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PROTON-DEUTERON BREMSSTRAHLUNG AT 145 AND 195 MeV

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Energy spectra and angular distributions have been measured for high energy gamma rays ($E_\gamma \geq 20$ MeV) from the p + d reaction at 145 and 195 MeV. Gamma rays were observed up to the maximum energy allowed by kinematics. A comparison is made with previous measurements for the p + d system at 140, 197 and 200 MeV. Below the free $pn\gamma$ threshold the general shape of the energy spectra and angular distributions are in reasonable agreement with a recent calculation of the free $pn\gamma$ elementary process. However, the magnitude of the predicted cross section is not in good agreement with the present data.

I. INTRODUCTION

Reports on hard photon production by several research groups [1–6] prompted investigations which covered the periodic table from light systems, such as d + C [7] to heavy systems, such as Xe + Sn [8]. Incident beam energies have ranged from E/A = 10 MeV to E/A =124 MeV. The characteristics of photon emission for the majority of these studies strongly suggest that the main source of the radiation is first-chance proton–neutron bremsstrahlung. Proton–proton bremsstrahlung is expected to play a minor role in this energy regime. With all the interest in the heavy-ion data it is quite suprising that there is little information on proton–nucleus bremsstrahlung [9–11]. Unfortunately, there is even less data on free pnγ, and the published data that does exist is with poor statistics [12–14]. Lacking incontrovertible data on the free pnγ cross section, information on the cross section can still be gleaned by studying proton–nucleus bremsstrahlung. As was described in an accompanying paper on high gamma ray production in proton–nucleus collisions [15] the phase space problem is more tractable than in the nucleus–nucleus case.

In this paper we report on p + d bremsstrahlung (pdγ) at incident proton energies of 145 and 195 MeV. The pdγ reaction is important because the reaction makes the transition between the elementary pnγ reaction and the proton–nucleus bremsstrahlung. For low and intermediate energy photons the pdγ result should be a good approximation to the free pnγ cross section, while at energies above the kinematic limit for free pnγ the gamma ray production cross section should reflect the influence of the internal momentum distribution in deuteron. Comparisons between the deuteron results and the heavier targets is the best way to obtain information on the importance of multistep collision processes in proton–nucleus bremsstrahlung reactions and phase space considerations. These ideas can then be extended to explain the nucleus–nucleus bremsstrahlung data.

Previously there have been three pdγ measurements reported in the literature [9, 16, 17]. Edgington and Rose [9] used a 140 MeV proton beam at Harwell to study inclusive photon production. In this measurement they employed a (D_2O - H_2O) subtraction and obtained a poor resolution gamma ray energy spectrum. They found a total pdγ gamma ray cross section of 4.3 $\pm$ 0.3 μb for gamma rays with energies $E_\gamma \geq 40$ MeV. Koehler, Rothe and Thorndike [16] used a 197 MeV proton beam in conjunction with a liquid deuterium target. Photons above 40 MeV were detected in coincidence with one or two charged particles. Koehler, Rothe and Thorndike measured a total pdγ cross section of $\approx$23 μb for gamma rays above 40 MeV which was clearly incompatible with the result of Edgington and Rose. It should be noted that there is a value of 26 μb for the total cross section at 148 MeV [18] for gamma rays above 25 MeV. Using this value to make a crude estimate of the cross section for gamma rays above 40 MeV at a beam energy of 148 MeV, we obtain a value of at least 12 μb. The most recent measurement of pdγ bremsstrahlung was completed by Pinston *et al.* [17] with 200 MeV protons incident on targets of C and CD_2. The pdγ result was obtained by a (CD_2 – C) subtraction. Inclusive gamma ray energy spectra above 20 MeV were measured in a large NaI(Tl) + BaF_2 telescope [19]. They found the pdγ cross section for gamma rays with $E_\gamma \geq 40$ MeV to be $\approx$ 34 μb, which supports the value obtained by Koehler, Rothe and Thorndike and casts serious doubt on the value obtained by Edgington and Rose. Earlier work by Kwato *et al.* [10] and Pinston and co-workers [11] was also in disagreement with the values obtained by Edginton and Rose for heavier target data.

The objective of the experiment discussed in this paper was to study photon production for the pdγ reaction at 145 and 195 MeV and measure the angular distribution and the total cross section for these bremsstrahlung photons. We also measured the angular distribution for this reaction and will compare our value to the earlier measurements mentioned above. We will also compare our data to the most recent calculations by Herrmann, Speth and Nakayama on free pnγ [23].

II. EXPERIMENT

The energy spectra and angular distribution of gamma rays were measured in the energy range between 20 and 170 MeV. Details of the experimental setup can be found in a separate paper on high energy gamma ray production in proton induced reactions [15]. Proton beams of 145 and 195 MeV bombarded self supporting foils of C and CD_2. The thicknesses of the targets ranged from 31 mg/cm^2 to 51.3 mg/cm^2 for the CD_2 target. The CD_2 target was monitored by comparing the rates in four BGO detectors arranged around the target. The BaF_2 detectors covered the angles between 45° and 135°. We also made several runs in which both detectors were operated simultaneously at the same angle and found that to within statistical uncertainties there was no discernable loss of deuterium in the CD_2 targets.

The extraction of the bremsstrahlung cross section for deuterium from the CD_2 target was made quite simple by the fact that there is an excited state gamma ray transition at 15.1 MeV in ^{12}C. This discrete gamma ray state is clearly evident in Fig. 1 where the gamma ray energy spectra for both the CD_2 and C target are displayed. The procedure was then to find the 15.1 MeV yield for the two runs at each of the angles and subtract the properly normalized C spectra from the CD_2 spectra. The yield of 15.1 MeV gamma rays from the C target is given by:

$$Y = \sigma_{15.1} N_p \left(\frac{N_A \rho t \Delta\Omega}{A} \right) \tag{1}$$

where σ is the cross section for the 15.1 MeV state, N_p is the number of protons incident on the target and N_A is Avagadro's number. A is the atomic number of either the C or CD_2, ρt is the target thickness in units of mg/cm^2, and $\Delta\Omega$ is the solid angle covered by the detector. The normalization factor is therefore given by the ratio of the yield of the 15.1 MeV state with the CD_2 target to that of the C target. Empirically, this ratio is given by:

$$R = \frac{N_{p1}\rho_1 t_1 A_2}{N_{p_2}\rho_2 t_2 A_1} \tag{2}$$

This was used as a cross check against the experimentally derived value which was determined by fits to the 15.1 MeV peak for both targets. A smooth polynomial background was assumed for both spectra. In general the results for both methods showed small variations overall (less than 10%) with largest difference at 30% for the value at 60° for the 145 MeV data set. After the properly normalized C spectrum is subtracted from the CD_2 spectrum, what remains is the bremsstrahlung spectrum for deuterons. The results of the subtraction are displayed in Fig. 2. The peak near the endpoint arises from the radiative capture process p + d → ^{3}He + γ. The magnitude of this cross section and its energy have been verified by comparing with previous measurements by Pikar *et al.* at 150 and 200 MeV [20]. The measurement by Pikar *et al.* was a coincidence experiment detecting both the ^{3}He as well as the emitted gamma ray. Also shown in Fig. 2 is an energy spectrum constructed from the capture cross section at 150 MeV reported by Pikar *et al.* at 90° in the laboratory. The cross section was adjusted according to the observed systematic decrease in the yield as the incident energy is increased. This adjusted value of the cross section was assumed to be Gaussian and then transformed from the nucleon-nucleon center-of-mass to the laboratory frame. The transformed Gaussian function for the capture cross section was then folded with the measured response function for the BaF_2 detector. The agreement demonstrates the validity of our subtraction method. All of the energy spectra are then corrected for this capture contribution using the data from Pikar *et al.* and the procedures outlined above.

III. RESULTS AND DISCUSSION

A comparison of the deuteron energy spectra at 90° using the reduced variable E_γ/E_p at 145 and 195 MeV shows reasonable agreement between the two incident energies (Fig. 3) reflecting the consistency of the methods used to derive the deuteron bremsstrahlung energy spectra. Figure 4 shows a direct comparison between the energy spectrum for our data at 90° in the laboratory for protons at 195 MeV to the data of Pinston *et al.* at 200 MeV and there is reasonable agreement between the present measurements and the data of Pinston *et al.* . At the most backward angle, ≈150 deg, all the data sets agree to within statistical uncertainty. However, the present data and the data of Pinston *et al.* exhibit a discrepancy with the measurements of Koehler, Rothe and Thorndike at the forward angles. The magnitude of this discrepancy increases for smaller angles. It should be noted that the data from Pinston *et al.* required proper treatment for not only the capture process but also for the contribution from π^0 decay. The threshold for the reaction p + d → ^{3}He + π^0 is 198.7 MeV [22], and Pinston *et al.* found the contribution to the total cross section for gamma rays with $E_\gamma \geq 40$ MeV to be roughly 10%. The measurement by Koehler, Rothe and Thorndike was performed at 197 ± 5 MeV so this data may also contain some background contribution due to π^0 decay. A comparison of the measured angular distributions measured by Koehler, Rothe and Thorndike and Pinston *et al.* to the present data at 195 MeV is displayed in Fig. 5. The energy threshold is 40 MeV in the laboratory frame, but the cross section is in the nucleon-nucleon center-of mass frame, and again it can be clearly seen that there is reasonable agreement between the measurements. It should be noted that the angular distribution in the nucleon-nucleon center-of-mass frame is not the expected isotropic plus dipole component but exhibits an isotropic plus $\cos(\theta)$ dependence. The ratio of $\sigma(45°)/\sigma(135°)$ in the nucleon-nucleon center-of-mass is 2.5 ± 0.3 at 195 MeV and 3.1 ± 0.3 at 145 MeV which contrasts with value of 1.1 $\pm$ 0.1we found for our earlier measurements on a Pb target [15]. This forward peaking in the emitting frame may be due to the asymmetry of the collision, since in heavy-ion collisions it is generally believed that the reaction mechanism is incoherent proton-neutron bremsstrahlung and in these reactions there is an average over protons from the target colliding with projectile neutrons and vice versa. As a result, we are only left with isotropic and dipole terms, but in the proton-nucleus case that symmetry is lost. One other explanation may be the influence of multiple collisions in the target which could explain the difference between deuteron and lead. The value of the total cross section for $E_\gamma \geq 40$ MeV that we obtain at 195 MeV is 34 $\pm$ 4 μb which is agreement with the value of 35 $\pm$ 12 μb reported by Koehler and the $\approx$ 34 μb value of Pinston *et al.*

The value for the total cross section at 145 MeV is 21 $\pm$ 2 μb which is 4.7 times greater than the value reported by Edgington and Rose at 140 MeV [9]. It is also higher than the estimated value of 12 μb which is based on the cross section of 26 μb reported by Rothe for photons with $E_\gamma \geq 25$ MeV. In that measurement Rothe [18] used a beam degrader to lower the incident beam energy from 197 to 148 MeV. The results from all the measurements are compiled in Table I.

Recent calculations on free pnγ by Herrmann, Speth and Nakayama use a meson-exchange potential model and they also give a careful treatment of one-body rescattering. It is shown that the one-body term enhances the cross section near the photon maximum. Figure 6 shows a comparison of our data in the nucleon-nucleon center-of-mass frame for both incident proton energies. The calculation reproduces the shape of the low energy portion of spectrum and does well up to the kinematic limit for the free pnγ cross section. The calculation is in much better agreement with the data at 200 MeV than the data at 145 MeV. In fact, the calculation underpredicts the magnitude of the data at 145 MeV by roughly 30%. At 195 MeV the agreement is quite good up to 80 MeV; after this energy it is not possible to compare pdγ with free pnγ if the internal momentum distribution is not taken into account. We see a decrease in the cross section for pdγ at high photon energies which arises from Pauli blocking effects in the deuterium nucleus. The calculated values for the total cross section reported by Herrmann, Speth and Nakayama for photons above $E_\gamma \geq 40$ MeV was 14.5 μb at 140 MeV and 22 μb at 197 MeV.

IV. CONCLUSIONS

In conclusion, the present measurement confirms the earlier findings of Pinston *et al.* and is in strong disagreement with the cross sections reported by Edgington and Rose. In contrast, we are also in agreement with the earlier measurement of Koehler, Rothe and Thorndike. Recent preliminary calculations by Nakayama [24] which take into account the deuteron wavefunction reproduce the data reasonably well.

V. ACKNOWLEDGEMENTS

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FIGURES

FIG. 1. Gamma ray energy spectra at 90° in the laboratory for both the C (lower frame) and CD_2 (upper frame) target at 145 MeV. The 15.1 MeV gamma ray transition in ^{12}C is clearly observed.

FIG. 2. Bremmstrahlung gamma ray spectrum for deuterium at 145 MeV, also shown is a comparison of the radiative capture peak p + d $\rightarrow$ ^{3}He + γ. The capture peak is generated by using the value for the radiative capture process meausered by Pikar *et al.* [20] and a procedure described in the text.

FIG. 3. A comparison of the energy spectra at 90° in the laboratory for deuterium at 145 and 195 MeV versus a reduced variable E_γ/E_p which is the measured photon energy divided by the incident proton energy.

FIG. 4. A comparison of the gamma ray energy spectra for deuterium at 195 MeV to the data of Pinston and co-workers at 200 MeV [17]. Both energy spectra have been corrected for the radiative capture cross section

FIG. 5. A comparison of the measured angular distribution for pdγ at 195, 197 [16] and 200 MeV [17].

FIG. 6. Comparison of the measured pdγ energy spectra at 145 and 195 MeV in the

nucleon-nucleon center-of-mass frame with the free pnγ calculation of Herrmann, Speth and Nakayama at 150 and 200 MeV [23].

TABLES

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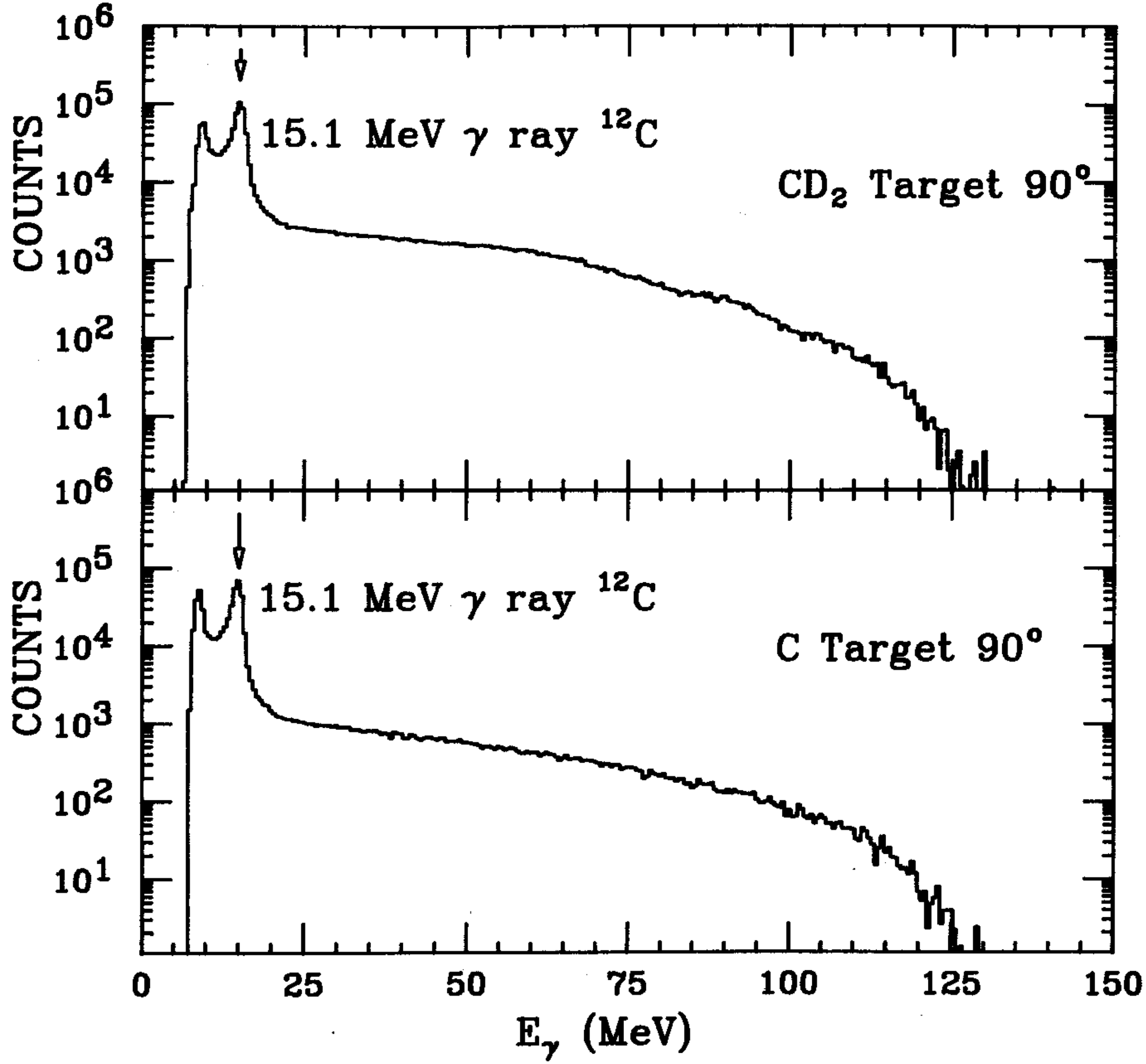
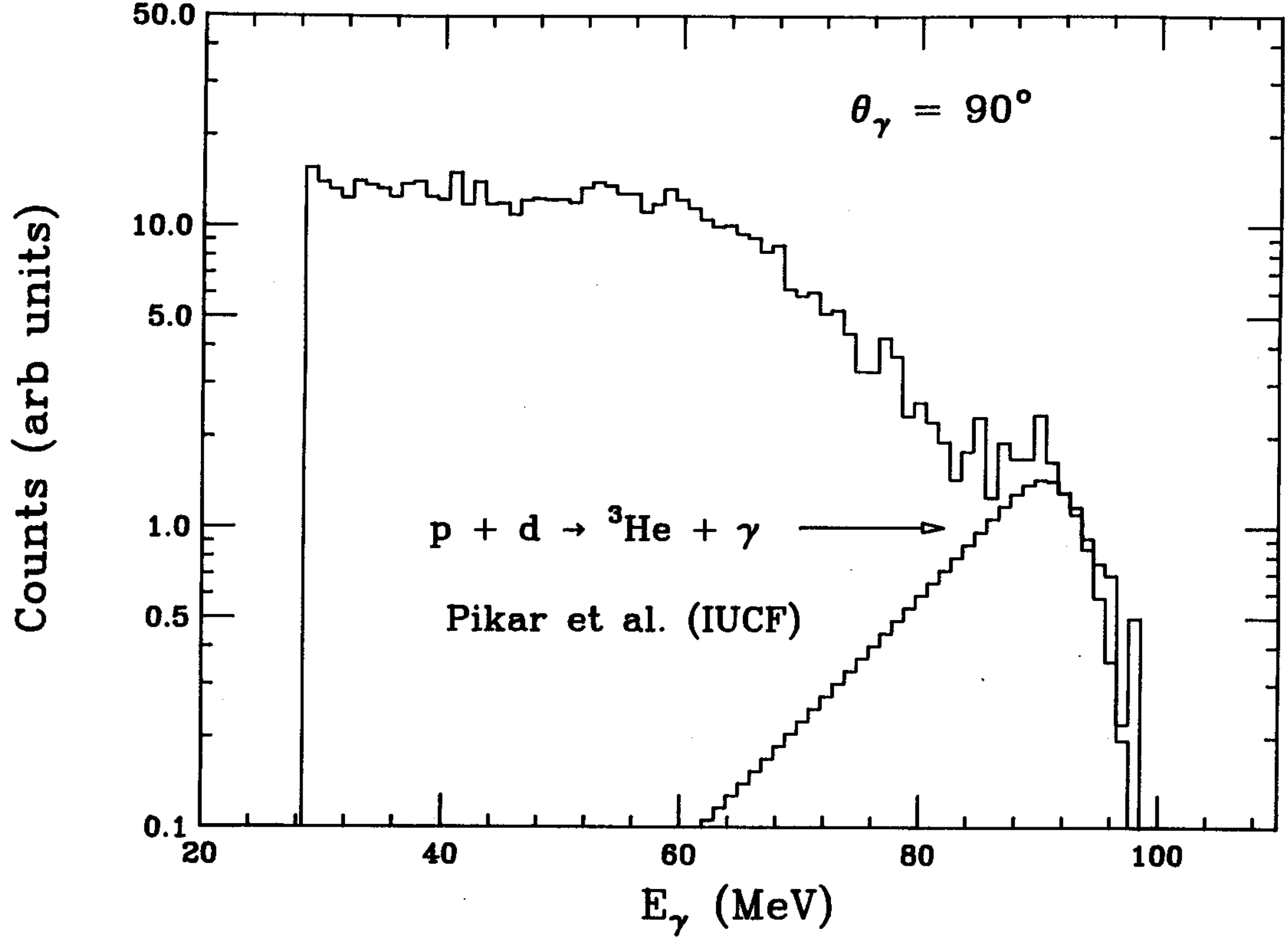
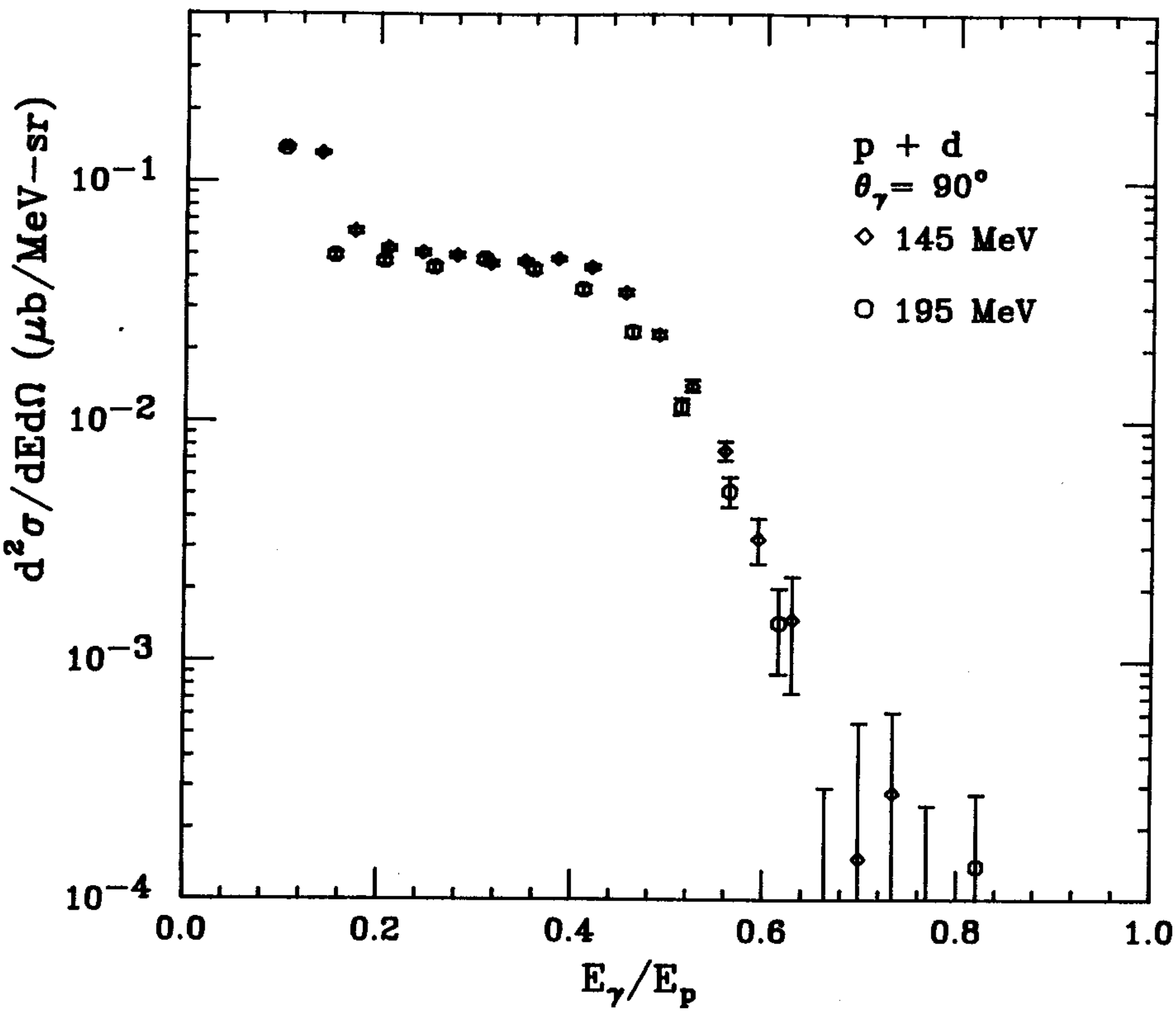
TABLE I. A comparison of the total cross section for gamma rays above 40 MeV from proton induced reactions on deuterium at incident energies of 140 [9], 145, 148 [18], 195, 197 [16], and 200 MeV [11].

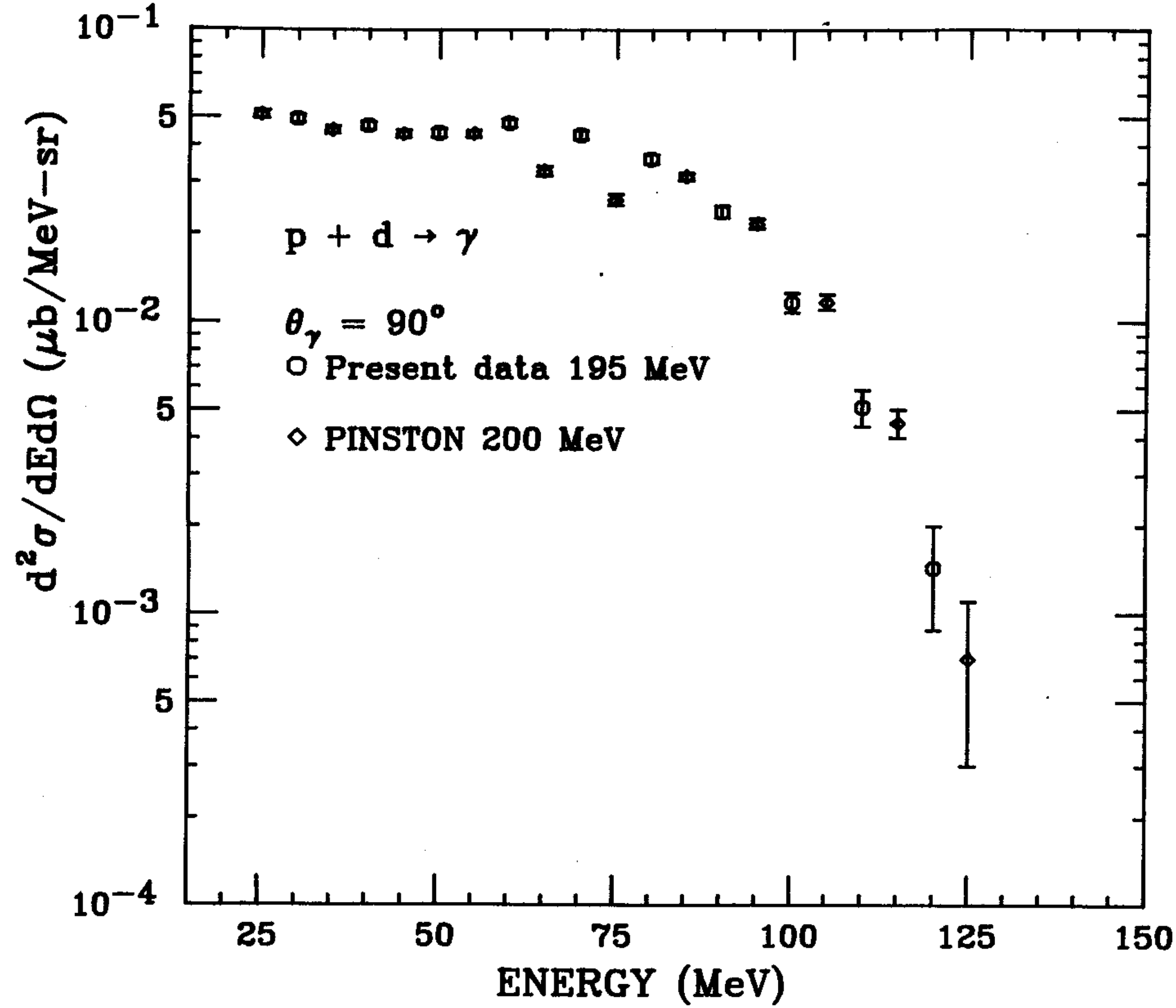
E_p	Target	σ_{tot} μb	Author
140	^{2}H	4.3 ± 0.3	Edgington and Rose
145	^{2}H	21 ± 2	Present Data
148	^{2}H	12	Rothe *et al.*
195	^{2}H	34 ± 4	Present data
197	^{2}H	35 ± 12	Koehler *et al*
200	^{2}H	34	Pinston *et al.*


15.1 MeV γ ray 12C
CD2 Target 90°
C Target 90°
COUNTS
10^6
10^5
10^4
10^3
10^2
10^1
0
25
50
75
100
125
150
Eγ (MeV)

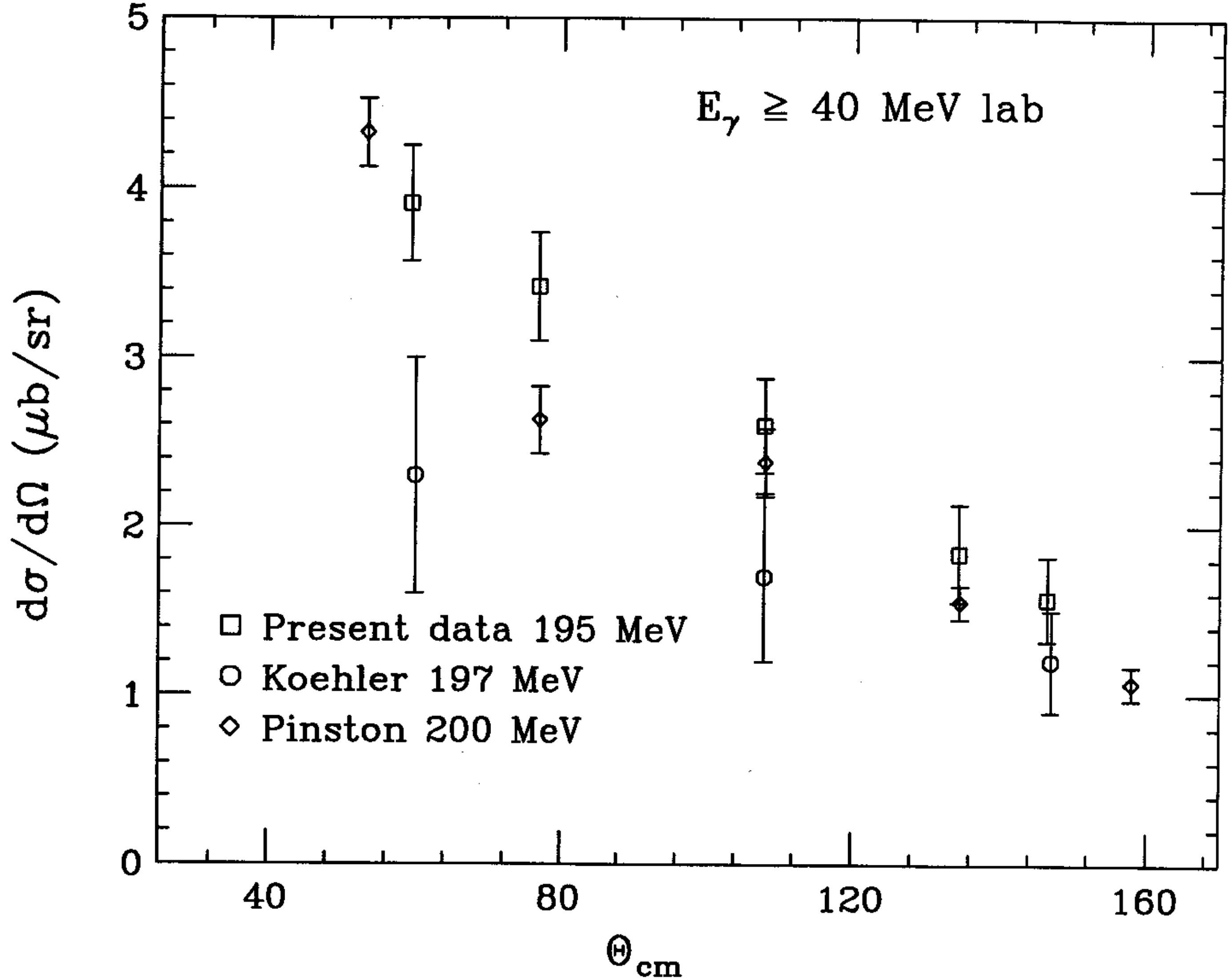


$\theta_\gamma = 90°$
$p + d \rightarrow {}^3He + \gamma$
Pikar et al. (IUCF)
Counts (arb units)
50.0
10.0
5.0
1.0
0.5
0.1
20
40
60
80
100
E_γ (MeV)

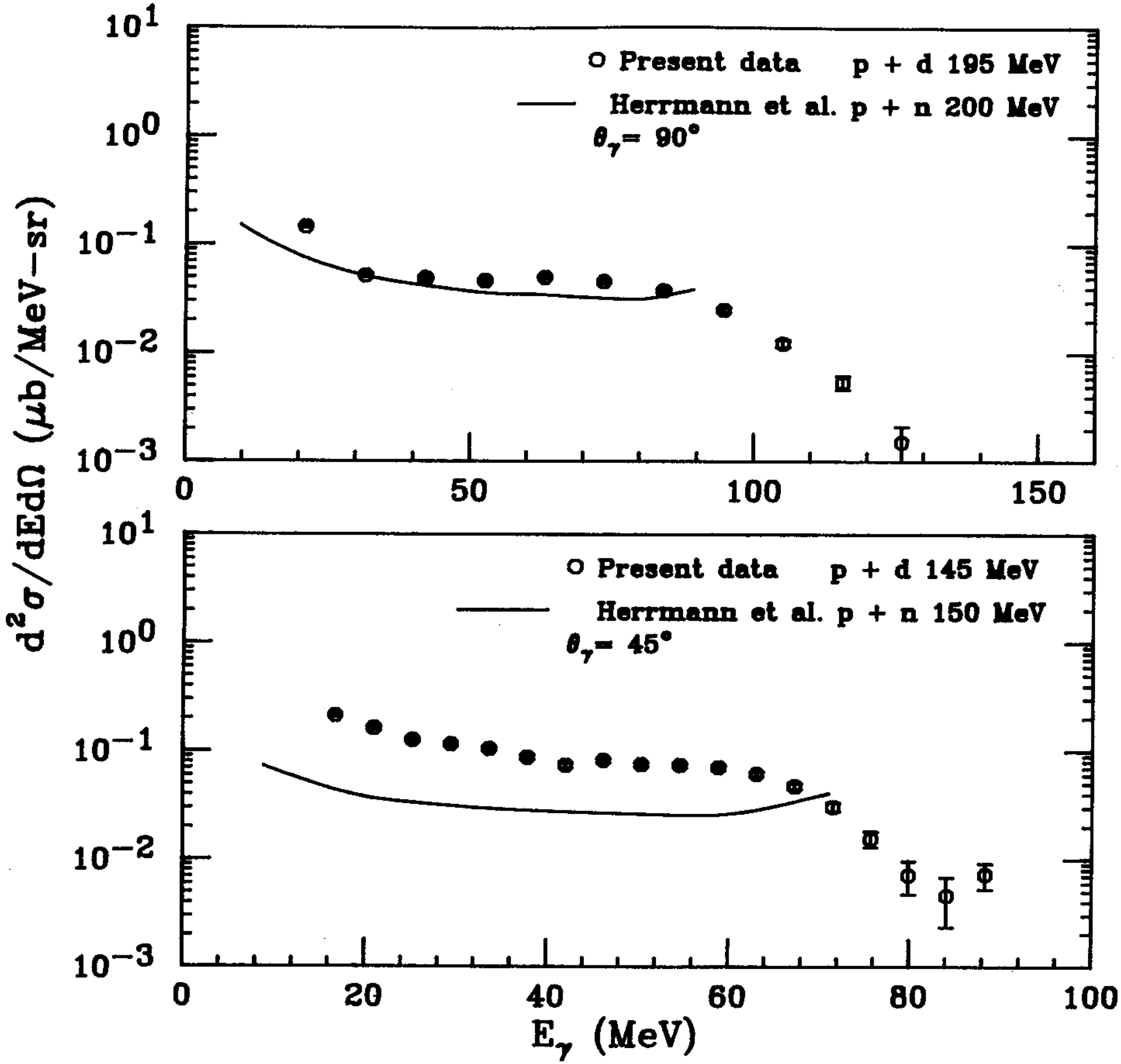

p + d
θγ= 90°
◇ 145 MeV
○ 195 MeV
d²σ/dEdΩ (μb/MeV−sr)
10⁻¹
10⁻²
10⁻³
10⁻⁴
0.0
0.2
0.4
0.6
0.8
1.0
Eγ/Ep



10^{-1}
5
10^{-2}
5
10^{-3}
5
10^{-4}
$d^2\sigma/dEd\Omega$ (μb/MeV–sr)
25
50
75
100
125
150
ENERGY (MeV)
$p + d \rightarrow \gamma$
$\theta_\gamma = 90°$
○ Present data 195 MeV
◇ PINSTON 200 MeV



$E_\gamma \geqq 40$ MeV lab
Present data 195 MeV
Koehler 197 MeV
Pinston 200 MeV
$d\sigma/d\Omega$ (μb/sr)
Θ_{cm}
0
1
2
3
4
5
40
80
120
160



Present data p + d 195 MeV
Herrmann et al. p + n 200 MeV
θ_γ= 90°
Present data p + d 145 MeV
Herrmann et al. p + n 150 MeV
θ_γ= 45°
$d^2\sigma/dEd\Omega$ (μb/MeV−sr)
E_γ (MeV)