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A. TITLE: A Test of Reduced Nuclear Amplitudes in the Two-body Photodisintegration of ^3He for $E_\gamma \leq 2.0$ GeV

B. CONTACT PERSON: Stephen A Wood

ADDRESS, PHONE, AND ELECTRONIC MAIL ADDRESS:

Physics Division, Mail Stop 12H
CEBAF
SAW@CEBAF

C. IS THIS PROPOSAL BASED ON A PREVIOUSLY SUBMITTED PROPOSAL OR LETTER OF INTENT?

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Two Body Photodisintegration of ^3He as a Test of Reduced Nuclear Amplitudes 88-29

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A Test of Reduced Nuclear Amplitudes in the Two-body Photodisintegration of ^{3}He for $E_\gamma \leq 2.0$ GeV

S. A. Wood (Spokesperson), D. J. Abbott, O. K. Baker,
R. Carlini, Y. Chen, D. Mack, J. Napolitano, W. Vulcan
Physics Division, CEBAF

O. K. Baker
Physics Department, Hampton University
Physics Division, CEBAF

D. Geesaman, R. Holt, H. Jackson,
V. Papavassiliou, D. Potterveld, B. Zeidman
Physics Division, Argonne National Laboratory

E. Kinney, R. J. Peterson, R. Ristinen
Physics Department, University of Colorado

L. Cardman
Department of Physics, University of Illinois

A. Klein
Physics Department, Old Dominion University

October 1, 1991

Abstract

We propose to measure the differential cross section of ^{3}He(γ,d) at center-of-mass deuteron angles of 45° and 90° for incident photon energies between 300 and 2000 MeV. This experiment is an extension of existing and proposed measurements of the reactions $d(\gamma,p)n$ and $d(\gamma,d)\pi^0$. This and the other proposed measurements represent a crucial test of quark models of nuclei via the Reduced Nuclear Amplitude or constituent counting formalisms. The constituent counting rule predicts a cross section dependence of s^{-17}, while the Reduced Nuclear Amplitudes predict an even faster drop with incident energy. Thus ^{3}He may be the heaviest nucleus (and only "real" nucleus) that can be studied in an energy region where one of these models may apply to exclusive two body reactions. Depending on how rapidly the cross section drops with photon energy, this proposal has the potential to extend the maximum energy of existing ^{3}He(γ,d) measurements by about a factor of four.

1 Introduction

Photonuclear knockout reactions are characterized by a large transfer of momentum to the knocked out particle. Because such (γ,X) reactions can reach higher momentum transfers than the typical $(e,e'p)$, they are appropriate for CEBAF's role in exploring the transition between a nuclear and a quark description of nuclei. Measurements of the reactions $d(\gamma,p)n$ and $d(\gamma,d)\pi^0$ at several fixed center of mass angles are already planned at CEBAF[1]. Such highly exclusive reactions drop quickly with increasing A or incident energy, but a measurement of the reaction ^{3}He(γ,d) over a modest energy range is both possible and a desirable addition to the planned deuteron measurements.

Perturbative QCD can make predictions of the asymptotic energy dependence of two-body reaction processes. These predictions are presented as "constituent counting rules"[2, 3, 4, 5, 6] which state that for a fixed angle scattering of hadrons $A+B\rightarrow C+D$ at high energies, the asymptotic form is

$$\lim_{s\rightarrow\infty}\frac{d\sigma}{dt}(A+B\rightarrow C+D)=f(\theta)s^{2-(n_A+n_B+n_C+n_D)}, \qquad (1)$$

where $s=(p_A+p_B)^2$, $t=(p_A-p_C)^2$, and the n_x's are the minimum number of fields or constituents in each particle. Despite theoretical uncertainties, this counting rule work well for scattering reactions involving elementary particles. For example, this rule predicts that elastic proton-proton scattering is proportional to s^{-10}, while experimentally, the behaviour $s^{-9.7\pm0.4}$ is observed. For photonuclear reactions, the reaction $\gamma p\rightarrow\pi^+n$ follows the expected s^{-7} scaling for $s>5$ GeV^2[7] as seen in figure 1a. There are equivalent counting rules for form factors. Figure 1b shows the form factors for the pion, proton and neutron. These form factors have been divided by the expected asymptotic behaviour of Q^{2-2n}, showing that by Q^2 of 4 (GeV/c)^2, the counting rule applies.

In principle, this scaling behaviour should be present in scattering reactions involving nuclei as well as elementary particles. However, because the cross sections fall so quickly, it is generally believed that "large enough" values of s are not readily accessible. For example, asymptotic scaling does not seem to occur in $e-d$ elastic scattering, for which data exist up to about $Q^2 = 4\,(\mathrm{GeV/c})^2$. (Fig. 1b)

The elastic form factor of the deuteron has been described well by the Reduced Nuclear Amplitudes model proposed by Brodsky and Chertok[8]. (Fig. 2a) Brodsky and Hiller[9] have subsequently applied this model to two-body photodisintegration of the deuteron. Measurements of $d(\gamma,p)n$ (for $\theta_{\rm cm} = 90°$) between 0.7 and 1.6 GeV[10, 11] show a reasonable agreement with the Reduced Nuclear Amplitudes model. (Fig. 2b) There are deviations from the model that can be accounted for with reasonable corrections. However, above 1 GeV, this data is also rather well described by the expected power law s^{-11} from constituent counting arguments. These measurements of deuteron photodisintegration will be extended to incident energies of 4 GeV in the CEBAF proposal PR-89-012[1].

Photodisintegration of ^{3}He can provide another test of these models. The constituent counting rule predicts that $d\sigma/dt$ will scale by s^{-17} above some unknown photon energy. The Reduced Nuclear Amplitude model of Brodsky and Hiller[9] can be extended to apply to $^3\mathrm{He}(\gamma,d)$. Above some unknown photon energy, this model predicts the center of momentum cross section

$$\frac{d\sigma}{d\Omega_d} = \frac{\sqrt{s-m_p{}^2}}{s\sqrt{s-m_3{}^2}}\frac{1}{p_T{}^2}F_p{}^2(\hat{t}_p)F_d{}^2(\hat{t}_d)f^2(\theta_{\rm cm}), \tag{2}$$

where the subscripts p, d, and 3 refer to the proton, deuteron and ^{3}He respectively; s is the square of the center of momentum energy; and p_T is the transverse momentum of the final state proton or deuteron. The quantities F_p and F_d are the elastic form factors of the proton and deuteron, evaluated at momentum transfers $\hat{t}_p = (p_p - p_3/3)^2$ and $\hat{t}_d = (p_d - 2p_3/3)^2$. This model can be said to apply when $f^2(\theta_{\rm cm})$ becomes independent of the photon energy above some critical value.

The available data on $^3\mathrm{He}(\gamma,d)$ do not extend much beyond 400 MeV[12, 13, 14]. There are some older measurements near 600 MeV[15, 16], but at energies below 400 MeV the cross sections from these measurements are larger and have a different energy dependence than the later measurements. The more recent data taken at 90°(cm) are shown in figure 3. In the figure 3b, the cross sections have been scaled by s^{17}. In figure 3c, the Reduced Nuclear Amplitudes model (Eq. 2) has been used to extract $f^2(\theta_{\rm cm})$ as a function of photon energy. Clearly, up to 400 MeV, neither model appears to be valid as the data is not yet approaching a constant when scaled by either prediction. We note though, that at 400 MeV and 90° in the center of momentum, the momentum transfer to the deuteron is less than 0.3 GeV^2. Based on the deuteron elastic form factor measurements, neither constituent counting or Reduced Nuclear Amplitudes are expected to apply at this energy.

2 Experiment

We propose to measure the differential cross section for ^{3}He(γ, d) at center-of-mass deuteron angles of 45° and 90° for incident photon energies between 300 and 2000 MeV. The lower limit of 300 MeV photons represent an electron beam energy of 400 MeV. Producing a beam at CEBAF with an energy as low as 400 MeV should be within the normal operating abilities of the accelerator. It is valuable to cover as large an energy region as possible in a single experiment, given the discrepancies between different data sets at lower energies. The cross sections should be large enough that low energy measurements will not make a major contribution to the total running time. This energy range will also give some overlap to previous measurements which will give a check on our normalization.

Measurements to study asymptotic scaling behaviour in two-body scattering are traditionally done at $\theta_{\rm cm} = 90°$ in order to maximize the momentum transfer to each of the final particles. Given this, and the fact that many previous measurements of ^{3}He photodisintegration have been made at this angle, we will choose this as one of our two angles. A second angle of 45° has been chosen because, for a given proton angle, a much larger momentum is transferred to the deuteron.

A summary of some of the experimental requirements is presented in table 1.

2.1 Photon Beam

Unlike the photonuclear experiments proposed for the CLASS, we propose to use an untagged bremsstrahlung beam generated by electrons impingent on a radiator slightly upstream of the target. While the photon beam is a continuous spectrum, by detecting a limited range of the highest momentum deuterons, one can insure that the final state consists of solely the detected deuteron and an unobserved proton. Furthermore, measurement of the deuteron emission angle and the deuteron momentum is sufficient to derive the energy of the incoming photon. By restricting deuteron momenta to those that correspond to the top 110 MeV of the bremsstrahlung spectrum, pion production is kinematically forbidden.

The radiator will be 0.06 radiation lengths of a metal with a high Z such as tantalum. It is desirable to use a high Z radiator, since for the same thickness in radiation lengths, a high Z radiator is thinner by weight than a low Z radiator. By maximizing the radiator Z, the ratio of forward going hadrons to bremsstrahlung photons is minimized.

The beam incident on the target will be a mixture of photons and electrons. Thus the spectrometer will detect deuterons from both ^{3}He(γ, d) and ^{3}He(e, d). The later reaction can be estimated by assuming that the electroproduction spectrum is the equivalent of a photoproduction spectrum from a 2% radiator. Thus the electrodisintegration deuterons rate will be about one third of that from photodisintegration. This "background" will be corrected by making measurements with the radiator removed for each data point.

2.2 ^{3}He target

For large beam currents, compressed gas targets are often preferred to liquid targets. The previous measurement[12] used a compressed gas target run at 81 °K with a pressure of 1.03 MPa. We propose here to run with a target approximately 10 times more dense, achieved by doubling the pressure and reducing the temperature to 15 °K. A target operating at 20 atmospheres at 15 °K, with a visible length of 7.5 cm, gives a thickness of 365 gm/cm^2 (7.3×10^{22} nuclei/cm^2). The actual target will be a circular aluminum can with a diameter of 10 cm. The visible length of the target will be defined with slits placed near the target which will shield the walls of the target from the spectrometer.

An operating temperature of 15 °K is convenient because there will be a "utility" supply of helium gas at this temperature. Thus this target can operate at a heat load of approximately 50 watts without a dedicated refrigerator.

The "Bates" measurement[12] found at most a 5.5% reduction in local gas density for beam currents of up to 50 microamps. While this proposed experiment will use similar beam currents, the beam-heating effects could potentially be worse given the lower target operating temperature and higher density. Beam heating effects depend on the size of the beam. Since the CEBAF beam is quite small, a beam rastering system will be used to move the beam over a several square millimeter spot to simulate a more diffuse beam. Since the the resolution requirements of this experiment are not great, the beam may be rastered in the vertical direction as well as the horizontal.

Rastering the beam is not expected to entirely eliminate beam heating effects, but we expect to be able to keep them under 10%. The effect of the beam heating will be checked by making measurements of ^{3}He(γ, d) at several currents between 1 and $50 \mu A$. This will be done at two different beam energies.

Target empty measurements will be made with an empty target that will be in the target ladder along with the ^{3}He target. This empty target will be a cell of identical geometry to the full target. A distinct empty target will minimize the need to empty and fill the target during the experiment.

2.3 Spectrometer

The deuterons from $^3\text{He}(\gamma, d)$ will be detected by the HMS spectrometer. This spectrometer is chosen rather than the SOS, because three of the measurements at $\theta_{\text{cm}} = 45°$ have deuteron momenta above the 2 GeV/c limit of the SOS. (See table 4)

The HMS spectromter will be focused with a point to point tune in the transverse direction. The point to point tune will allow the position of the event to be resolved to a few millimeters and thus detect the presence of any slit scattering. The expected 0.1% resolution of the HMS is sufficient to measure the endpoint from the top 110 MeV of the bremsstrahlung end point.

The HMS focal plane will be configured as discussed below (Sec. 2.5) to have the hodoscope planes separated by as large a distance as possible to provide time-of-flight discrimination between deuterons and protons. (See figure 4)

The possibility of using the SOS spectrometer as a "Luminosity monitor" is being explored. The SOS could be set to monitor elastic electron scattering from ^3He. Running for each beam energy could be commenced with a short period of beam a low current. Rates in the SOS during higher current running could then be normalized to the low current data giving a continuous monitor of the beam current - target thickness product.

2.4 Rate Estimates and Kinematics

Figure 5 shows the $\theta_{\text{cm}} = 90°$ measurements of Sober *et. al.*[12], Gassen *et. al.*[13], and Argan *et. al.*[14]. The solid curve is the Reduced Nuclear Amplitude Scaling prediction assuming that this scaling is in effect at $E_\gamma = 400\,\text{MeV}$ ($f^2(\theta_{\text{cm}}) = 600$). Since the reduced amplitude f^2 still appears to be rising at 400 MeV (fig. 3c), it is not unreasonable to assume that this prediction represents a lower limit to the cross section for the purpose of estimating rates. Figure 5 also shows the expected s^{-17} asymptotic behaviour of the $^3\text{He}(\gamma, d)$ cross section. The normalization of the s^{-17} curve is arbitrarily chosen such that $s^{17} d\sigma/dt$ is $10^{19}\,\text{nb} \cdot \text{GeV}^{32}$. If the existing data is extrapolated exponentially, it intersects this curve at approximately 800 MeV.

Count rate estimates are made for both assumptions about cross sections in tables 2 and 3 for $\theta_{\text{cm}} = 90°$. (The lab deuteron angles and momenta are also included in table 2) The estimates for the Reduced Nuclear Amplitudes assumption suggest that we will be able to make measurements up to a beam energy of 1.5 GeV where the count rate is estimated to be 1 per hour. If $f^2(90°)$ is larger than we assume, or if the s^{-17} scaling sets in at a low enough energy, the rates will be higher and we can carry the measurments to a higher beam energy.

For $\theta_d(\text{cm}) = 45^\circ$ we assume that the center of momentum frame cross section is one half the value for 90°. This is roughly the ratio at $E_\gamma = 400$ seen in existing experiments.

For the counting rates estimates, in tables 2-5, we assume a 50 microamp beam incident on a 6% tantalum radiator, a target thickness of 7.3×10^{22} nuclei/cm^2, and a spectrometer solid angle of 6.4 msr. We assume that the spectrometer momentum bite is large enough to accommodate all deuterons ejected by the top 110 MeV of the bremsstrahlung spectrum.

2.5 Backgrounds and Particle ID

The backgrounds for this experiment can be broken in to four groups.

- **Room Background.** This background is anything that does not come straight from the target through the optics of the spectrometer. It may be cosmic rays, beam induced radiation the penetrates the shielding, or particles from the target that bounce in the spectrometer. The 100% duty factor of CEBAF is valuable for reducing the instantaneous rates of these backgrounds. Such background will be reduced offline by requiring optically consistent tracks in the wire chambers, requiring both TOF and pulse height identification of deuterons, and requiring that a majority of the scintillator hodoscope planes have hits.
- **(γ, p) and (γ, π^+) backgrounds.** To reject protons and pions we will rely primarily on time of flight in the detector stack. For the highest planned deuteron momenta of 2.6 GeV/c, a 3 meter drift space will give a difference in flight times for deuterons and protons of $\Delta t = 1.65$ns. To obtain this drift distance, the second wire chamber will be moved as close as possible to the first wire chamber, and the Cerenkov detector will be removed. The two hodoscope planes will then be placed as far apart as possible in the remaining space. (Fig. 4)
- **(e, d) virtual photon background.** The deuterons arising from "virtual photons" will be subtracted by making measurements with the bremsstrahlung radiator removed.
- **Non ^{3}He(γ, d) deuteron backgrounds.** There are a number of possible sources of deuterons of momenta comparable to those of interest. The primary source of deuterons is from the target walls. These will be eliminated first by placing slits near the target that will provide shadow shielding between the target walls and the spectrometer. These slits will define the effective target length of 7.5 cm. Furthermore, a target empty measurement will be made for each data point. The other deuteron backgrounds are expected to be negligible, but are discussed further below.

There are several sequential reactions that can, in principle, produce a deuteron at momentum comparable or even above those of interest. The relatively thick radiator can produce forward going pions, protons or deuterons. These secondaries can then knock a deuteron from the ^{3}He target into the spectrometer through one of the following reactions: ^{3}He$(p,d)pp$, ^{3}He$(d,d)X$ or ^{3}He$(\pi^-,d)n$. Since both the production of the initial forward going hadron, and the second scattering must produce a particle near the kinematic maximum, we expect these backgrounds to be negligible. However, the cross section for ^{3}He(γ,d) is expected to decrease rapidly with photon energy, so it is important to provide some experimental checks of this assertion. This will be done in two ways:

- Several runs will be made with an aluminum radiator. To produce the same photon flux as a tantalum radiator, an aluminum radiator must be 4 times thicker by mass. This will roughly increase the ratio of secondaries through electroproduction to photons by a factor of 4. If a small increase in cross section is seen with the lighter radiator, one can assume that the double scattering background is one quarter of this difference.
- The deuteron spectrum observed in the spectometers will have a predictable shape that comes from a convolution of the bremsstrahlung spectrum and the energy dependence of the ^{3}He(γ,d) cross section. Since the background deuterons will have different maximum momenta, and different shapes, any deviation from the expected spectrum shape will be an indication of double scattering contamination.

There are also double scattering reactions that can occur entirely in the ^{3}He target that give rise to deuterons of high enough momenta. Double scattering depends on the square of the target thickness, so we will plan at least one run at half the normal ^{3}He density to put a limit on such backgrounds.

3 Beam Time Request

We propose to make measurements at eight electron beam energies of 0.4, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75, and 2.0 GeV. A measurement of the differential cross section of ^{3}He(γ,d) will be made at deuteron center of momentum angles of 45°and 90°for each beam energy. Because the laboratory angle at each incident energy is different for a fixed center of momentum angle, the spectrometer angle will need to be changed between every measurement. Furthermore, since each measurements requires four combinations of radiator in/out and target full/empty, we assume a minimum time of 3 hours per data point.

- Measurements at E_e = 0.4, 0.5, and 0.75 GeV. Given the high rates, we estimate 6×3 hours = 18 hours.
- E_e = 1.0 and 1.25 GeV. The estimated rates are still over 100 per hour for these energies, but good statistics are desirable so that the bremsstrahlung end-point may

be divided into several E_γ bins. Thus we request 20 hours per point so that 10 hours may be devoted to radiator in/target full runs while leaving time for good radiator out and target empty runs. 4×20 hours = 80 hours.

- $E_e = 1.5$, 1.75, and 2.0 GeV. We request 30 hours per point for a total for these energies of 180 hours. If the reaction appears unobservable at 2.0 GeV, the time will be devoted to obtaining better statistics at 1.5 and 1.75 GeV.
- Beam heating studies will be made at two different beam energies. Background studies involving measurements with different radiator thicknesses and materials will also be made at two different beam energies. We request 60 hours for these measurements.

The above totals to 14 days of data taking. For our total request we add 50% for beam energy changes, angles changes, other overhead, and contingency. (After setting the first energy, seven more energy changes will be required.) Thus our total request is for 21 days of beam with currents up to 50 μA. This does not include the time needed to commission and calibrate the HMS spectrometer.

It is entirely possible that measurements at 2.0 GeV will be impossible because of the low cross sections. In this case we still plan to make measurements at 8 beam energies, but spaced closer together than 250 MeV. Because it is impossible to predict the maximum energy at which measurements will be possible, we need the flexibilty to request arbitrary beam energies (up to 2.0 GeV) during the course of the run. It would be preferrable to schedule this experiment before all three halls are operational to more easily allow for this flexibility.

4 Collaboration Commitments

Our collaboration is composed from a group which carried out a similar experiment in deuteron photodisintegration at SLAC[10, 11], and from groups committed to build the HMS and detector systems. Some specific responsibilities are as follows.

- **CEBAF:** Beamline including position and current monitors, radiator target, data acquisition and spectrometer calibrations.
- **Hampton University:** HMS drift chambers.
- **Illinois:** TOF and triggering hodoscopes.

At present there is no funded compressed gas ^{3}He target in the Hall-C CDR. We are optimistic that Argonne National Laboratory and/or Hampton University will develop efforts to construct such a target. We seek approval of this experiment at this PAC so that it will be possible to include this experiment as support for a proposal to the funding agencies to build a ^{3}He target.

References

[1] R. J. Holt et al., Two-Body Photodisintegration of the Deuteron at Forward Angles and Photon Energies Between 1.5 and 4.0 GeV, Proposal, CEBAF, 1989.

[2] S. J. Brodsky and G. Farrar, Phys. Rev. Lett. **31**, 1153 (1973).

[3] V. A. Mateev et al., Lett. Nuov. Cim. **7**, 1309 (1973).

[4] S. J. Brodsky and G. R. Farrar, Phys. Rev. D **11**, 1309 (1975).

[5] G. P. Lepage and S. J. Brodsky, Phys. Rev. D **22**, 2157 (1975).

[6] D. Sivers, Ann. Rev. Part. Sci. **32**, 149 (1982).

[7] R. Anderson et al., Phys. Rev. D **14**, 679 (1976).

[8] S. J. Brodsky and B. Chertok, Phys. Rev. D **13**, 3003 (1976).

[9] S. J. Brodsky and J. Hiller, Phys. Rev. C **28**, 475 (1983).

[10] J. Napolitano et al., Phys. Rev. Lett. **61**, 2530 (1988).

[11] T. Y. Tung et al., to be published.

[12] D. I. Sober et al., Phys. Rev. C **28**, 2234 (1983).

[13] H. J. Gassen et al., Z. Physik A **303**, 35 (1981).

[14] P. E. Argan et al., Nuc. Phys. **A237**, 447 (1975).

[15] P. Picozza et al., Nuc. Phys. **A157**, 190 (1970).

[16] C. A. Heusch et al., Phys. Rev. Lett. **37**, 405 (1976).

[17] S. Rock et al., Phys. Rev. Lett. **19**, 1139 (1982).

Table 1: Summary of experimental requirements

Beam Energies	400–2000 GeV
Beam Current	1–50 μA
Bremsstrahlung Radiator	6% Tantalum (400 mg/cm^2)
Target Material	^{3}He
Target Temperature	15 °K
Target Pressure	20 atm
Visible Target Length	7.5 cm
Target Thickness	365 mg/cm^2 (7.3×10^{22})
Power dissapated in target	50 watts
Spectrometer	HMS (Hall-C)
Solid Angle	6.4 msr
Tune	Point to Point (Y)
Scattering Angles	26–34°, 55–72°

Table 2: Kinematics and rate estimates for ^{3}He(γ, d) at θ_d(cm) = 90°. The second column $< E_\gamma >$ is the center of the accepted region of the bremsstrahlung endpoint from 110 to 20 MeV below the incident electron energy. The kinematic quantities, cross sections and rates correspond to this "average" photon energy. The cross section estimates assume that $d\sigma/dt = s^{-17} 10^{19}nb\cdot$GeV^{32}. (Actual measurements are larger than this for $E_\gamma < 500$MeV.) The photon flux assumes a 50 microamp beam incident on a 6% radiator. The rates assume a 365 gm/cm^2 (7.3×10^{22} nuclei/cm^2) target and a spectrometer solid angle of 6.4 msr.

E_e GeV	$< E_\gamma >$ GeV	s GeV^2	p_d(lab) GeV/c	θ_d(lab) deg	$d\sigma/d\Omega_{\rm lab}$ nb/str	Φ_γ sec^{-1}	Rate hour^{-1}
0.40	0.335	9.77	0.683	71.8	1.07×10^1	5.068×10^{12}	9.1×10^4
0.50	0.435	10.33	0.791	69.8	6.20×10^0	3.893×10^{12}	4.1×10^4
0.75	0.685	11.73	1.029	65.9	1.43×10^0	2.467×10^{12}	5.9×10^3
1.00	0.935	13.14	1.238	63.0	3.36×10^{-1}	1.806×10^{12}	1000
1.25	1.185	14.54	1.430	60.7	8.57×10^{-2}	1.425×10^{12}	210
1.50	1.435	15.95	1.611	58.7	2.39×10^{-2}	1.176×10^{12}	47
1.75	1.685	17.35	1.784	57.0	7.25×10^{-3}	1.002×10^{12}	12
2.00	1.935	18.76	1.949	55.5	2.38×10^{-3}	8.723×10^{11}	3.5

Table 3: Kinematics and rate estimates for ^{3}He(γ, d) at θ_d(cm) = 90° based upon the prediction of the Reduced Nuclear Amplitudes model. It is assumed that the $f^2(90°)$ from the formula in section 1 is 600. The same experimental parameters as used in table 2 are used here to calculate the rates.

E_e GeV	$< E_\gamma >$ GeV	p_T GeV/c	$-t_p$ GeV^2	$-t_d$ GeV^2	$d\sigma/d\Omega_{\rm lab}$ nb/str	Rate hour^{-1}
0.50	0.435	0.74	0.50	0.60	1.74×10^1	1.1×10^5
0.75	0.685	0.94	0.78	0.99	6.11×10^{-1}	2.5×10^3
1.00	0.935	1.10	1.04	1.39	4.46×10^{-2}	140
1.25	1.185	1.25	1.30	1.81	5.00×10^{-3}	12
1.50	1.435	1.38	1.56	2.24	7.54×10^{-4}	1.5
1.75	1.685	1.50	1.81	2.67	1.41×10^{-4}	0.24
2.00	1.935	1.61	2.06	3.11	3.14×10^{-5}	0.05

Table 4: Kinematics and rate estimates for ^{3}He(γ, d) at $\theta_d(\mathrm{cm}) = 45°$. The center of momentum cross sections are assumed to be half the values shown in table 2.

E_e GeV	$<E_\gamma>$ GeV	s GeV^2	p_d(lab) GeV/c	θ_d(lab) deg	$d\sigma/d\Omega_{\mathrm{lab}}$ nb/str	Φ_γ sec^{-1}	Rate hour^{-1}
0.40	0.335	9.77	0.816	34.2	7.42×10^0	5.068×10^{12}	6.3×10^4
0.50	0.435	10.33	0.960	33.2	4.39×10^0	3.893×10^{12}	2.9×10^4
0.75	0.685	11.73	1.282	31.2	1.05×10^0	2.467×10^{12}	4.4×10^3
1.00	0.935	13.14	1.574	29.7	2.56×10^{-1}	1.806×10^{12}	780
1.25	1.185	14.54	1.848	28.5	6.70×10^{-2}	1.425×10^{12}	160
1.50	1.435	15.95	2.109	27.5	1.91×10^{-2}	1.176×10^{12}	38
1.75	1.685	17.35	2.362	26.6	5.91×10^{-3}	1.002×10^{12}	10
2.00	1.935	18.76	2.609	25.8	1.97×10^{-3}	8.723×10^{11}	2.9

Table 5: Kinematics and rate estimates for ^{3}He(γ, d) at $\theta_d(\mathrm{cm}) = 90°$ based upon the prediction of the Reduced Nuclear Amplitudes model. It is assumed that the $f^2(90°)$ from the formula in section 1 is 300, half the value used for 90° in table 3.

E_e GeV	$<E_\gamma>$ GeV	p_T GeV/c	$-\hat{t}_p$ GeV^2	$-\hat{t}_p$ GeV^2	$d\sigma/d\Omega_{\mathrm{lab}}$ nb/str	Rate hour^{-1}
0.50	0.435	0.53	0.37	0.87	1.04×10^1	6.8×10^4
0.75	0.685	0.66	0.53	1.48	3.13×10^{-1}	1.3×10^3
1.00	0.935	0.78	0.67	2.15	2.03×10^{-2}	62
1.25	1.185	0.88	0.79	2.84	2.09×10^{-3}	5.0
1.50	1.435	0.97	0.90	3.55	2.98×10^{-4}	0.6
1.75	1.685	1.06	1.01	4.27	5.38×10^{-5}	0.09
2.00	1.935	1.14	1.11	5.01	1.17×10^{-5}	0.002

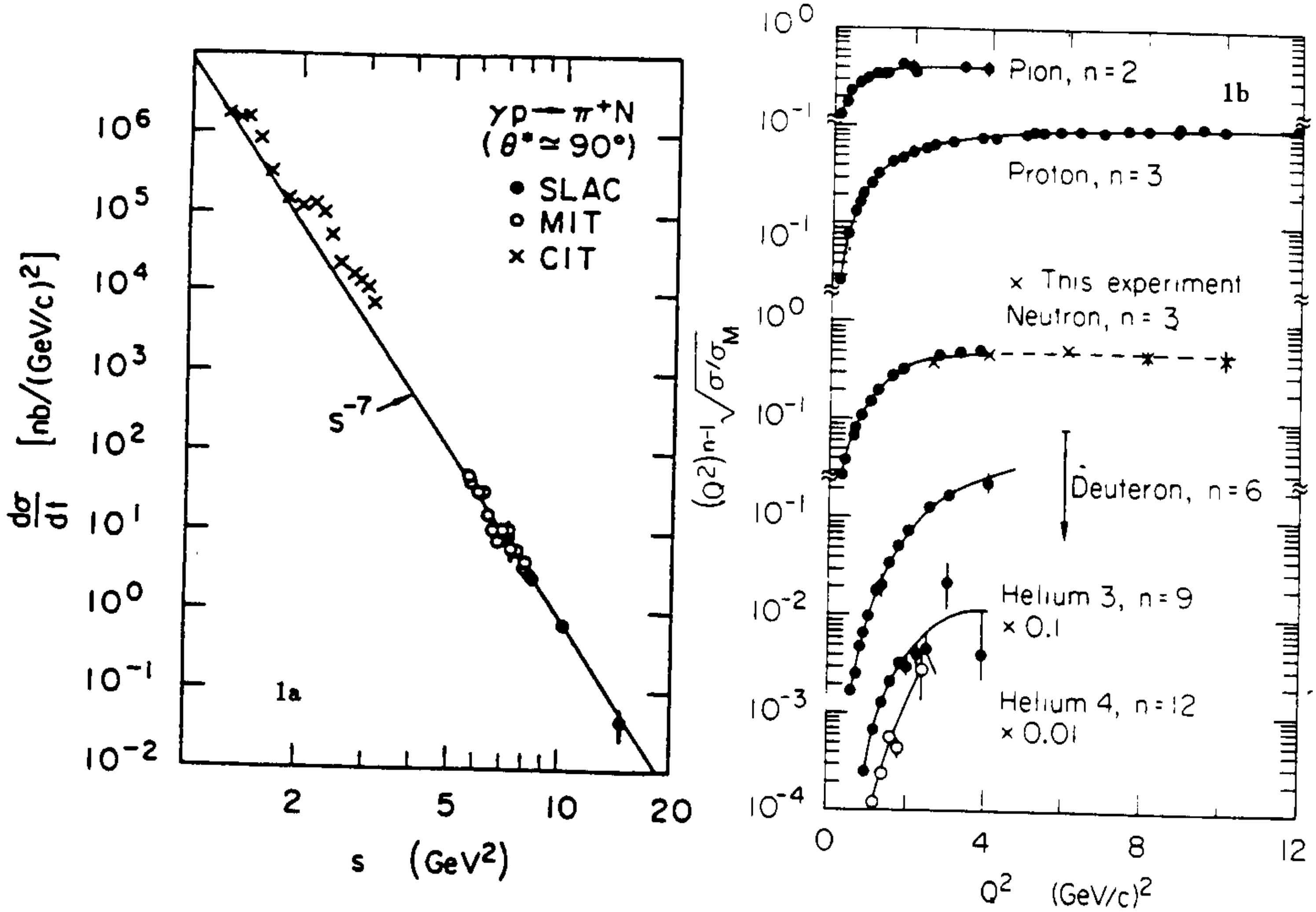

Figure 1: Figure 1a shows the cross section for the $\gamma p \to \pi^+ n$ reaction at 90° in the center of mass. [7] The s^{-7} line is that expected from constituent counting rules. (Eq. 1) Figure 1b shows form factors for several elementary particles and light nuclei.[17] These form factors have been scaled by $Q^{2(n-1)}$ where n is the number of quarks in the target particle.

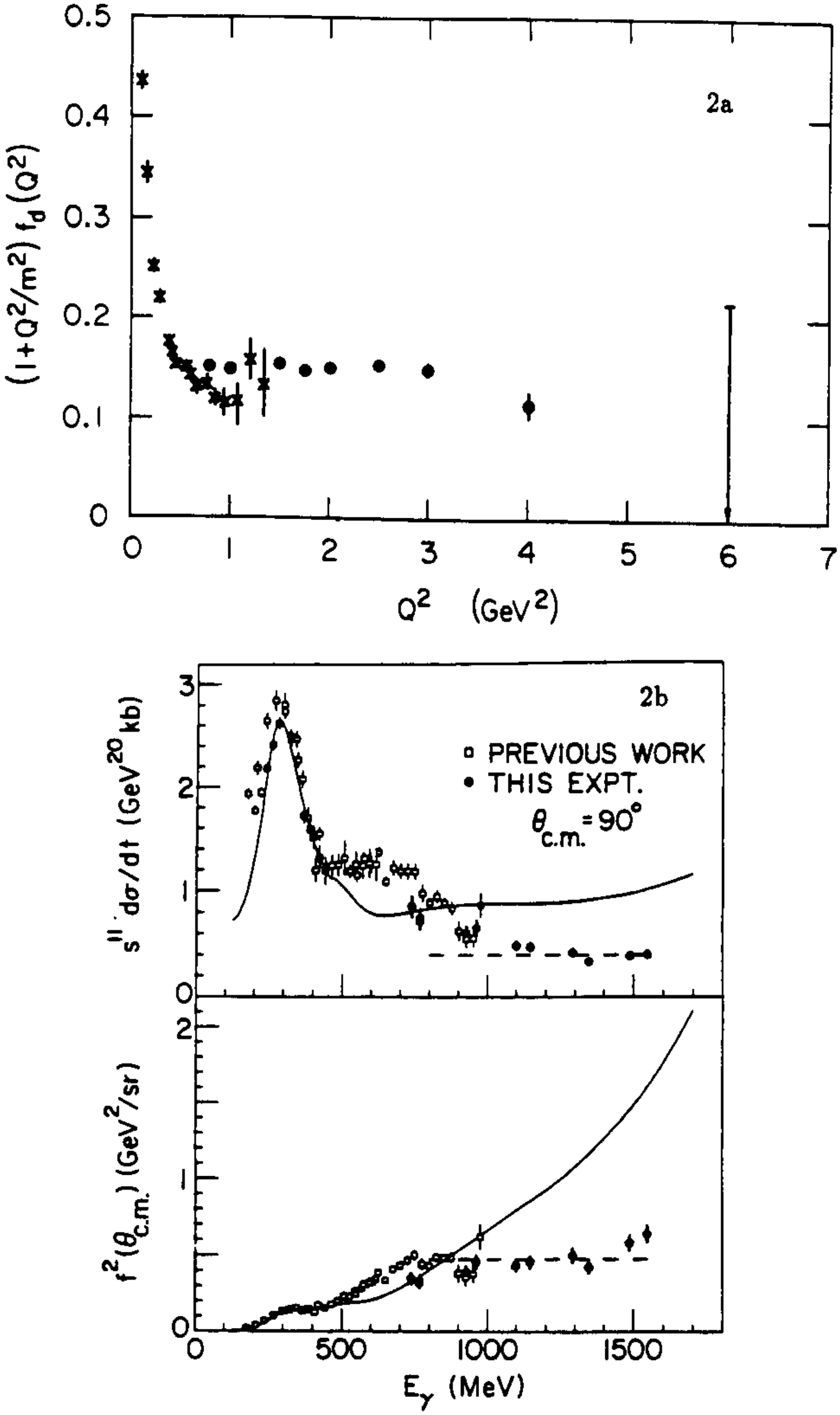

Figure 2: Figure 2a shows the Reduced Nuclear Amplitude for the deuteron form factor.[9] Figure 2b shows $d(\gamma,p)n$ at $\theta_{cm} = 90°$.[10, 11] Cross sections in the top of the figure have been multiplied by s^{11}, the inverse of the expected asymptotic behaviour from constituent counting rules. The lower part of the figure shows the Reduced Nuclear amplitude extracted from the same photodisintegration data.

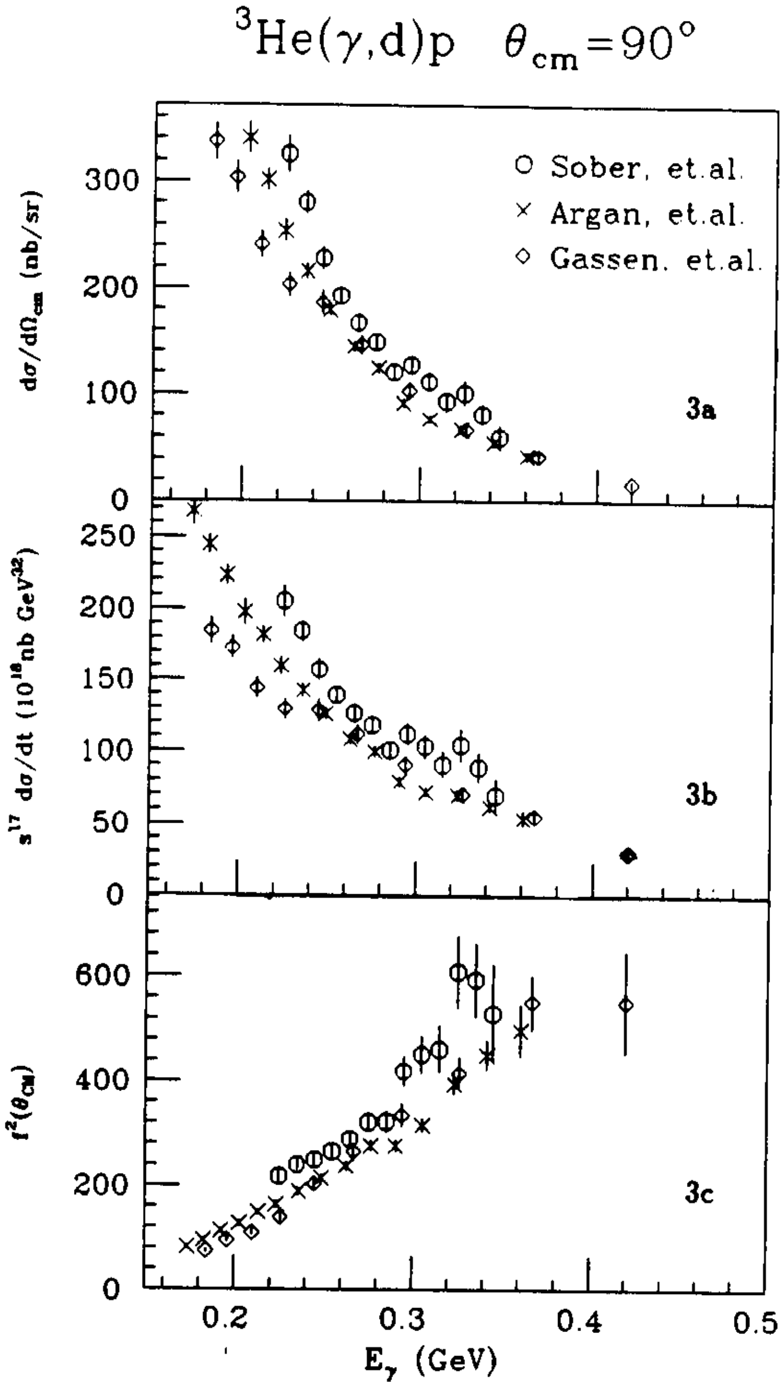

Figure 3: ^{3}He(γ, d) cross sections at $\theta_{cm} = 90°$. Circles are data of Sober *et. al.*[12], diamonds are from Gassen *et. al.*[13] and the crosses are from Argan *et. al.*[14]. In figure 3b, the cross sections have been converted to $d\sigma/dt$ and multiplied by s^{17}, the inverse of the expected asymptotic dependence from constituent counting rules. In figure 3c, the cross sections have been "reduced" to the Reduced Nuclear Amplitude $f^2(\theta_{cm})$ from equation 2.

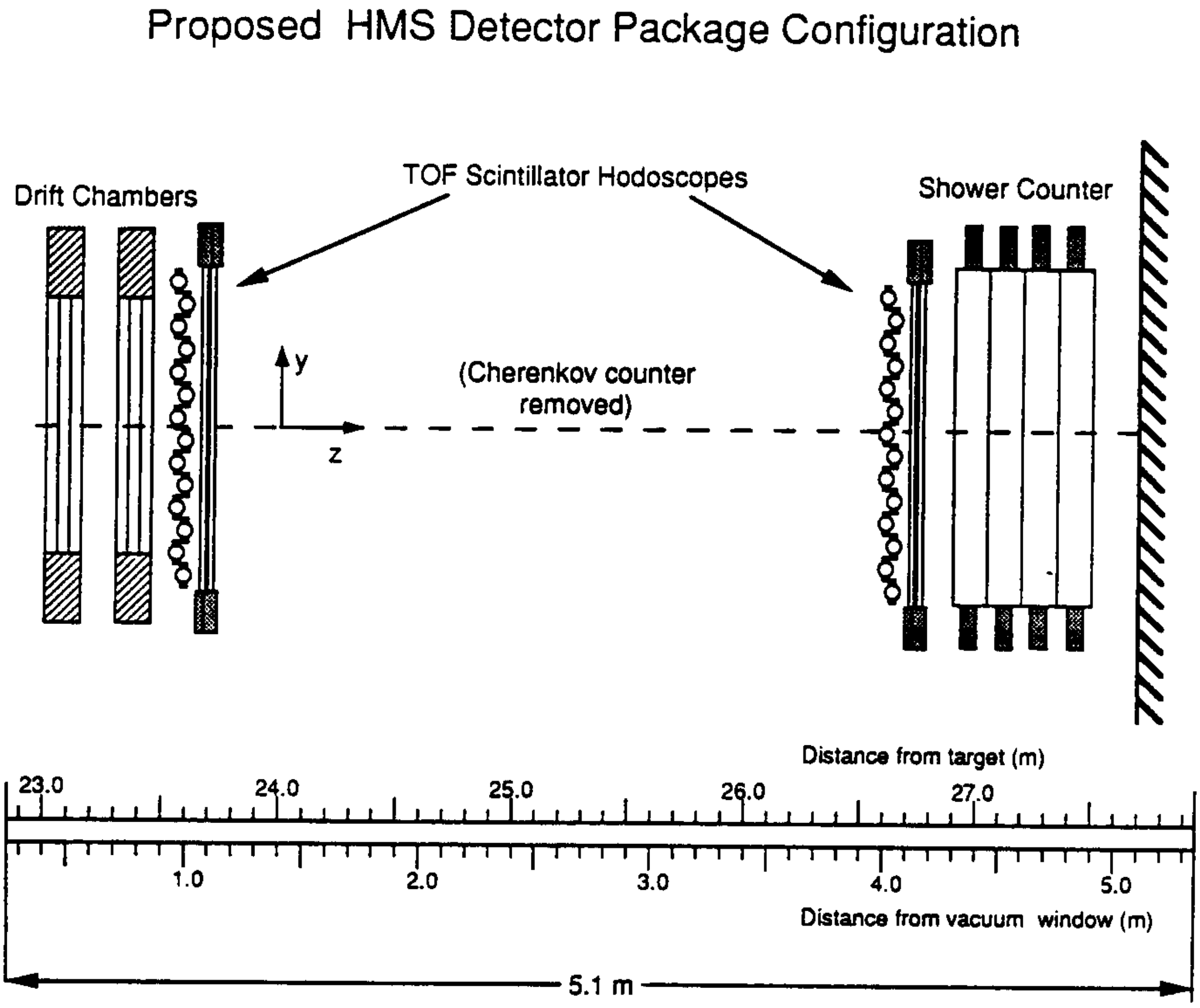

Figure 4: HMS focal plane instrumentation. The second wire chamber is moved as close as possible to the first chamber to give a large drift distance between the two hodoscope planes.

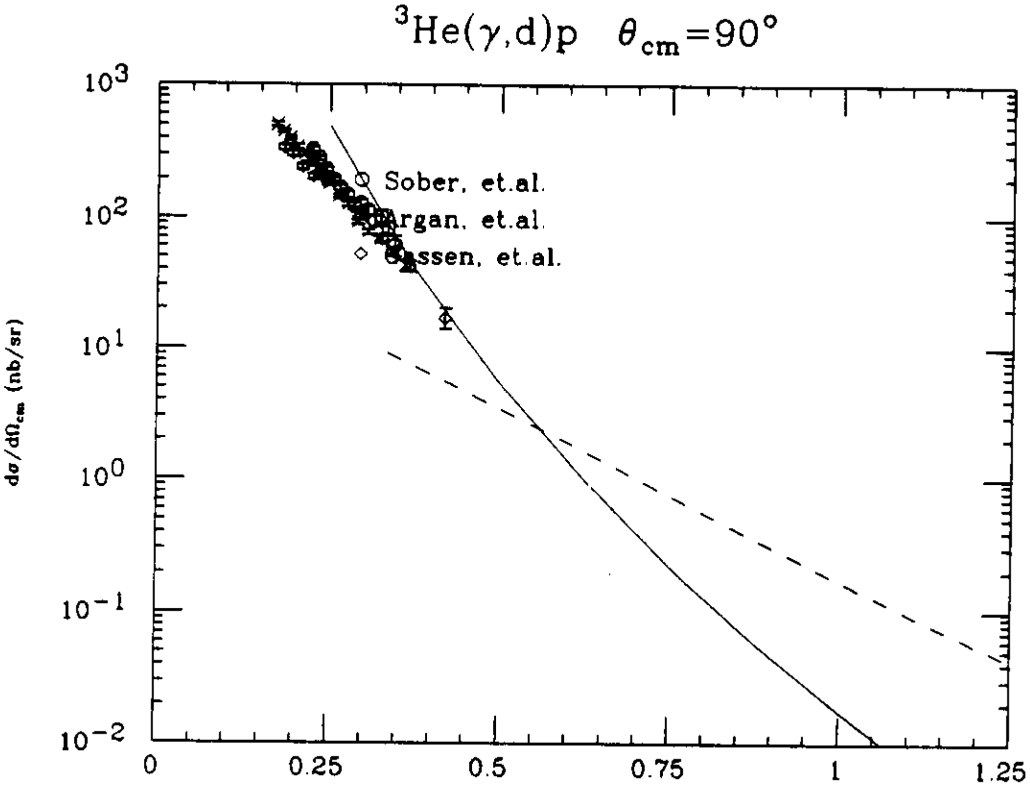

Figure 5: ^{3}He(γ, d) cross sections at $\theta_{cm} = 90°$. The solid line is the Reduced Nuclear Amplitude prediction scaled to match the data at 400 MeV. The dashed line is the constituent counting rule prediction of $d\sigma/dt = Cs^{-17}$, where the normalization has been chosen such that a exponential extrapolation of the existing data intersects this line at approximately 800 MeV.