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# Experimental results of the $p + d \rightleftharpoons {}^3\text{He} + \gamma$ reactions up to 450 MeV

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**Abstract**

Experiments on proton-deuteron radiative capture and the inverse reaction, the photo-disintegration of $^3$He, performed since 1963, up to the intermediate energies are reviewed. Differential cross sections in the center-of-mass system for the radiative capture ($\theta_\gamma^{c.m.} = 90°$) and the inverse reaction ($\theta_p^{c.m.} = 90°$) as a function of photon energy are presented. The experimental data are compared with a calculation based on CD-Bonn+$\Delta$ with the hadronic potential including Coulomb and relativistic 1N current corrections. This study demonstrates a success for time-reversal invariance for the electromagnetic interaction, except for $35 < E_\gamma < 55$ MeV where there is no agreement between the proton-deuteron radiative capture and the reverse reaction data sets.

**Keywords:** Proton-deuteron radiative capture, Photodisintegration, Cross section, Time-reversal

## Background

The characteristics of the strong force acting between nucleons are long-standing questions in nuclear physics. Nucleon-nucleon (NN) scattering as an unbound system and deuteron as the simplest bound nucleus have been extensively studied [1-3] . On the theoretical side, the modern analysis of NN scattering data has been constructed which fits the data with a $\chi^2$ per degree of freedom of the order of approximately 1 [4-7]. In the last decades, high-precision NN and nucleon-deuteron (Nd) elastic scattering and state-of-the-art few-body calculations increased our knowledge on two- and three-nucleon potentials significantly. Recent experimental results in three-body systems have unambiguously shown that calculations based only on NN forces fail to accurately describe many experimental observables and that one needs to include effects which are beyond the realm of the two-body potentials. An excellent review on this aspect can be found in [8]. The importance of relativity in the 3N continuum, particularly of boost and Wigner spin rotation, on observables in elastic scattering and breakup has been discussed in [9]. A complete review of the experimental investigations of discrepancies in three-nucleon (3N) reactions is done by Sagara [10].

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The proton-deuteron radiative capture (PDRC) reaction involves the lightest nucleus ($^3$He) which allows studying of the system of three interacting nucleons. Since neutron beams are scarce, neutron targets are nonexistent, and the detection of two neutrons is a complicated experimental endeavor; in electromagnetic reactions, the PDRC reaction has an advantage over the neutron-deuteron capture. This channel is of particular interest since it provides valuable information on the high-momentum components of the $< {}^3He|pd >$ overlap wave function. Moreover, the vector analyzing powers of the PDRC reaction are rather sensitive to MECs, making them a good testing ground for the details of exchange currents. The importance of studying the $^3$He system is therefore evident since it forms the bridge between the well-understood two-body nucleon-nucleon case and heavier nuclei. The study of PDRC at ultra-low proton-deuteron collision energies in order to verify and determine the amount of variation of the astrophysical $S_{pd}$ factor for the pd reaction caused by electron screening of interacting particles is also important [11].

Technical information of almost all experiments of the PDRC and the inverse reactions, performed since 1963, are collected in Table 1. Differential cross sections in the center-of-mass system for the PDRC ($\theta_\gamma^{c.m.} = 90°$) and the inverse reaction ($\theta_p^{c.m.} = 90°$) as a function of photon energy are plotted in Figure 1. The PDRC differential cross sections are multiplied by an appropriate detailed balance factor. The detailed balance relationship between reversed

**Table 1 Experimental results for $p + d \rightleftharpoons {}^3He + \gamma$ reactions up to 450 MeV**

| Beam | Projectile energy (MeV) | $E_\gamma^{c.m.}$ (MeV) | Target(s) | Ejectile(s) under study | $\theta^{c.m.}$ (deg.) | Observables | Year | Ref. |
|---|---|---|---|---|---|---|---|---|
| $\gamma$ | 8.5-21.5 | | $^3$He gas | p,d | 90 | $\frac{d\sigma}{d\Omega}$ | 1963 | [12] |
| $\gamma$ | 8.9-46.1 | | $^3$He gas | p,d | 90 | $\frac{d\sigma}{d\Omega}$ | 1964 | [13] |
| p | 156 | 109.7 | $CD_2$ | $\gamma$ | 21-155 | $\frac{d\sigma}{d\Omega}$ | 1970 | [14] |
| d | 19.8, 29.6 | 12.1, 15.4 | $CH_2$ | $^3$He | 5-175 | $\frac{d\sigma}{d\Omega}$ | 1970 | [15] |
| $\gamma$ | 185-560 | | $^3$He liquid | p,d | 75-105 | $\frac{d\sigma}{d\Omega}$ | 1970 | [16] |
| e | 86.4 | 13-45 | $^3$He gas | d | 90 | $\frac{d\sigma}{d\Omega}$, $\sigma_{tot}$ | 1971 | [17] |
| d | 20-45 | 11-18 | $CH_2$ | $\gamma$ | 90 | $\frac{d\sigma}{d\Omega}$ | 1971 | [18] |
| $\gamma$ | 40-150 | | $^3$He gas | p,d | 30-140 | $\frac{d\sigma}{d\Omega}$ | 1972 | [19] |
| $\gamma$ | 11-65 | | $^3$He gas | d | 90 | $\frac{d\sigma}{d\Omega}$ | 1973 | [20] |
| p | 16 | 16.1 | $CD_2$ | $^3$He | 30-150 | $\frac{d\sigma}{d\Omega}$ | 1974 | [21] |
| e | 21, 23 | 10-21 | $^3$He gas | d | 95 | $\frac{d\sigma}{d\Omega}$ | 1974 | [22] |
| $\gamma$ | 150-450 | | $^3$He liquid | p,d | 60, 90 | $\frac{d\sigma}{d\Omega}$ | 1975 | [23] |
| $\gamma$ | 200-600 | | $^3$He liquid | p,d | 30- 150 | $\frac{d\sigma}{d\Omega}$ | 1976 | [24] |
| p | 337,462,576 | 257,314,390 | $LD_2$ liquid | $\gamma$ | 45-135 | $\frac{d\sigma}{d\Omega}$ | 1976 | [25] |
| p | 8.8,9.8,10.8 | 11.1,11.8,12.4 | $CD_2$ | $\gamma$ | 30-150 | $\frac{d\sigma}{d\Omega}$ | 1979 | [26] |
| p | 450, 550 | 306, 372.8 | $CD_2$ | $^3$He | 50-90 | $\frac{d\sigma}{d\Omega}$ | 1980 | [27] |
| $\gamma$ | 200-450 | | $^3$He liquid | p,d | 20-150 | $\frac{d\sigma}{d\Omega}$ | 1981 | [28] |
| p | 200,300,350 | 140,208,242 | $CD_2$ | $\gamma$+ $^3$He | 60,90 | $\frac{d\sigma}{d\Omega}$ | 1982 | [29] |
| p | 400,450,500 | 273,308,341 | $CD_2$ | $\gamma$+ $^3$He | 60,90 | $\frac{d\sigma}{d\Omega}$ | 1982 | [29] |
| p | 6.5,8.0,11.0,15.0,16.0 | 9.8-16.2 | $D_2$ gas | $\gamma$ | 30-150 | $\sigma_{tot}$ | 1983 | [30] |
| $\gamma$ | 150-350 | | $^3$He gas | d | 90,120 | $\frac{d\sigma}{d\Omega}$ | 1983 | [31] |
| p | 18-43 | 21,24,27,29,32 | $D_2$ gas | $\gamma$ | 38-139 | $\frac{d\sigma}{d\Omega}$ | 1983 | [32] |
| $\vec{p}$ | 6-16 | 9.8-16 | $D_2$ gas | $\gamma$ | 30-150 | $\frac{d\sigma}{d\Omega}_{\text{unnorm.}}$, $A_y$ | 1984 | [33] |
| $\vec{d}$ | 3.65 | | $H_2$ gas | $\gamma$ | 50-135 | $\frac{d\sigma}{d\Omega}_{\text{unnorm.}}$, $A_y$ | 1984 | [34] |
| $\vec{p}$ | 6.9 | 6.0 | $D_2$ gas | $\gamma$ | 50-135 | $\frac{d\sigma}{d\Omega}_{\text{unnorm.}}$, $A_y$ | 1984 | [34] |
| p | 200,300,350 | 138,205,239 | $CD_2$ | $\gamma$+ $^3$He | 30-150 | $\frac{d\sigma}{d\Omega}$ | 1984 | [35] |
| p | 400,450,500 | 273,305,339 | $CD_2$ | $\gamma$+ $^3$He | 30-150 | $\frac{d\sigma}{d\Omega}$ | 1984 | [35] |
| p | 300,350,400,425 | 206,233,273,289 | $CD_2$, $LD_2$ | $\gamma$+ $^3$He | 54-92 | $\frac{d\sigma}{d\Omega}$ | 1985 | [36] |
| p | 450,470,500 | 306,319,339 | $CD_2$, $LD_2$ | $\gamma$+ $^3$He | 54-92 | $\frac{d\sigma}{d\Omega}$ | 1985 | [36] |
| d | 376,600 | 131.1, 205.9 | $LH_2$ | $^3$He | 83-110 | $\frac{d\sigma}{d\Omega}$ | 1985 | [36] |
| $\vec{d}$ | 19.8 | 12.1 | $CH_2$ | $^3$He | 20-165 | $T_{20}$ | 1985 | [37] |
| $\vec{d}$ | 29.2, 45.3 | 15.2,20.6 | $LH_2$ | $\gamma$ | 96 | $A_{yy}$ | 1985 | [38] |
| $\vec{p}$ | 99.1,150.3,200.7 | 69.9,102.1,133.1 | $CD_2$ | $\gamma$ | 19-154 | $\frac{d\sigma}{d\Omega}$, $A_y$ | 1987 | [39] |
| $\vec{d}$ | 95 | 37.0 | $CH_2$ | $\gamma$ | 45-130 | $\frac{d\sigma}{d\Omega}$,$A_y$,$A_{yy}$ | 1988 | [40] |
| $\vec{p}$ | 5 | 8.8 | $D_2$ gas | $\gamma$ | 25-155 | $\sigma_{tot}$, $A_y$ | 1992 | [41] |
| $\vec{d}$ | 10 | 8.8 | $H_2$ gas | $\gamma$ | 25-155 | $\sigma_{tot}$,$iT_{11}$ | 1992 | [41] |
| $\vec{d}$ | 10 | 8.8 | $H_2$ gas | $\gamma$ | 25-155 | $iT_{20}$,$iT_{21}$,$iT_{22}$ | 1992 | [41] |
| $\gamma$ | 172,185,197,208 | | $^3$He gas | p,d | 40-150 | $\frac{d\sigma}{d\Omega}$ | 1994 | [42] |
| $\vec{d}$ | 45 | 20.3 | $LH_2$ | $\gamma$+ $^3$He | 50-160 | $A_{yy}$ | 1998 | [43] |
| p | 98,176 | 70.7,122.8 | $CD_2$ | $\gamma+e^+e^-$ | 40,80 | $\frac{d\sigma}{d\Omega}$ | 1998 | [44] |
| p | 190 | 132.2 | $LD_2$ | $^3$He+$\gamma+e^+e^-$ | 60-170 | $\frac{d\sigma}{d\Omega}$ | 2000 | [45] |
| $\vec{d}$ | 17.5 | 11.3 | $H_2$ gas | $^3$He | 25-150 | $A_y$,$A_{yy}$,$A_{zz}$,$A_{xx}$ | 2001 | [46] |

**Table 1 Experimental results for $p + d \rightleftharpoons {}^3$He $+ \gamma$ reactions up to 450 MeV *(Continued)***

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $\vec{d}$ | 200 | 72.1 | $LH_2$ | $^3$He | 40-160 | $\frac{d\sigma}{d\Omega}$,$A_y$,$A_{yy}$,$A_{xx}$ | 2003 | [47] |
| $\vec{d}$ | 110,133,180 | 42,49.7,65.4 | $LH_2$, $CD_2$ | $^3$He+$\gamma$+$e^+e^-$ | 30-115 | $A_y$,$A_{yy}$,$A_{zz}$ | 2003 | [48] |
| $\vec{d}$ | 110,133,180 | 42,49.7,65.4 | $LH_2$, $CD_2$ | $^3$He +$\gamma$+$e^+e^-$ | 30-115 | $\frac{d\sigma}{d\Omega}$ | 2003 | [49] |
| $\vec{d}$ | 137 | 51.3 | $LH_2$ | $^3$He | 40-160 | $A_{yy}$,$A_{xx}$ | 2007 | [50] |

The sixth column represents the center-of-mass angles which are covered by the experimental setup.

differential cross sections involving unpolarized particles at the same center-of-mass energy and angle is as follows:

$$\frac{d\sigma(a+b\rightarrow c+d)}{d\sigma(c+d\rightarrow a+b)} = \frac{(2S_c+1)(2S_d+1)}{(2S_a+1)(2S_b+1)} \times \left(\frac{P_c^*}{P_a^*}\right)^2. \quad (1)$$

The factors (2*S*+1) are the spin multiplicities, and $P_a^*$ and $P_c^*$ are the center-of-mass momenta in the initial and final two-body system, respectively. For the unpolarized photon, the (2*S*+1) factor is to be taken as 2, which corresponds physically to the two possible directions of polarization which remain after the direction of propagation has been fixed.

From the theoretical point of view, the PDRC and two- and three-body photodisintegration of $^3$He are described using the following: the triangular diagram based on the dispersion method [51], the role of three-body exchange currents [52], full three-body calculation with a realistic NN interaction [53], the triangular diagram within a relativistic framework [54], impulse approximation for

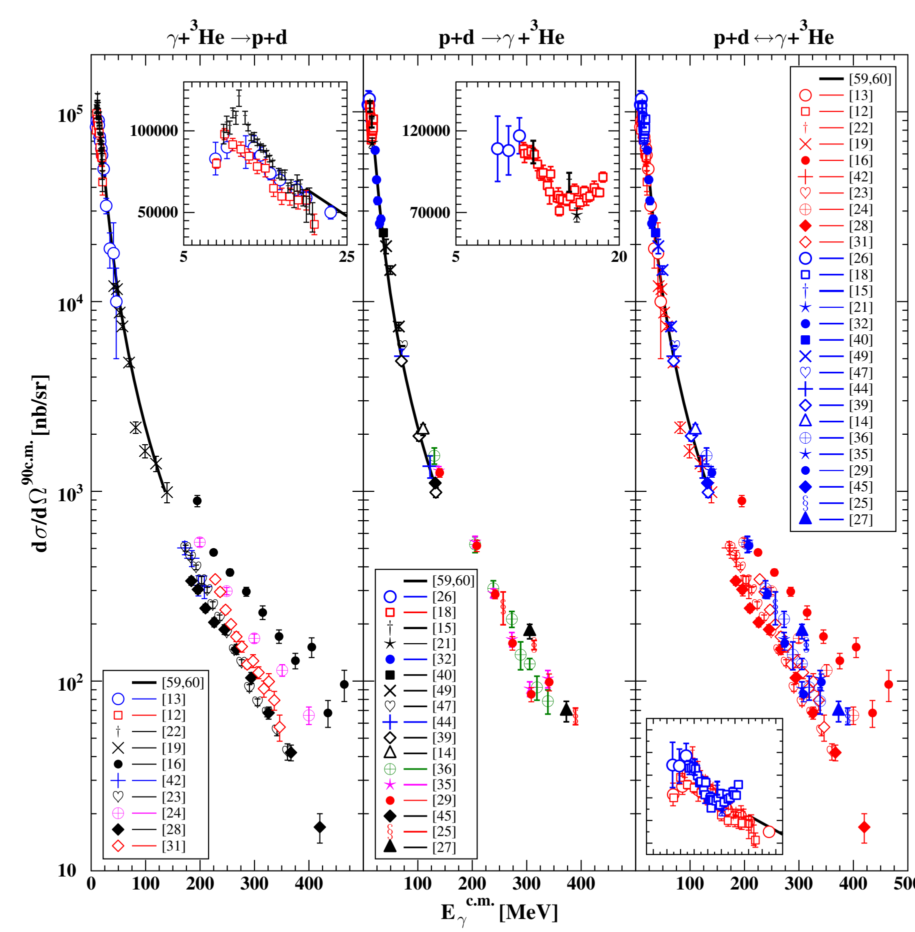


**Figure 1 Differential cross sections.** The cross sections in the center-of-mass system for the PDRC ($\theta_\gamma^{c.m.} = 90°$; middle panel) and the inverse reaction ($\theta_p^{c.m.} = 90°$; left panel) as a function of photon energy. In the right panel, the PDRC data (blue) are plotted along with the inverse reaction (red). Only the statistical errors are indicated by the error bar. The systematical errors of all experiments are in the range of 5% to 10%. The solid curves are the Deltuva's calculations based on CD-Bonn+Δ including Coulomb and relativistic 1N current corrections.

dilepton production following the PDRC [55], covariant and gauge-invariant model for dilepton production following the PDRC [56], meson exchange currents and dipole and quadrupole contributions and the full initial state interaction of the PDRC [57], Faddeev calculation of the PDRC with $\pi$ and $\rho$ Meson exchange currents of the Argonne potentials [58], purely nucleonic charge-dependent CD-Bonn potential and its coupled-channel extension CD-Bonn+$\Delta$ [59], Coulomb interaction between protons [60], and realistic hadronic dynamics including relativistic corrections of the one-nucleon electromagnetic current operator [61]. The theoretical predictions of the Hannover group based on CD-Bonn+$\Delta$ including Coulomb and relativistic 1N current corrections are plotted as a solid line in Figure 2 for the range of 20 to 140 MeV. For the higher energies, the pion production as well as relativistic effects becomes more important which is not included into the calculations. In most calculations, the $2\pi$3NF effect is less than 10% in tensor analyzing powers. This would indicate that the experimental accuracy should be less than a few percent to look for a signature of 3NF. There is a clear disagreement between the theoretical predictions and experimental data at small laboratory scattering angles where the database is poor [59].

## Results and discussion

For $E_\gamma < 20$ MeV, the PDRC results are in good agreement with the inverse reaction results. The ORNL results [18] show a resonance shape at $E_\gamma \sim 18$ MeV. For $20 < E_\gamma < 150$ MeV, the Illinois result [19] is in good agreement with the capture measurements of the Orsay group [14] and with those at the Indiana University Cyclotron Facility (IUCF) [38]. For $E_\gamma > 150$ MeV, the Frascati [16] and Bonn [28] results have the biggest deviation from each other and from the PDRC results. The agreement among the capture measurements is good, although deviations of up to 35% between the TRIUMF [35] and SATURNE [36] data are seen for incident proton energies above 400 MeV (corresponding to photon energies greater than 270 MeV). The photodisintegration experiment at Bates [31] finds cross sections in agreement within errors with the capture measurements at SATURNE and IUCF. All of these are in agreement with the Illinois results where they overlap but are significantly higher than the Saclay [23] and Bonn [28] measurements. The Frascati [16] and Caltech [24] results are higher by factors from 1.8 to 2.2 and 1.4 to 1.5, respectively. The results of the photodisintegration performed at Saskatchewan Accelerator Laboratory using the tagged photon facility are in agreement with the

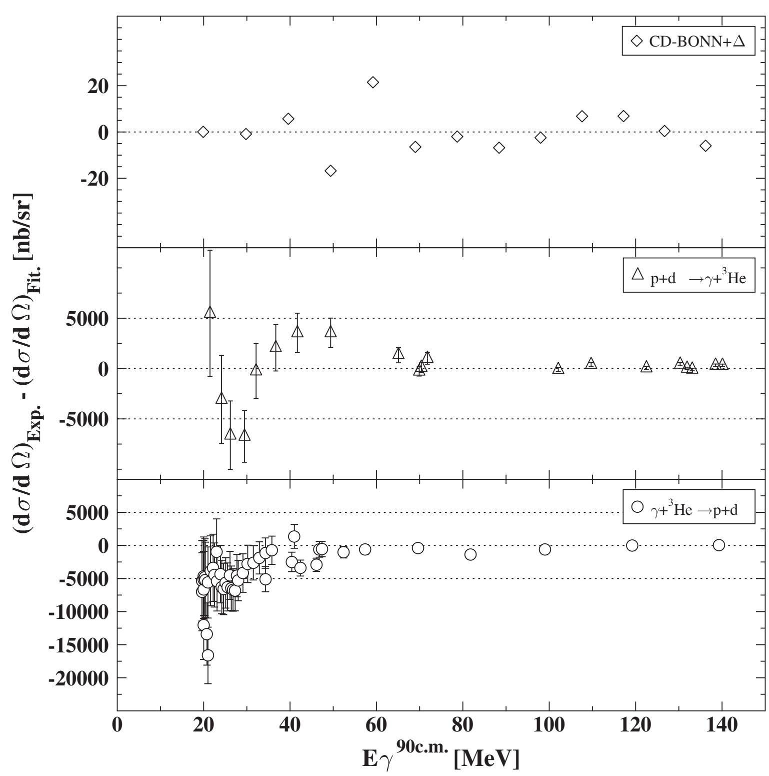


**Figure 2 Deviations of cross sections and a fitted function to the theoretical predictions.** The deviations between the experimental differential cross sections and a fitted function to the theoretical predictions are plotted as a function of the center-of-mass energy; 10% error bars are included to the data. For more detailed explanations, see the text.

Bonn and Saclay photodisintegration measurements [42]. The data set for spin-dependent observables is poor. The relation $A_{xx} \approx A_{yy}$ was found to be valid at PDRC with polarized deuteron beams at $E_d = 17.5$ [46], 137 [50], and 197 [47] MeV, while there is a big discrepancy with KVI data at $E_d = 133$ MeV [10,50].

Figure 2 shows a more quantitative comparison between the experimental results and the theoretical predictions of the Hannover group which are based on the CD-Bonn+$\Delta$ as the hadronic potential including Coulomb and relativistic 1N current corrections. These data are limitted to an $E_\gamma$ of approximately 150 MeV which corresponds to the pion production threshold that is not included in the assumed theoretical dynamics. In addition, relativistic effects would become more important. Therefore, predictions at higher energies would be less reliable. To have a better comparison, an exponential decay function with three components is fitted to the theoretical differential cross sections. The top panel of Figure 2 shows the deviation of the theoretical predictions from the fitted function. It is clear that the function fits the Hannover theoretical data with a $\chi^2$ per degree of freedom of the order of approximately 1. Deviation of the experimental differential cross sections of the PDRC reaction from the fitted function is plotted in the middle panel of Figure 2. The bottom panel shows the deviation for the inverse reaction. For $E_\gamma > 50$ MeV, the PDRC results have good agreement with the inverse reaction results, which is a test of time-reversal invariance in the electromagnetic interaction. For $35 < E_\gamma < 55$ MeV, there is no agreement between the PDRC [32,40,49,50] and the inverse reaction [13,20,22] results even within the 10% error bars.

## Conclusions

Experiments on PDRC and the inverse reaction, the photo-disintegration of $^3$He, performed since 1963, up to the intermediate energies are reviewed. The cross section of the PDRC is less than approximately 1.5 $\frac{\mu b}{sr}$ which makes measuring the experimental observables rather difficult. Most experiments were done in a single mode, which are affected by the large amount of background. In most experiments, only the same particle in the final channel was detected which makes the accuracy of the experiment poor. It is only in the experiment at KVI [48] that both $\gamma$ and the $^3$He were studied. These data clearly disagree with the calculation in which meson-exchange contributions are constructed using the Siegert approximation [48,49]. The experimental data at extreme angles, where some model details are more sensitive, are scarce. Almost all experimental data sets have about 10% statistical and systematical errors. There are some discrepancies between the different experiments. Only two experiments have studied the virtual photon radiative capture. Only one experiment studied both gamma and the $^3$He in the final channel, with the photon detection efficiency of approximately 50% [49]. For $E_\gamma > 50$ MeV, the PDRC results have good agreement with the inverse reaction results, which is a test of time-reversal invariance in the electromagnetic interaction. For $35 < E_\gamma < 55$ MeV, there is no agreement between the PDRC and the inverse reaction results even within the 10% error bars. There is no PDRC data set for $70 < E_\gamma < 100$ MeV.

**Competing interests**
The author has no competing interests.

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