetic interaction.

We propose to investigate the case of $^{16}O\ (\pi^+,\pi^{+\prime})$. The choice of ^{16}O is dictated partly by familiarity$^{(1)}$ but more importantly by the nature of the giant dipole structure which is fine enough to be interesting but coarse enough to be resolved. In addition the theory of the ^{16}O dipole state is very well developed$^{(2)}$.

The charge-exchange cross-sections measured in the activation experiments are remarkable in the respect that there is a factor $\gtrsim 10^2$ between the cross-section for $^{13}C(\pi^+,\pi^o)^{13}N$ and that for $^{14}N(\pi^+,\pi^o)^{14}O$. It is thought that the small ^{14}N cross-section is related to the notorious ^{14}C β-decay problem. We propose to investigate this problem further by looking for $(\pi^+,\pi^{+\prime})$ excitation of the first excited state of ^{14}N which is the analogue of the ground state of ^{14}O. The $(\pi^+,\pi^{+\prime})$ and (π^+,π^o) reactions to mirror states are simply related.

Extremely high momentum components in the nucleon wave functions should be amenable to investigation through the reaction:

$$\pi^+ + \text{bound neutron} \rightarrow p.$$

The momentum which must be supplied by the motion of the bound neutron in this reaction is approximately 500 MeV/c compared to the maximum of the Fermi gas distribution of roughly 250 MeV/c. We propose to look for high momentum protons resulting from π^+ bombardment of ^{16}O. In this case ^{16}O offers the advantage of an easily resolved final state i.e. the ground state of ^{15}O which is separated by 5 MeV from the lowest excited state. A recent estimate$^{(3)}$ of the $^{16}O(\pi^+,p)$ cross-section based on harmonic-oscillator wave functions gave ≈ 50 μb/sterad; this estimate is probably pessimistic because of the use of harmonic-oscillator wave functions.

In general terms we propose to construct a high-resolution π^+ beam of fixed energy (about 250 MeV) obtained from the external beam of the SC, incident upon a polyethylene target. Ultimately the quality of the pion beam is dictated by the horizontal emittance of the proton beam which is believed to be very small ($\approx 5\pi$ mm x m rad.). The proposed beam-spectrometer system is described below. Measurements at two angles to the incident beam are contemplated; 25° which is "small" but outside the diffraction-scattering peak and 90°.

During the setting up of the pion beam we propose to make a brief examination of the spectra of pions resulting from the bombardment of targets other than polyethylene with the external proton beam from the SC. This is an alternative approach to the study of the high-momentum components of the nucleon wave functions, e.g. the reaction:

$$B^{10} + p \rightarrow B^{11} \text{(many bound states)} + \pi^+,$$

might be revealed by a high-energy peak in the spectrum of the pion beam.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows a highly schematic view of the experimental arrangement. The external proton beam of the synchro-cycltron is focused by the quadrupole pairs LA1 and LA2 onto the primary pion target. For experiments other than those investigating pion production by protons on light nuclei, a polyethylene target will be used, and pion production will take place via the $p + p \rightarrow d + \pi^+$ reaction. The small Lagrange product of the CERN machine should allow one to obtain a small effective source volume of approximately 2 mm diameter by 10 cm in length. The pions produced in the primary target are focused into a parallel beam by the quadrupole pair Q_1, Q_2, deflected through an angle of 25° by the MPS analysing magnet, and after traversing a 20-cm-diameter beam pipe through the wall of the SC hall these are are refocused onto the target to be bombarded by the lens pair Q_3,Q_4. Michaelis et al. have found that this system should be able to produce a pion flux of approximately 2×10^5 250-MeV π^+'s per second with a momentum spread of 3%. In order to effectively reduce the momentum spread of the incident pion beam without decreasing the flux, a hodoscope of 10 scintillation counters will be placed in the focal plane of Q_3 and Q_4. By using a horizontal focal length of approximately 3 metres for the quadrupoles, a primary target diameter of 2 mm, and scintillators of 2 mm width, it should be possible to achieve an effective momentum resolution of approximately 0.2% for 250 MeV pions. In order to achieve this resolution, it will be necessary to replace the present helium-bag tube with a vacuum pipe to reduce the effects of multiple scattering, and it may be also be necessary to shim the magnets and to line the pole faces with polyethylene to reduce small-angle pole-face scattering. Although a single wire spark chamber could, in principle, be used instead of the counter hodoscope with a considerable simplification of the electronics, the high pion flux makes the use of such a device extremely difficult in this location. For the investigation of the pion spectrum produced by replacing the primary polyethylene target with various light nuclei it will, of course, be unnecessary to use the hodoscope arrangement, since the momentum acceptance of 3% for the total pion beam is much smaller than the momentum spread of 6% due to the external proton beam from the synchro-cyclotron.

The charged particles resulting from pion bombardment of the target are analysed by the spectrometer consisting of the quadrupole pairs Q_5, Q_6 and Q_7, Q_8, and the MA1 bending magnet. Those particles emitted at 25° to the incident pion beam are focused by Q_5, Q_6 onto MA1; deflected through an angle of 45°, and refocused onto the detector by the pairs Q_7, Q_8. Since the counting rate in the detector is expected to be a few counts per second, it is feasible to use a core-read-out wire spark chamber as the position-sensitive detector. Assuming a spatial resolution of 1 mm in the spark chamber and a focal length of 2 metres for the quadrupoles, it should be possible to achieve a momentum resolution of 0.2% with this spectrometer system. Again it will probably be necessary to shim MA1 and reduce pole-tip scattering in order to achieve this resolution.

REFERENCES

(1) Earle and Tanner, Nucl. Phys. 95, 241 (1967),
Tanner, Thomas and Earle, Nucl. Phys. 52, 29 (1964);

(2) Buch and Hill, Nucl. Phys. 95, 271 (1967);

(3) Letourneux and Eisenberg, Nucl. Phys. 87, 331 (1967).

REQUEST FOR MACHINE TIME

1. Initially it will be necessary to investigate the quality of the proton focus. There may be complications due to dispersion of the protons, but excluding these, the measurements should occupy only 2 or 3 shifts.

2. Setting up a dispersed and focused pion beam will require the use of the spectrometer magnet (MA1) at 0°. A preliminary analysis will require between 10 and 20 shifts, but this depends critically on the results of item 1.

3. Measurements on the high-energy tail of pions produced by protons on B^{10} may require about 20 shifts.

4. Setting up the spectrometer at 25° should be relatively simple if the beam is well understood so that monochromatic particles can be selected. About 10 shifts will be needed for checking the system.

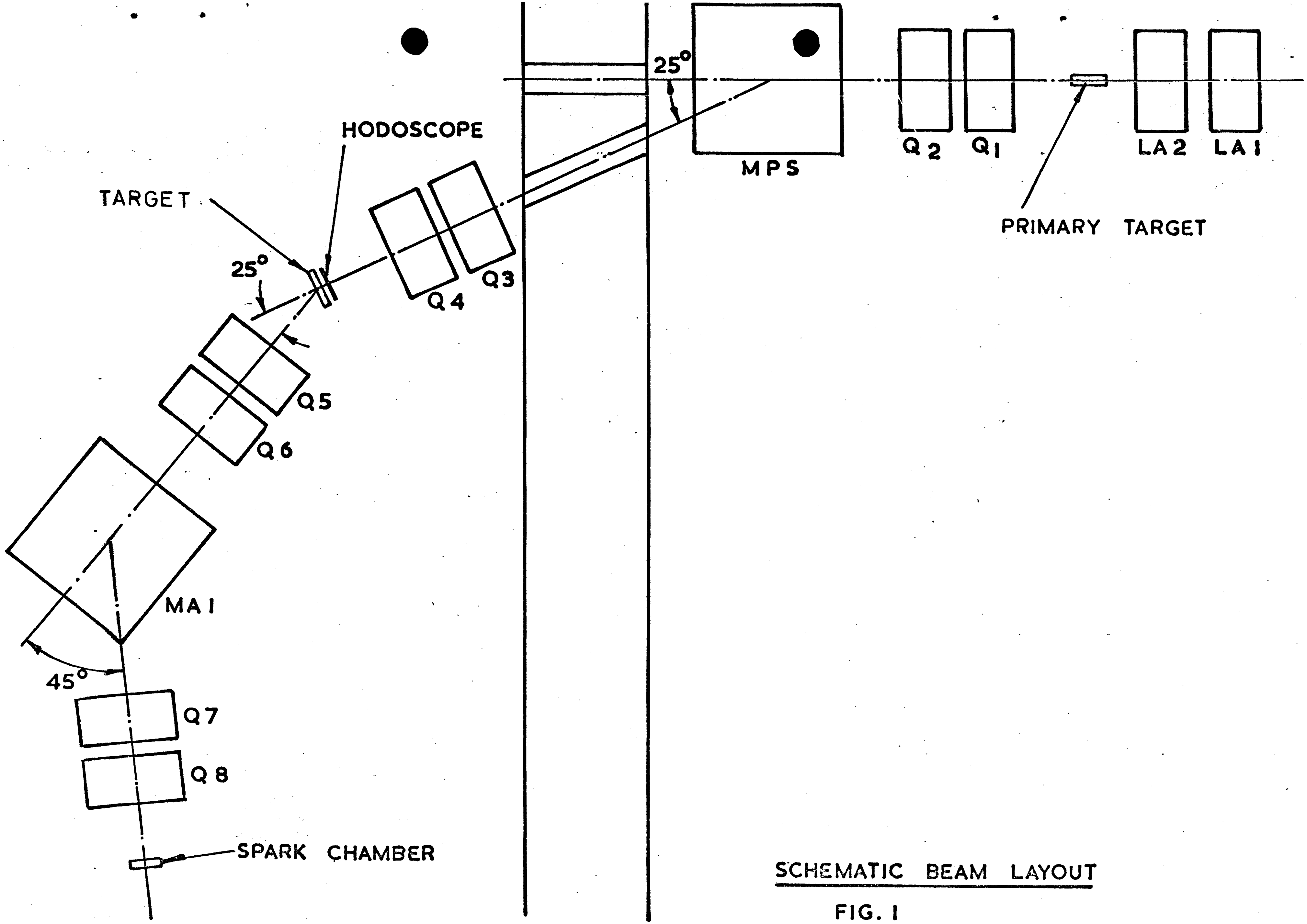
5. Inelastic pions and protons from pions incident on light nuclei should give count rates of the order of a few per minute for a cross-section of 1 mb sterad^{-1} for 10% momentum bite. In fact, the evidence from activation and a crude magnet measurement suggests that pion inelastic scattering excites a collective state of the nucleus at 20 to 30 MeV with a cross-section of several tens of mb/sr. A complete momentum spectrum of pions scattered at 25° from O^{16} with a few hundred counts per MeV will require about 20 shifts. A further 25 shifts will be necessary for a spectrum at 90°. The search for $N^{14}(\pi,\pi')N^{14*}$ (2.3 MeV level) and for $O^{16}(\pi^+,p)O^{15}$ will be very sensitive to background. We ask for 10 shifts for

the N^{14} measurement, 5 shifts to modify the spectrometer for protons and 15 shifts for the proton search.

6. There are various ways of improving the over-all energy resolution at the expense of beam intensity, perhaps with a limit of 0.3 MeV (0.1% in momentum). In the case of ^{16}O, this would resolve the dipole resonance structure. We ask for a nominal 25 shifts for this purpose.

TOTAL REQUEST

About 150 shifts during 1 year.



SCHEMATIC BEAM LAYOUT

FIG. 1

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REACTIONS OF PIONS WITH LIGHT NUCLEI *)

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The reaction of pions (π^+ and π^-) in the energy range from 80 to 280 MeV with a series of light nuclei from ^{9}Be to ^{18}O have been investigated. Reactions were identified by the residual radioactivity following pion bombardment.

Pions were obtained from the bombardment of polythene with 600 MeV protons extracted from the CERN Synchro-cyclotron. The intensity and quality of the pion beam varied drastically with momentum: at best a record 10^6 π/sec plus 10% muons and 5% protons with a momentum spread of 6%; at worst 2×10^4 π/sec with an equal number of muons and electrons and with a 20% momentum spread. In general the energy definition was 20 to 30 MeV and measurements were made at 20 MeV intervals with positive pions and, for intensity reasons, at only three energies with the negative pions. For each energy and particle the momentum distribution was determined by magnetic analysis, and composition by scintillator spectrum for the protons and Čerenkov spectrum for the muons and electrons. In addition measurements of total absorption by hydrogen (CH_2 minus C) gave a direct determination of the pion fraction, using the known hydrogen cross-section.

Most of the targets were about 1 gr/cm^2, thick which made a negligible contribution to the energy spread. The diameter of 5 cm was large enough to intercept essentially all the beam (focus about 5 cm^2). Measurements were made by bombarding a target, switching off the beam and simultaneously transferring the target to the shielded activity counters. The target transfer was essential to avoid background, but meant that the shortest lifetime that could be studied was 0.1 sec. Various arrangements of β and γ-ray counters were used for detecting the activities; the most common was two NaI scintillators in coincidence detecting positron annihilation.

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*) Work carried out at CERN, Geneva, Switzerland.

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Not very surprisingly all the results seem to reflect the influence of the 3-3 pion-nucleon resonance at 180 MeV, distorted in various ways. No evidence was observed of a structure finer than the 3-3 resonance in the excitation functions.

The detailed results that follow are distinctly preliminary as not all checks and corrections have been made. Probably the remaining corrections are not important but they might be.

THE PROCESS (π, π N)

This is the predominant interaction of pions with nuclei and probably accounts for a substantial fraction of the inelastic total cross-section. Two examples are shown: Figure 1 is the excitation function for $^{12}C(\pi^+, \pi^+n)^{11}C$ and Fig. 2 the excitation function for $^{9}Be(\pi^+, \pi^+p)^{8}Li$. together with the three points for $^{9}Be(\pi^-, \pi^-p)^{8}Li$. The form of the curves is in agreement with similar measurements by Reeden and Monkowitz on $^{12}C(\pi^-, \pi^-n)^{11}C$ and with the "quasi elastic" calculation of Shapiro for the π^- process. Qualitatively the curves look like a "knock-out" process with the 3-3 resonance broadened by the Fermi motion, and with the consequent displacement of the resonance peak to a lower energy being cancelled by binding energy effects. However, this simple model implies that the cross-section for (π^-, π^-n) should be three times larger than the sum of (π^+, π^+n) and (π^+, π^0p), which are not resolved by counting activities. In fact the ratios observed are very different from three:-

$^{12}C(\pi, \pi N)^{11}C$ $\quad \sigma^- : \sigma^+ = 1.03 \pm 0.1, \quad \sigma^+ = 72 \pm 7$ mb

$^{16}O(\pi, \pi N)^{15}O$ $\quad \sigma^- : \sigma^+ = 0.98 \pm 0.1, \quad \sigma^+ = 54 \pm 6$ mb

$^{9}Be(\pi, \pi N)^{8}Li$ $\quad \sigma^+ : \sigma^- = 1.96 \pm 0.1, \quad \sigma^+ \sim 25$ mb

all measured at $T_\pi = 180$ MeV. The quick answer, for ^{12}C and ^{16}O at least, is "final-state interaction" for the outgoing nucleon, but of a very extreme form. It might be better to rewrite the process e.g. $^{12}C(\pi, \pi')^{12}X\ (N)^{11}C$, where ^{12}X is probably the dipole resonance of ^{12}C or the analogue state of ^{12}N since the momentum transfer is small. The (π, π') interpretation finds support in two other observations: (a) a crude magnetic spectrometer examination of pions scattered by ^{12}C indicated some tens of mb/sr at 25° for excitation of ^{12}C to 20 to 30 MeV; (b) the reaction $^{11}B(\pi^+, \pi^0 n)^{10}C$ has been observed with a cross-section of ~ 1 mb which is most easily explained as $^{11}B(\pi^+, \pi^0)^{11}C^*(n)^{10}C$.

The π^+/π^- ratio for ^9Be is not obviously evidence for quasi-elastic scattering as ^9Be is not charge symmetric.

Processes such as (π^+, p) have been ignored above on the grounds that it is necessary to find a nucleon in the nucleus with a momentum of 500 MeV/c (c.f. the Fermi gas maximum of 250 MeV/c).

PION ABSORPTION

It is well known that pions are absorbed by a nucleus with the emission of a pair of nucleons. Conversely it was assumed that an activity resulting from the removal of a pair of nucleons indicated absorption. This may not be a particularly good guess for case $^{18}O \xrightarrow{\pi} {}^{16}N$ illustrated in Fig. 3, which could proceed either as $^{18}O(\pi, 2N)^{16}N$ or $^{18}O(\pi, \pi')^{18}O^*(p)^{17}N(p)^{16}N$. However, the shape of the curve appears to be somewhat different to the supposed (π, π') processes of Figs. 1 and 2. The magnitude of the cross-section for $^{18}O \rightarrow {}^{16}N \sim 16$ mb is similar to that for $^{10}B \xrightarrow{\pi^+} {}^{8}B \sim 15$ mb and $^{10}B \xrightarrow{\pi^-} {}^{8}Li \sim 12$ mb which is a little surprising as the removal of a neutron proton pair (^{18}O case) should be a good deal more probable than a neutron-neutron or proton-proton pair (^{10}B case).

CHARGE EXCHANGE

Activation identifies charge exchange uniquely and in some cases there are only one or two final states of the pion reaction which contribute to the activity.

Figure 4 shows the excitation function for $^{11}B(\pi^+, \pi^0)^{11}C$. The curve is approximately the form expected from the impulse approximation i.e. the 3-3 resonance broadened to a width of ~ 150 MeV with the peak displaced to about $T_\pi = 140$ MeV. The experimental points are not inconsistent with the impulse approximation, but the real test is the absolute cross-section which has not yet been calculated. Experimental cross-sections at $T_\pi = 180$ MeV are as follows:-

	σ	No. of bound state
$^{10}B(\pi^+, \pi^0)^{10}C$	0.9 mb	2
$^{11}B(\pi^+, \pi^0)^{11}C$	5.5 mb	10, including mirror state.
$^{13}C(\pi^+, \pi^0)^{13}N$	3.8 mb	1, mirror state
$^{14}N(\pi^+, \pi^0)^{14}O$	$\lesssim$ 0.05 mb	1, poor overlap with target ground state
$^{18}O(\pi^+, \pi^0)^{18}F$	3.1 mb	~ 19, including mirror state
$^{11}B(\pi^-, \pi^0)^{11}Be$	$\lesssim$ 0.4 mb	?
$^{19}F(\pi^-, \pi^0)^{19}O$	~ 1 mb^2	~ 5

The relative values of the (π^+, π^0) measurements ought to be quite reliable as both the beam and the activity counters were the same in all cases. It appears that the overlap of wave functions are remarkably important. The particular cases of ^{13}C and ^{14}N seem unambiguous as only one final state is involved and the overlap of initial and final wave functions is known from β-decay: for $^{13}C/^{13}N$ the square of the overlap integral is ~ 1 and for ^{14}N (ground state!)/$^{14}O \sim 10^{-4}$. The (π^+, π^0) cross-section ratio for ^{14}N: $^{13}C \lesssim 10^{-2}$ is surprisingly small considering that the momentum transfer is not necessarily zero. It is very doubtful whether the $^{14}N/^{13}C$ ratio will be reproduced by the impulse approximation.

A search for the double charge exchange process $^{18}O(\pi^+, \pi^-)^{18}Ne$ yielded an unsatisfactory upper limit of ~ 10^2 μb owing to background from ^{16}O in the target. The calculated cross-section for ^{18}Ne ground state is ~ 10 μb.

FIG 1

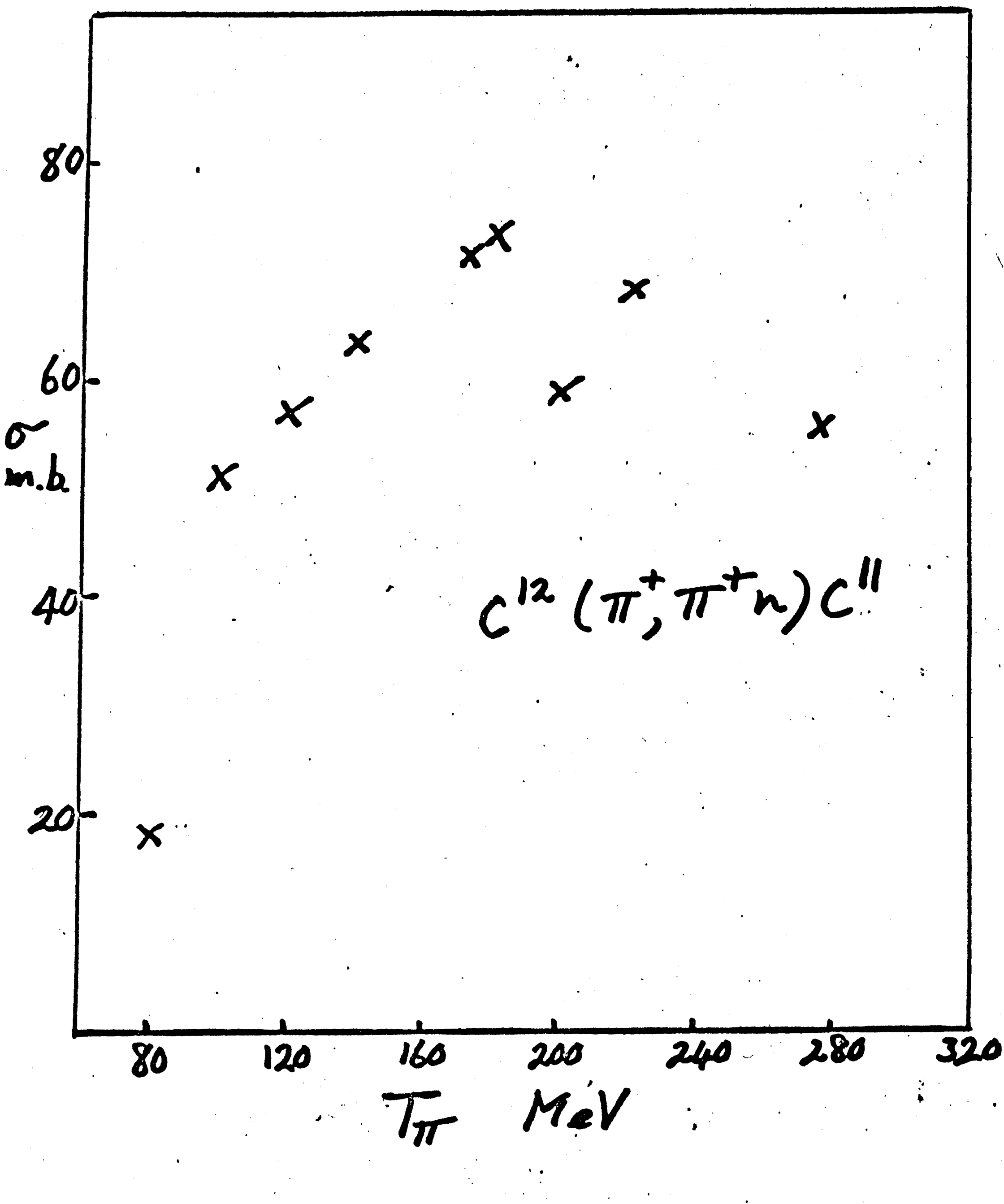


FIG 2

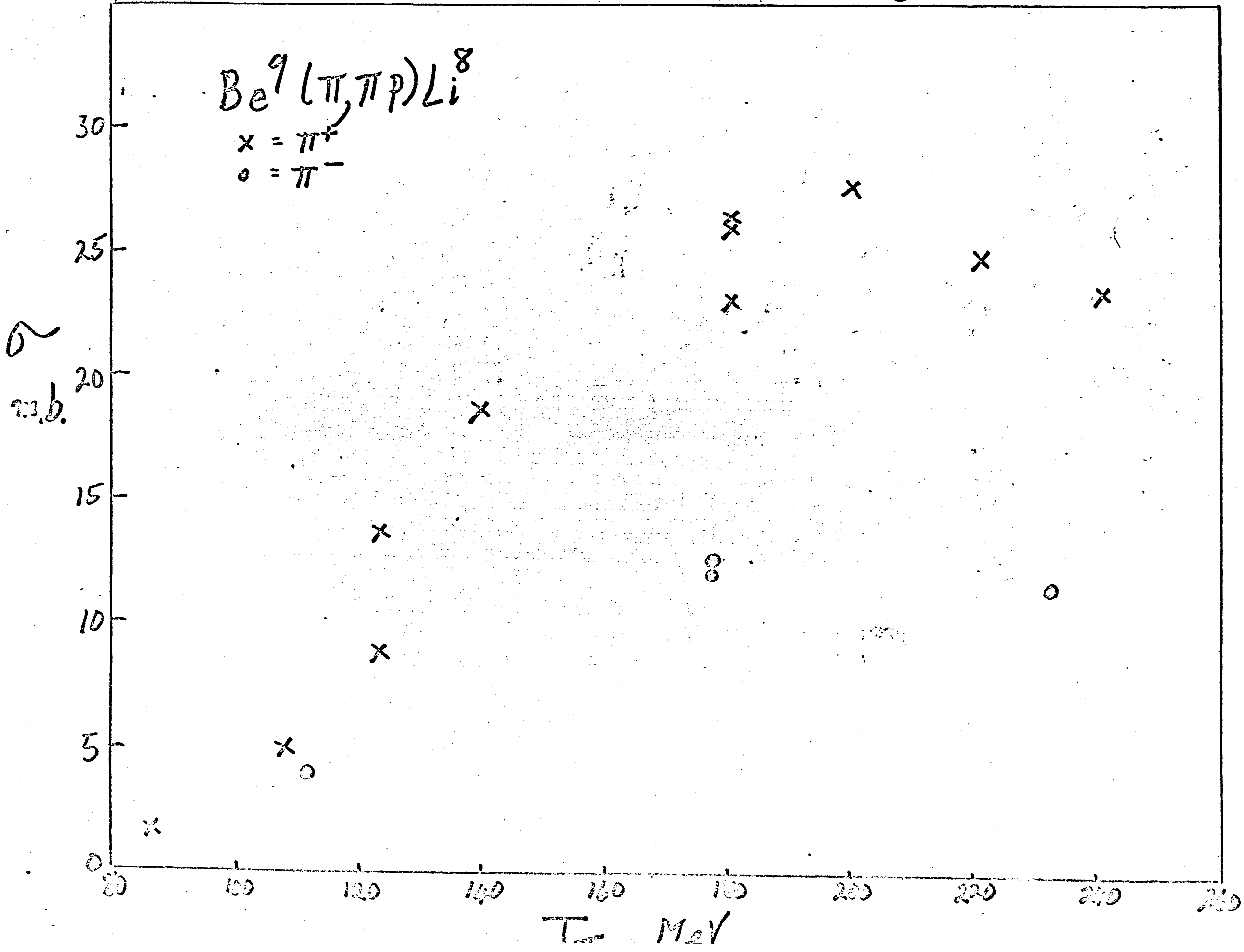
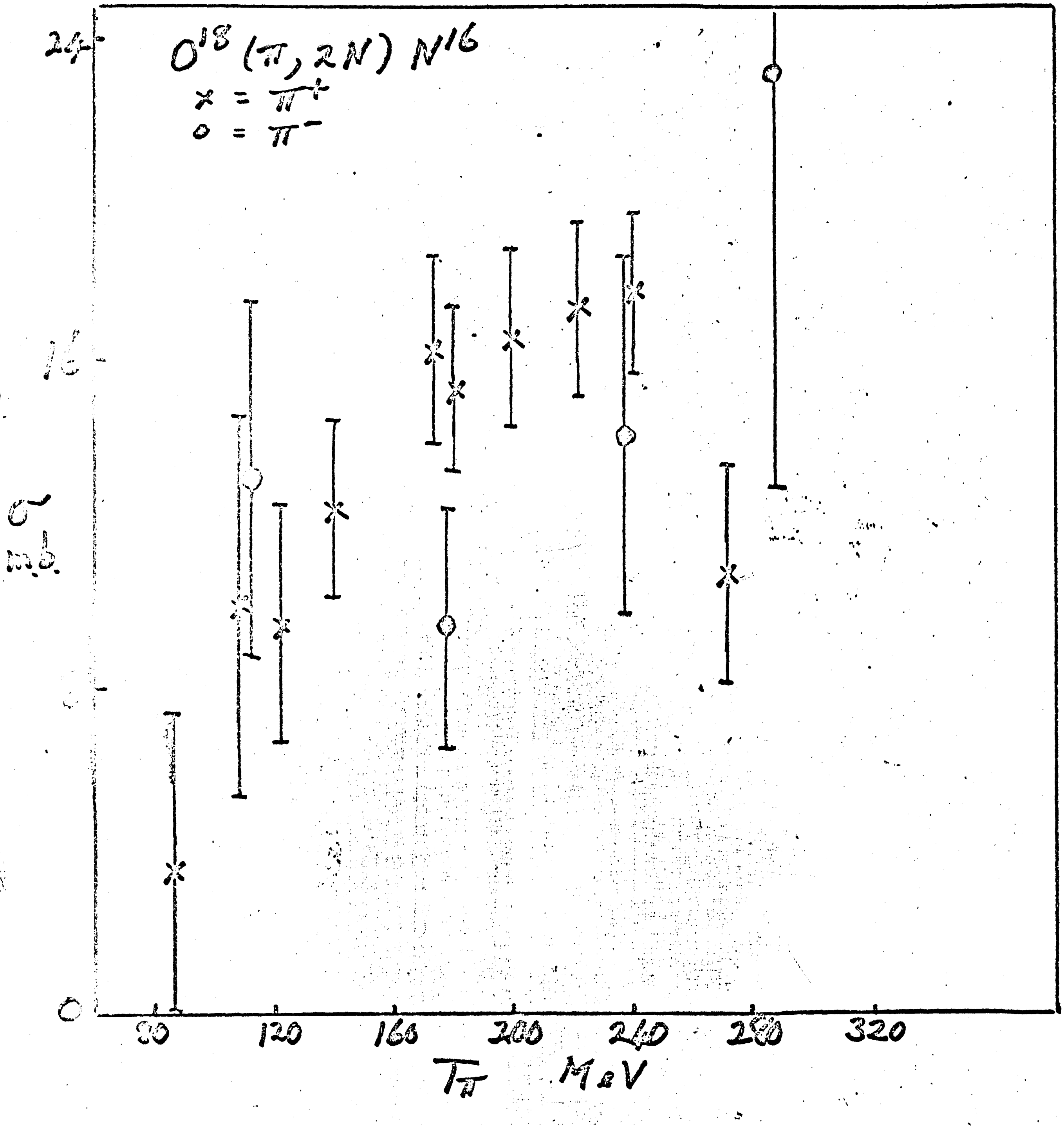
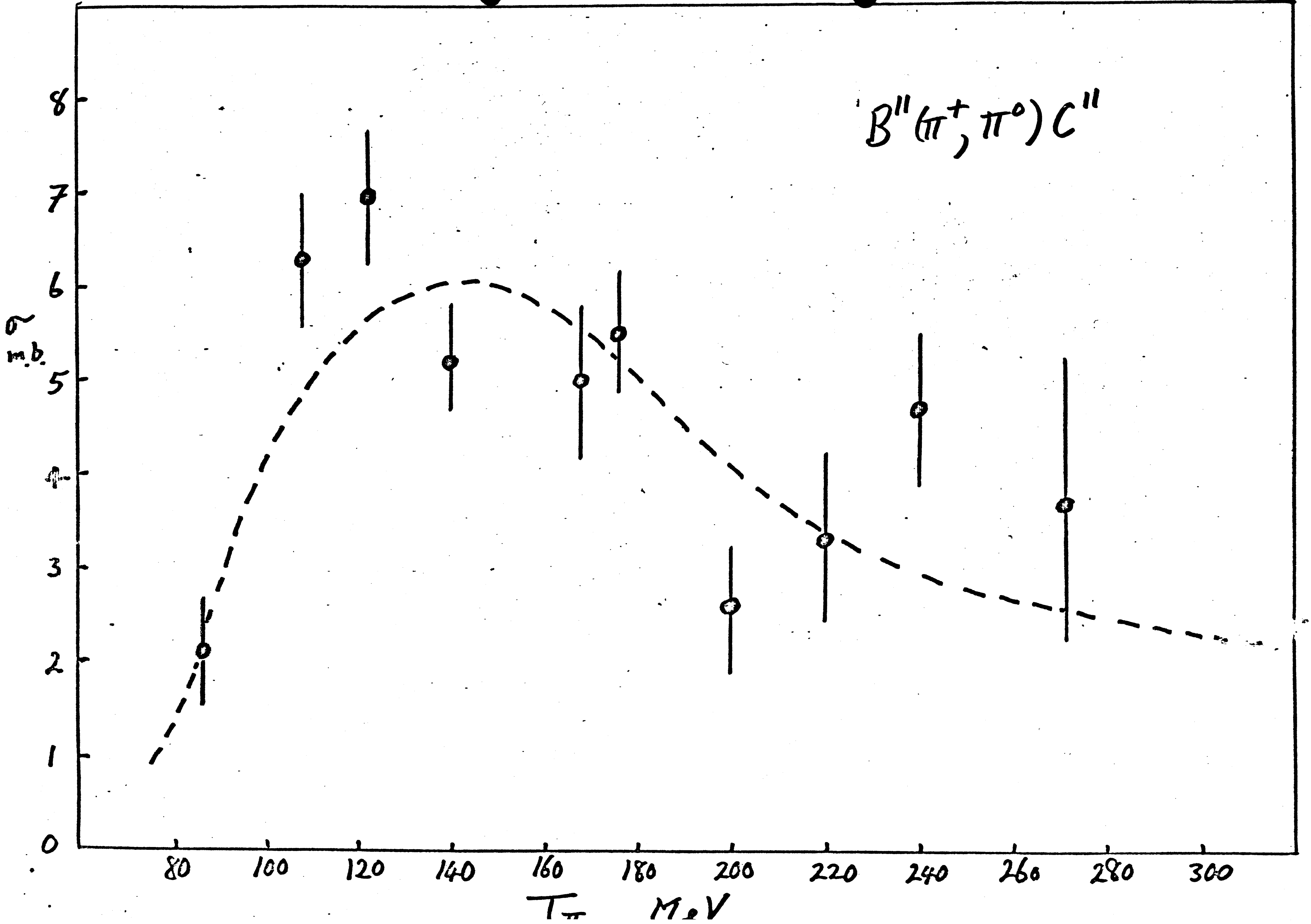

$Be^9(\pi,\pi p)Li^8$
x = π^+
o = π^-
σ m.b.
0
5
10
15
20
25
30
80
100
120
140
160
180
200
220
240
260
T_π MeV

FIG 3.



$O^{18}(\pi, 2N)\,N^{16}$
$\times = \pi^+$
$\circ = \pi^-$
24
16
8
0
σ mb.
80
120
160
200
240
280
320
T_π MeV

FIG 4.


$B^{11}(\pi^+,\pi^0)C^{11}$
σ m.b.
0
1
2
3
4
5
6
7
8
80
100
120
140
160
180
200
220
240
260
280
300
T_π MeV

4.8.67 NPRC A
NPRC Folder 16/8

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

MEMORANDUM

To : Members of the NPRC — Geneva, 3 August 1967

From : Tanner et al.

Re : <u>Proposal of Tanner et al. (PH III 67/20)</u>

The results of our preliminary beam tests, described in the revised machine time request, indicate that we should encounter no major difficulties in constructing a spectrometer system yielding a pion flux of at least 2 x 10^5 π^+'s per second at 250 MeV with a resolution of ≤ 1 MeV. In fact, because of the extremely small size of the primary proton focus, it seems probable that we can obtain a flux of 4 x 10^5 π's per second, by increasing the acceptance angle of the quadrupole lenses, with no appreciable sacrifice in energy resolution. The permissible flux increase depends on the lens abberations and this will be studied after substitution of the evacuated beam transport system in place of the previous helium bag system: multiple scattering from helium would otherwise obscure the effect of lens abberations.

At the present time all the major components of the spectrometer have been designed and are under construction. The target date for assembly and testing of the complete system is mid-September with on-line analysis of data available by mid-October.

The importance of constructing a high resolution π^+ beam when a high resolution π^- beam already exists has been questioned. Since we are mainly concerned with events dominated by the 3-3 resonance, it can be argued that π^+ scattering should be related to π^- scattering via isotopic spin considerations. While this is a perfectly reasonable argument, and simple models do indeed predict such a precise relation, the results of our activation experiments strongly disagree with these predictions. Namely, for single neutron knockout from a self-conjugate nucleus the activation measurements indicated that while the energy dependence of the cross-section was dominated by the 3-3 resonance, the ratio of the π^- to π^+ cross-sections was 1.0 ± 0.1 rather than 3 as predicted by the quasi elastic scattering model. In order to investigate the possible sources of disagreement with the simple quasi-elastic models, it is necessary to have both π^+ and π^- beams of high quality.

For example, in the case of neutron knock-out from O^{16} the activation measurements did not distinguish between the inelastic scattering processes $O^{16}(\pi^+,\pi^{+\prime},n)O^{15}$ and $O^{16}(\pi^+,\pi^\circ p)O^{15}$ and the pion absorption process $O^{16}(\pi^+,p)O^{15}$. While the possibility seems rather remote that the absorption process contributes strongly to the cross-section as determined by activation, we intend to investigate the $O^{16}(\pi^+,p)O^{15}$ process both as a possible source of the discrepancy with the predicted 3:1 ratio and as a means of studying the high momentum components of the neutron wavefunctions in O^{16}.

If the studies of the inelastic reaction O^{16} $(\pi^+, \pi^{+1} n) O^{15}$ yield a cross-section as large as that indicated by the activation measurements, it should be possible to make an unambiguous comparison of the π^+ and π^- scattering processes by using the charge conjugates of the reactions O^{16} $(\pi^+, \pi^{+1} n)$ O^{15} and O^{16} $(\pi^-, \pi^{-1} n)$ O^{15},

[i.e. $O^{16} (\pi^-, \pi^{-1}$ p) N^{15} and O^{16} $(\pi^+, \pi^{+1}$ p) N^{15}]and taking coincidences between the inelastically scattered pion and the outgoing proton. Thus it is clearly necessary to have both π^+ and π^- beams so that the coincidence experiments can both be performed with protons.

In summary, it is highly desirable to have good quality beams of both π^+ and π^- available at the SC for future nuclear structure studies. We feel that within the limitations imposed by pion production via the external proton beam, the spectrometer system we propose to assemble offers a reasonable compromise between flux and energy resolution and should be a valuable facility for future experiments. Since we desire to proceed as rapidly as possible to studying the 3:1 discrepancy, the rotating carriage for the magnet will, in the first instance, be "inelegant" but this can obviously be upgraded once the system has proved its effectiveness. Barring a major catastrophe, we should be able to complete the experimental programme contained in our proposal by September 1968. If the coincidence experiments look feasible on the basis of our studies of π^+ inelastic scattering we hope to be able to undertake them late next year.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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