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A MEASUREMENT OF THE SPIN-FLIP PROBABILITY IN NEGATIVE PHOTOPION PRODUCTION FROM DEUTERIUM

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Abstract

Negative pions photoproduced from deuterium (i.e., from the neutron) by the bremsstrahlung of the Berkeley synchrotron have been investigated by observing pion-proton coincidences. A $(CD_2)n - (CH_2)n$ subtraction yields the neutron contribution. The purpose of the investigation is to determine how often the initial triplet spin state of the deuteron changes to a singlet spin state for the two final identical nucleons in the reaction $\gamma + d \rightarrow \pi^- + p + p$. R.E. LeLevier has calculated the pion-energy spectra under two assumptions: (a) the spin state always remains the same, and (b) the spin state always changes. The experimental measurements are integral over meson energy from a lower limit upwards, and over the time of flight between the proton and the pion, within the resolution time of the coincidence system. Thus, when the theoretically predicted spectra are folded into the experimental resolution of the equipment and the bremsstrahlung spectrum, there results a number proportional to the experimental measurement. The ratios of various experimental measurements can be compared with the theoretically predicted ratios. Within the limitations of the theory and the accuracy of the experimental measurements, the results indicate an interaction that is intermediate between the spin state's always changing and the spin state's never changing. (This work was completed in the first half of 1953.)

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Introduction

Abstract

The problem of nucleon spin flip in the photoproduction of pions from deuterium is certainly one of the most interesting in this field; however, little experimental progress has been made.

Originally it was hoped that the present rough measurements would be refined; however, owing to the erratic character of the synchrotron beam intensity this has not been possible; the original investigators have moved on and this experiment is no longer being actively pursued. Because no reports of similar work have appeared, it was decided to publish the present crude results. The work reported here was completed in the first half of 1953, and is condensed from an unpublished report.[1]

The fact that the plus-minus ratios of photon-produced pions were close to unity and independent of angle and energy suggested that the photon interaction with the magnetic moment of the nucleon was important.[2] This naturally raised the question, what is the nucleon-spin dependence of production? In the phenomenological meson theory that was adopted to provide a framework for this question, the interaction Hamiltonian is assumed to be made up of two components, $H = L + (\vec{\sigma} \cdot \vec{K})$, where L and $\vec{K}$ are the amplitudes of the non-spin-flip and the spin-flip components, respectively.

*This work was performed under the auspices of the U.S. Atomic Energy Commission.

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[1] K. C. Bandtel, Characteristics of the High-Energy Negative Photopions from Deuterium (Thesis), UCRL-2324, July, 1953.

[2] K. A. Brueckner, Phys. Rev. 79, 641 (1950).

Previous Investigations

A number of theoretical predictions have been made that one could determine the relative amounts of these two components by comparing the ratio of π^+ production from deuterium with that from hydrogen. The idea is, of course, that in production from deuterium the Pauli principle excludes certain states, depending on whether the spin flips or does not, whereas production from hydrogen is not affected. Consider the reaction $\gamma + d \rightarrow \pi^{\pm} + 2$ nucleons. Considering states of the two final nucleons, we find that

$$^1S,\ ^3P,\ ^1D,\ ^3F,\ \ldots \text{ are allowed}$$

$$^3S,\ ^1P,\ ^3D,\ ^1P,\ \ldots \text{ are excluded}$$

by the Pauli exclusion principle.

It is evident that if one could select only that final state in which the two nucleons are in a pure S state then the reaction would proceed if spin flip were allowed, and it would be inhibited if spin flip were forbidden. This is the basis of the method.

Three-body kinematics show that this S-state condition of the two final nucleons occurs most often

(a) at threshold,

(b) when the meson is emitted forward,

(c) near the upper end of the meson spectrum (for a given photon energy).

Previous investigations[3,4,5] have all compared experimental deuterium-to-hydrogen cross-section ratios to theoretical predictions.[6,7]

---

[3] Lebow, Feld, Frisch, and Osborne, Phys. Rev. 85, 681 (1952).

[4] White, Jacobson, and Schulz, Phys. Rev. 88, 836 (1952).

[5] Hagerman, Crowe, and Friedman, Phys. Rev. 106, 818 (1957).

[6] Chew and Lewis, Phys. Rev. 84, 779 (1951).

[7] Lax and Feshbach, Phys. Rev. 88, 509 (1952).

A great many other peiple have calculated essentially the same thing and hence will not be listed here. Lax and Feshbach assume that the two final nucleon wave functions are plane waves, thus neglecting the important low-energy nucleon interaction that would tend to augment their prediction. Chew and Lewis usually make the same approximation, but for some calculations they employ a "Closure Approximation" which sums over some final states not actually allowed by energy and momentum conservation. They state that his tends to compensate the neglect of final-state interaction mentioned just previously. It should be noted that this neglect of final-state interaction is important when the two final nucleons are in an S state. The spin dependence is also most evident experimentally (because of the Pauli principle) in exactly the same circumstance. It is acknowledged by both authors that this approximation may not be justified. One should bear this in mind when comparing these predictions with experimentally measured ratios. Neglect of the multiple scattering of the outgoing pion (in the case of deuterium, but not hydrogen) is an additional difficulty with these calculations.[8] Crowe's article refers to calculations being made by J. J. Tieman, which presumably will correct some or all of these difficulties.

Lebow et al. present the D-H ratio as a function of pion laboratory-system angle (integrated over energy).

White et al. present the D-H ratio as a function of pion energy for various lab angles.

Crowe et al. present the ratio as a function of lab angle, and also show all the previous experimenters' points (with White's data integrated over meson energy). All experimenters show their measured values compared with the theoretical predictions by Chew and Lewis, or Feshbach and Lax. The theoretical curves shown in all these papers assume a plane wave for the wave function of the two final nucleons.

If one wants to take the statistics seriously, then in general the results at angles near 90° are in accord with no spin flip, while the results at angles near 30° are in accord with all spin flip. On the other hand, one can be conservative and say tha the data at forward angles favor spin flip somewhat, while at backward angles the accuracy is not good enough to distinguish between them. Within statistics, one could say that all the experiments are in agreement.

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[8] K. A. Brueckner, Phys. Rev. 89, 834 (1953).

It is the authors' opinion that one cannot conclude very much about spin flip from these data until the theoretical treatment is more realistic; however, there is general agreement with either the flip or no-flip prediction, and one may be able to conclude, as White points out, that these data support the validity of the impulse approximation.

LeLeviers Calculated Spectra

The experiment presented here is compared with calculations by LeLevier.[9] LeLevier's predicted spectra are integrated over the variables as determined by the particular experimental arrangement, thus giving a number to compare with our experimental number. An integral experiment may not be as satisfactory as a differential experiment, but a conclusion can be drawn just the same. If this experiment were to be pursued, a differential experiment would be the next logical step.

LeLevier calculated the spectrum of negative pions produced by monoenergetic photons on deuterium, subject to the conditions that the pion be at 120° (lab), and one of the protons be at 20° (lab) (the reason for this is elucidated in the next section). For the experimental arrangement see Fig. 1. The calculation was carried out on the basis of the same assumptions as made by Chew and Lewis and by Lax and Feshbach, except for one important addition: LeLevier treated the S state of the two final neutrons by fitting data from low-energy p-p scattering. The essence of our experimental method is that certain three-body kinematical conditions are sensitive to the spin flipping, while others are not; hence, by comparing this ratio we get a measure of the spin flip, using only deuterium. Note that multiple-scattering corrections to the impulse approximation are not involved if they are independent of the energy of the outgoing pion.

A typical calculated pion spectrum is shown in Fig. 2. Note the large broad maximum centered about the energy appropriate to production from a free neutron at rest. The spin-flip effect is manifested near the upper pion-energy limit, since this corresponds to a low relative-energy state of the two protons. However, the two protons do have an appreciable energy in the laboratory system (they are essentially recoiling as one particle), and thus their detection with counters is feasible.

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[9] R. E. LeLevier, Phys. Rev. 85, 771 (1952); also private communications.

Experimental Method and Results

The method developed out of investigations that the authors had been making of pion-proton coincidences from deuterium,[10,11,12] which indicated coincidences could be observed that were centered about the angles which would be predicted if the neutron were free. Other investigations of pion-proton coincidences have been made by Keck and Littauer.[13,14] Figure 3 shows these correlated angles as a function of photon energy. They do not change very much from 240 Mev to 320 Mev. Figure 4 shows the three-body kinematics, calculated for a given photon energy. We see that the relative energy decreases monotonically as we approach the maximum possible pion energy, as stated earlier. At this point the two nucleons, in effect, recoil as one particle. For convenience in discussion we refer to the "free-production peak" and the "spin-flip spike"--recognizing, of course, that in reality there is a gradual transition between the two conditions. These are the points corresponding to the two maxima shown in Fig. 2. Figure 5 shows a plot of these as a function of photon energy. Referring back to Fig. 4, we see that (for this particular photon energy) the proton (at 20°) associated with the free-production condition carries off about 80 Mev, whereas for the spin-flip condition the proton moves with about 20 Mev. This energy difference suggests that a time-of-flight measurement could be used to separate these two types of protons. In Fig. 5, there is a line drawn at 57 Mev and another at 80 Mev. Since the bremsstrahlung upper limit is 322 Mev, we can see that by using only absorbers to specify the lower energy limit of the pions as indicated, one would be able to partially separate the spin-flip condition.

Figure 6 shows the combined effect of proton time of flight and pion energy selection. The measurements will be denoted in the following way.

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[10] Madey, Bandtel, and Frank, Phys. Rev. 85, 771 (1952).

[11] R. Madey, The Photoproduction of Negative Pions from Deuterium (Thesis), UCRL-1634, Jan. 1952.

[12] Bandtel, Frank, and Madey, Phys. Rev. 91, 487 (1953).

[13] Phys. Rev. 86, 602A (1952).

[14] Phys. Rev. 88, 139L (1952).

Measurement	Minimum pion energy (Mev)	Relative pion-proton delay (10^{-9} sec)
A	57	6.38
B	57	12.24
C	80	6.38
D	80	12.24

Measurements B and D are designed to emphasize the spin-flip effect.

Measurements A and C are designed to provide a control point--either all flip or no flip should predict nearly the same thing.

The following experimentally measured ratios were obtained (probable errors quoted):

$$\frac{B}{A} = 0.08 \pm 0.02,$$

$$\frac{C}{A} = 0.26 \pm 0.03 ,$$

$$\frac{D}{A} = 0.017 \pm 0.007 .$$

Interpretation of Data

In order to obtain numbers that can be compared with our experimental numbers, we must start with the calculated spectra of LeLevier and fold in the experimental resolution of the equipment with respect to (a) time-of-flight resolution, using the experimentally measured resolution function, (b) pion-energy lower limit, (c) pion corrections (multiple scattering, decay in flight, nuclear absorption), (d) bremsstrahlung spectrum (corrected for finite expulsion time and for the occurence of expulsion before peak magnetic field), (e) finite target thickness (causing time-of-flight dispersion). The excitation function was taken to be constant over this energy range.[15,16]

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[15] J. Steinberger and A.S. Bishop, Phys. Rev. 86, 171 (1952).

[16] Walker, Teasdale, Peterson, and Vette, Phys. Rev. 99, 210 (1955); Tollestrup, Keck, and Worlock, Phys. Rev. 99, 220 (1955).

To write down mathematical expressions for all these things would not add much to the discussion, because the volume of the numerical calculations that were done would make it impossible to present them. These calculations are detailed at greater length in UCRL-2324[1] for those persons particularly interested. The results of these calculations are

$$\frac{B}{A} = \begin{matrix} 0.140\text{--flip} \\ 0.00816\text{--no flip} \end{matrix}$$

$$\frac{C}{A} = \begin{matrix} 0.215\text{--flip} \\ 0.228\text{--no flip} \end{matrix}$$

$$\frac{D}{A} = \begin{matrix} 0.0427\text{--flip} \\ 0.0078\text{--no flip} \end{matrix}$$

These results are plotted and compared with the experimentally measured numbers in Fig. 7.

Conclusions

This experiment seems to indicate an interaction intermediate between all flip and no flip. Or, saying this another way, we can "explain" the experimental result within the framework of the theory used here by a proper choice of the ratio between flip and no-flip amplitudes.

Acknowledgments

It is a pleasure for us to acknowledge many helpful discussions with Dr. LeLevier, and in addition the wholehearted cooperation and support of all the people and services at the Berkeley Laboratory that helped to make this experiment possible.

LEGENDS

Fig. 1. Experimental arrangement.

Fig. 2. Example of a theoretically predicted meson spectrum.

Fig. 3. Free production angular correlation for various photon energies.

Fig. 4. Three body kinematics of the reaction $\gamma + d \rightarrow \pi^- + p + p$ for a photon energy of 280 Mev.

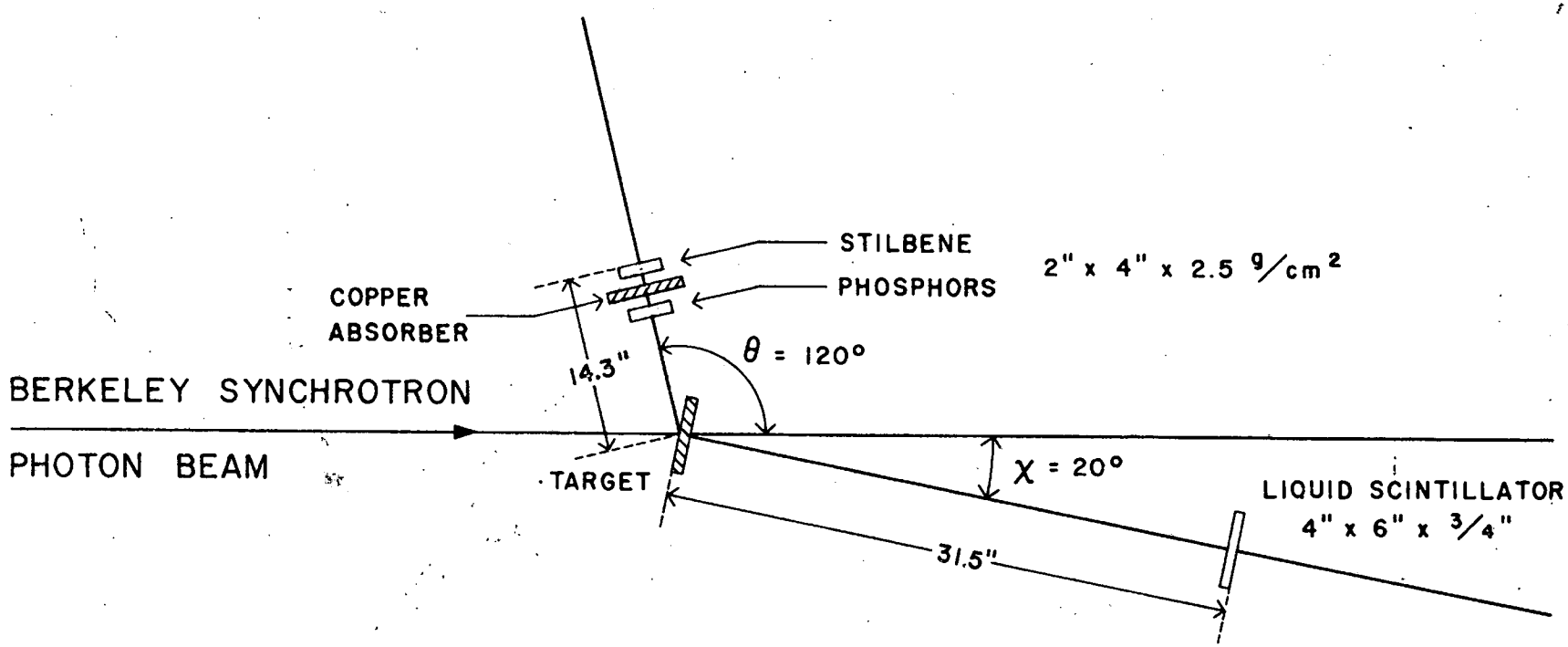
Fig. 5. "Free production peak" and "spin flip spike" vs photon energy.

Fig. 6. Effect of proton time of flight and pion energy selection on three body kinematics.

Fig. 7. Results - comparison of predictions with measurements.

EXPERIMENTAL ARRANGEMENT

$\gamma + d \longrightarrow \pi + p + p$



208101

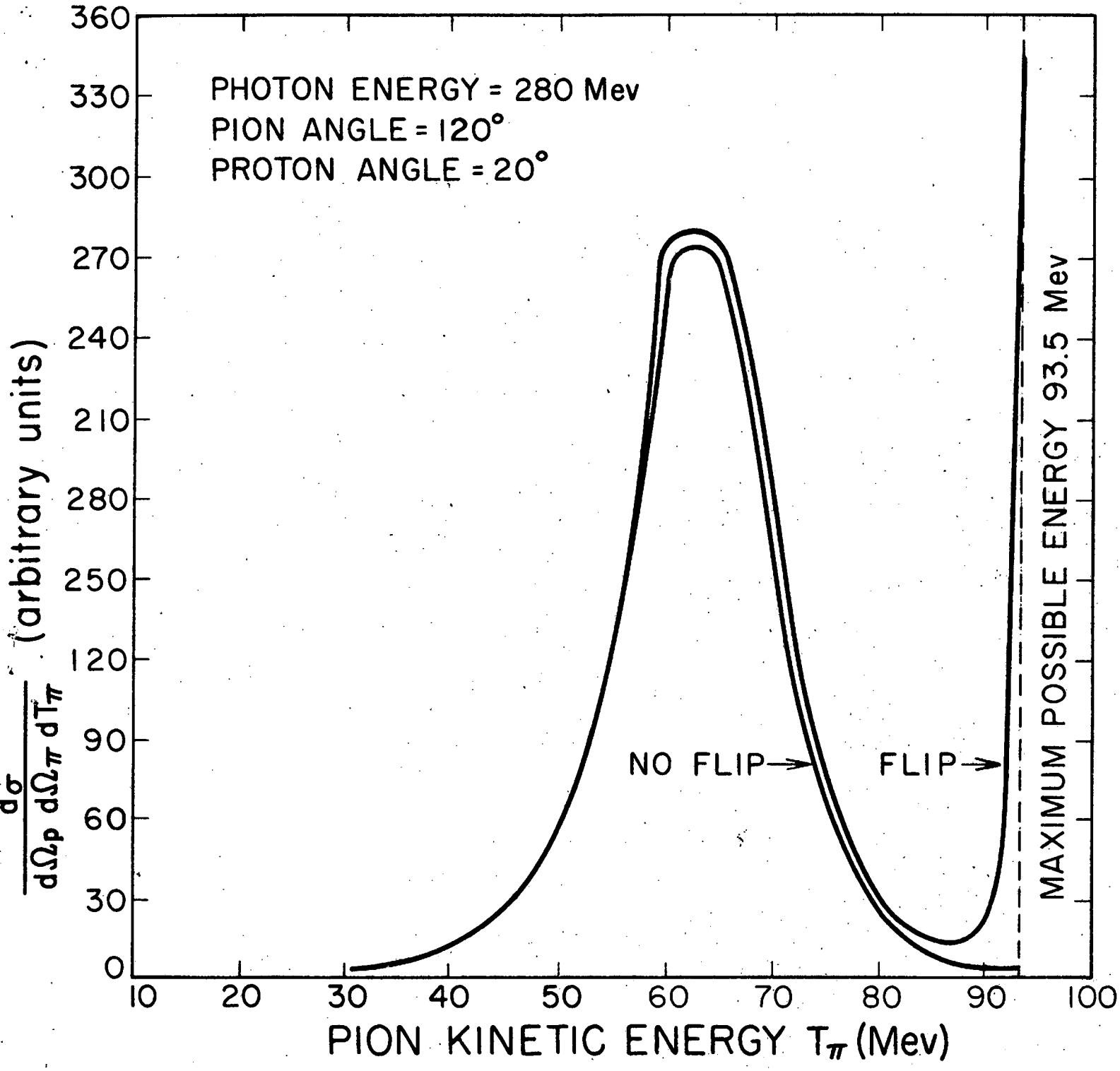
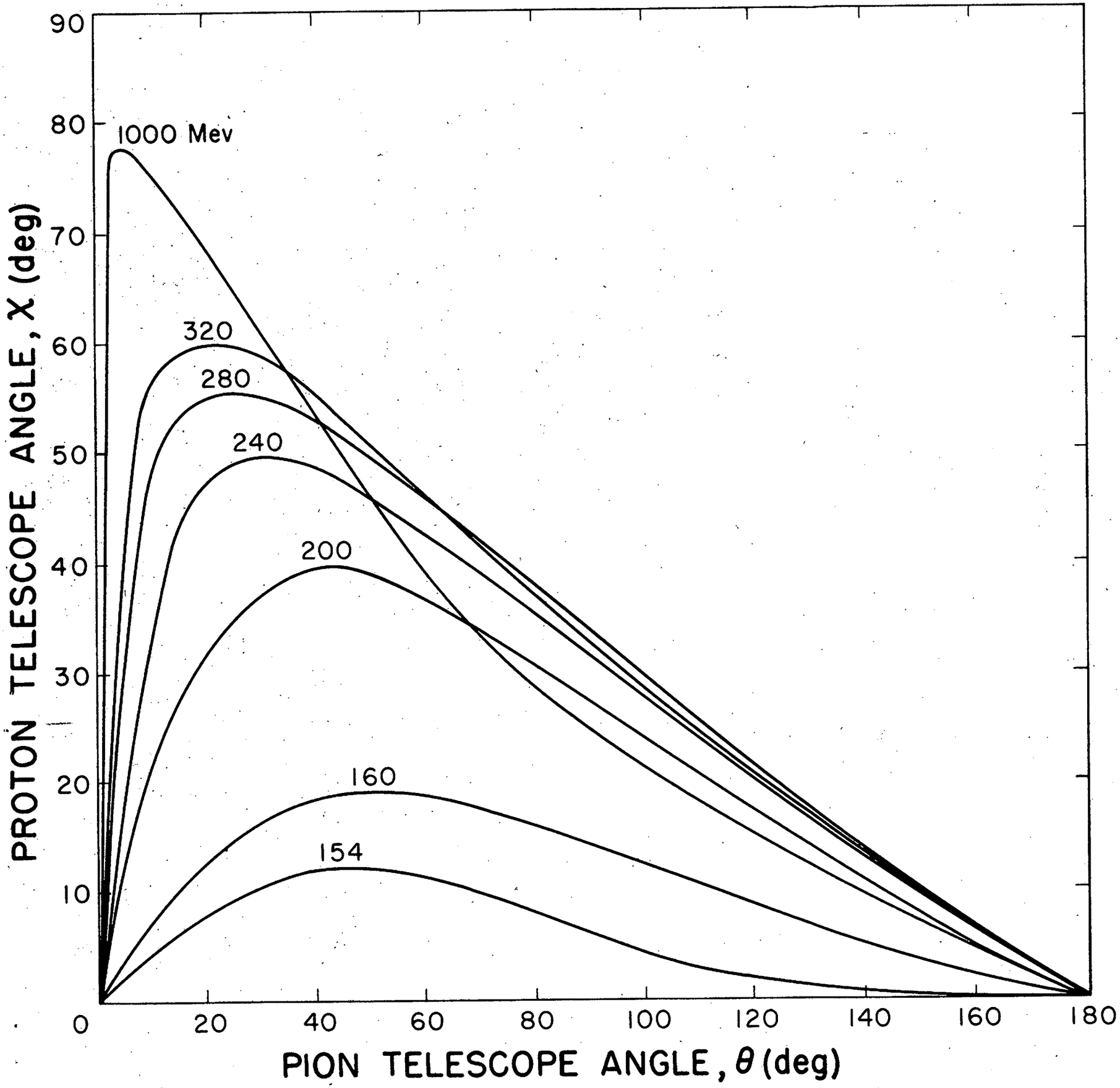


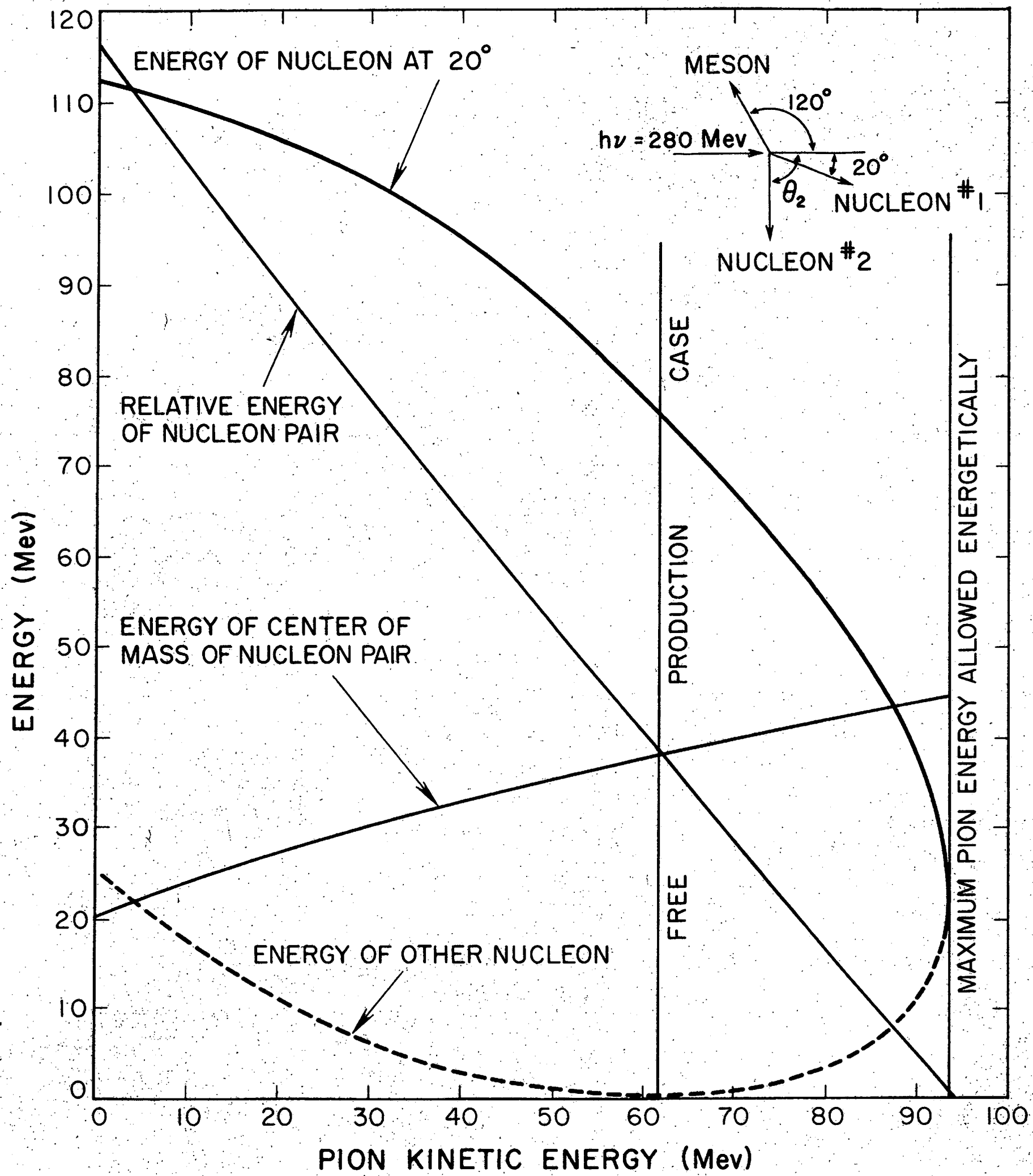
Fig 2

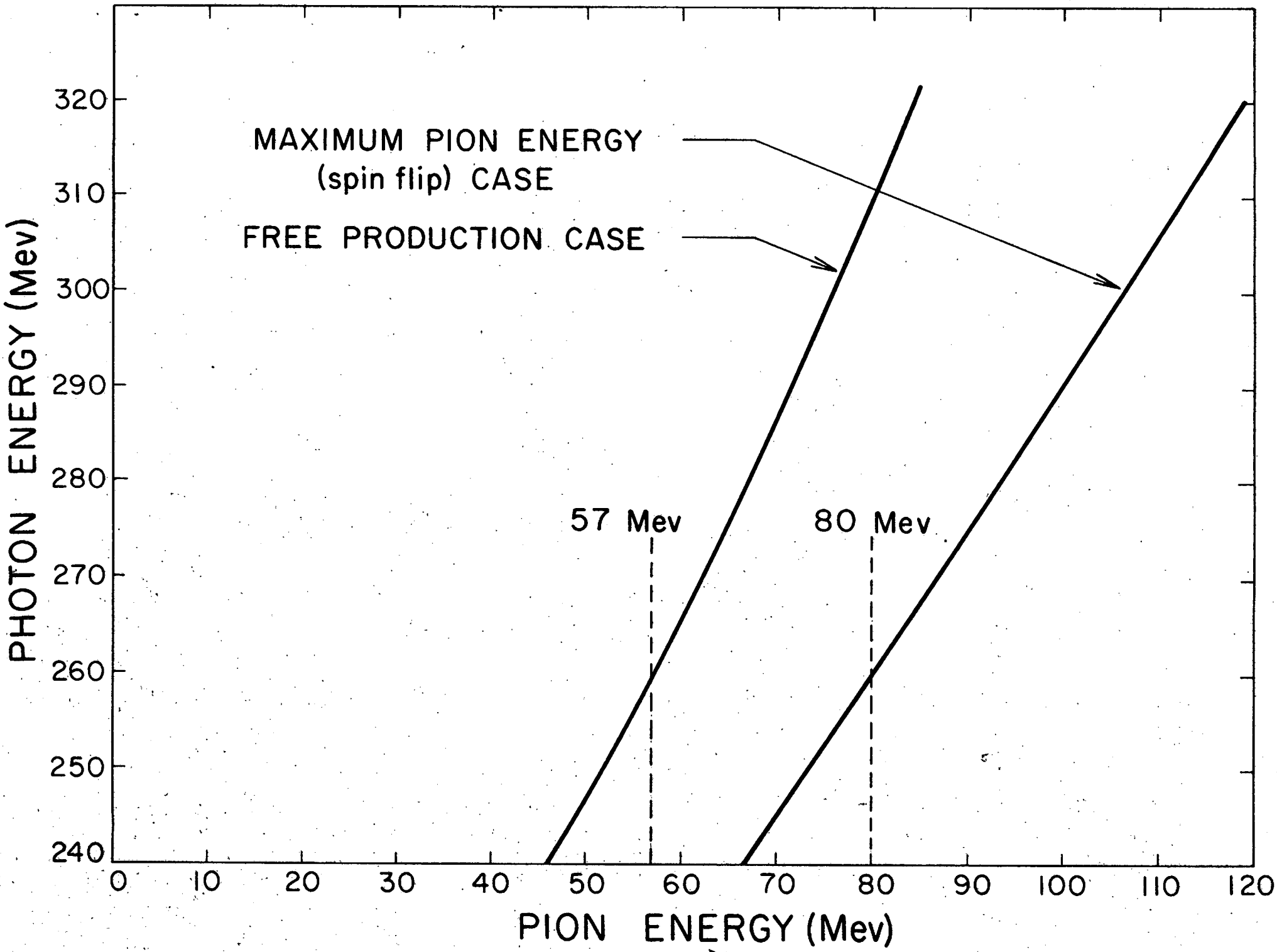
MU-5281

208091


1000 Mev
320
280
240
200
160
154
PROTON TELESCOPE ANGLE, χ (deg)
PION TELESCOPE ANGLE, θ (deg)
0
10
20
30
40
50
60
70
80
90
100
120
140
160
180

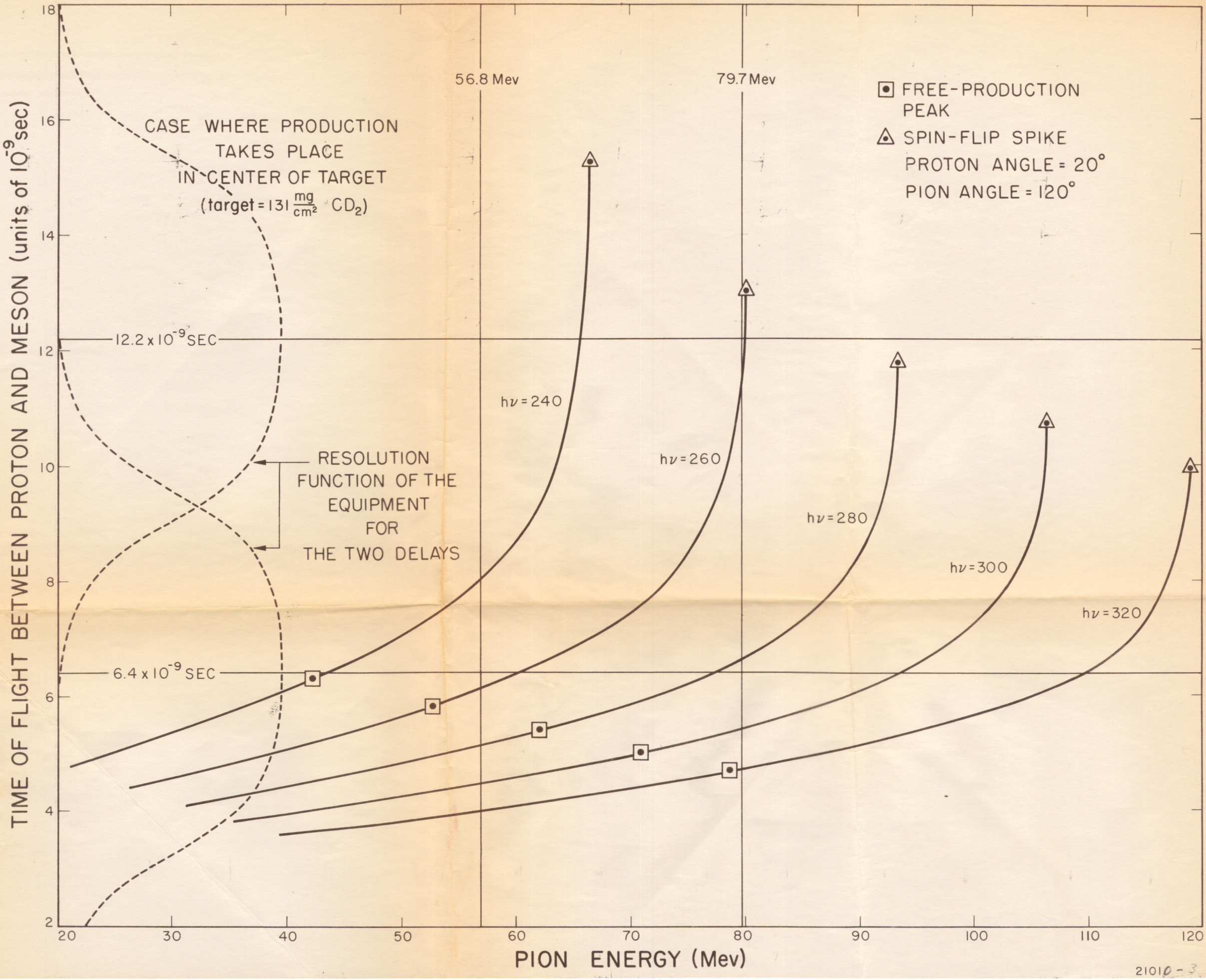
3


ENERGY OF NUCLEON AT 20°
MESON
120°
hν = 280 Mev
20°
θ2
NUCLEON #1
NUCLEON #2
RELATIVE ENERGY
OF NUCLEON PAIR
ENERGY OF CENTER OF
MASS OF NUCLEON PAIR
ENERGY OF OTHER NUCLEON
FREE PRODUCTION CASE
MAXIMUM PION ENERGY ALLOWED ENERGETICALLY
ENERGY (Mev)
PION KINETIC ENERGY (Mev)
0
10
20
30
40
50
60
70
80
90
100
110
120

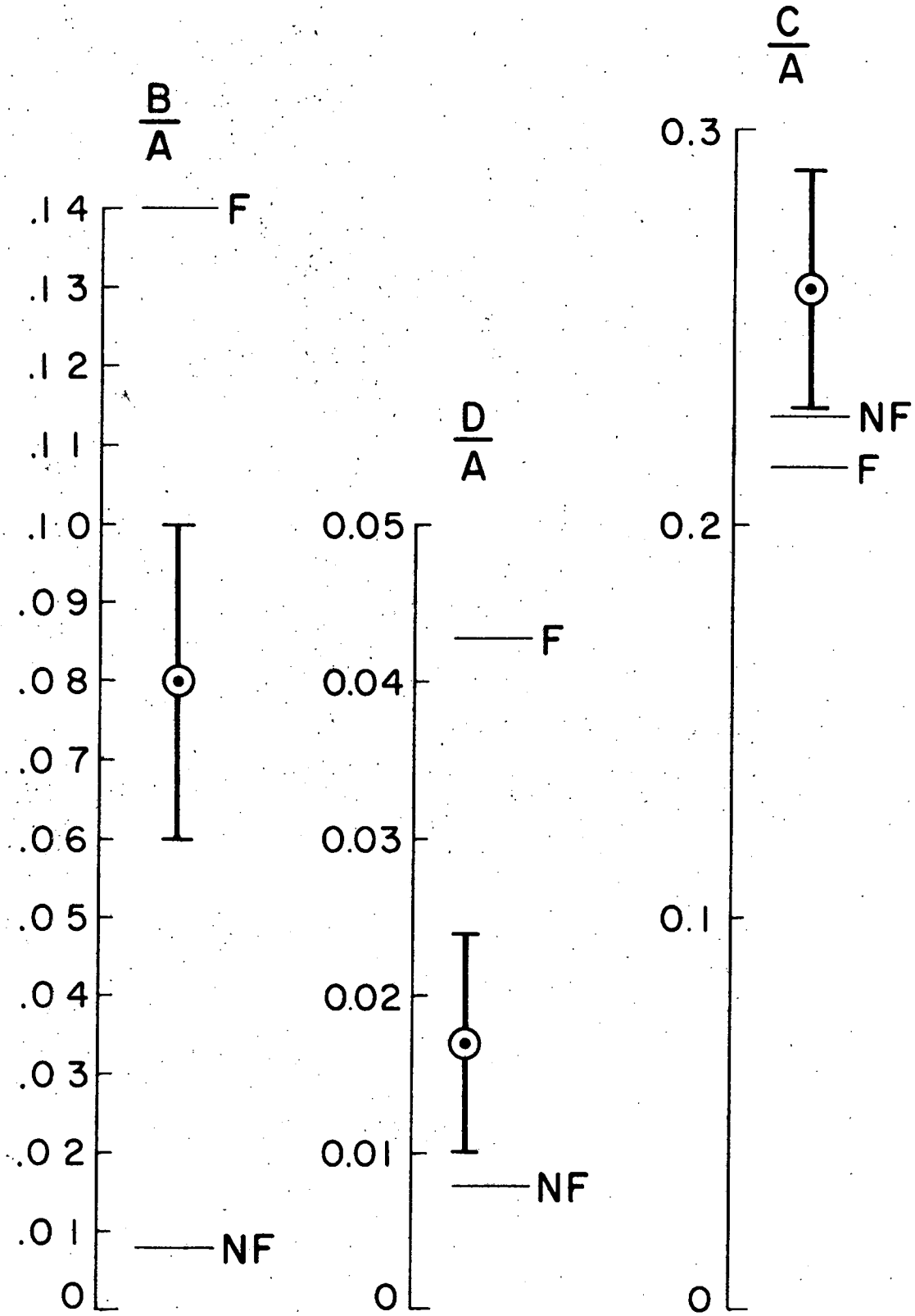

MAXIMUM PION ENERGY
(spin flip) CASE
FREE PRODUCTION CASE
57 Mev
80 Mev
PHOTON ENERGY (Mev)
PION ENERGY (Mev)
320
310
300
290
280
270
260
250
240
0
10
20
30
40
50
60
70
80
90
100
110
120

F-5

51907-1


TIME OF FLIGHT BETWEEN PROTON AND MESON (units of 10^{-9} sec)
PION ENERGY (Mev)
56.8 Mev
79.7 Mev
FREE-PRODUCTION PEAK
SPIN-FLIP SPIKE
PROTON ANGLE = 20°
PION ANGLE = 120°
CASE WHERE PRODUCTION TAKES PLACE IN CENTER OF TARGET
(target = 131 $\frac{mg}{cm^2}$ CD_2)
12.2×10^{-9} SEC
6.4×10^{-9} SEC
RESOLUTION FUNCTION OF THE EQUIPMENT FOR THE TWO DELAYS
$h\nu = 240$
$h\nu = 260$
$h\nu = 280$
$h\nu = 300$
$h\nu = 320$
2
4
6
8
10
12
14
16
18
20
30
40
50
60
70
80
90
100
110
120

21010-3


B/A
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
.03
.02
.01
0
F
NF
D/A
0.05
0.04
0.03
0.02
0.01
0
F
NF
C/A
0.3
0.2
0.1
0
NF
F

397

212492