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VECTOR AND TENSOR ANALYZING POWERS OF THE ^{1}H($\vec{\mathrm{d}}$,γ^3He) CAPTURE REACTION

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Abstract

Precise measurements of the deuteron vector analyzing power A_y^d and the tensor analyzing power A_{yy} of the ^{1}H($\vec{\mathrm{d}}$,γ^3He)-capture reaction have been performed at deuteron energies of 29 MeV and 45 MeV. The data have been compared to theoretical state-of-the-art calculations of the Bochum-Krakow, Hannover-Lisbon and the Pisa group. Due to the large sensitivity of polarization observables and the precision of the data small effects in the dynamics become visible.

1 Introduction

The three-body system is particularly interesting because its wave function can be exactly calculated in a non-relativistic framework. Ground and continuum states are treated on the same footing and realistic nucleon-nucleon potentials like CD Bonn or Argonne V18 are used. Even though the basic principles are the same for the three-body theoretical groups [1–6] the technique used to solve the Schrödinger equation are quite different. Therefore it is satisfying to see that their results on the one-body current level agree well to each other. Beyond the one-body current different descriptions of Meson Exchange Currents (MEC's) and three-body forces and different treatments of explicit inclusion of Coulomb interaction and relativistic corrections makes a comparison of the results from the Bochum-Krakow, Hannover-Lisbon and

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Pisa group interesting. However, comparison to experimental data is mandatory. These data should be preferably sensitive to small effects in the dynamics and the error bars should be smaller than these effects.

The data taken by the Basel-PNPI collaboration at the Philips injector cyclotron at the Paul Scherrer Institut (PSI) which will be described in the following, fulfill these requirements. In polarization observables like the vector and tensor analyzing powers, A_y^d and A_{yy}, the dominant S-S transition in the radiative capture reaction ^{1}H($\vec{\rm d}$,γ)^{3}He is suppressed compared to the S-D amplitude. The latter is closely related to MEC's as it was shown in the measurement of e.g. the elastic form factors in the A=3 system [8]. Therefore one can expect that measurements of polarization observables in capture reactions provide insight into the different roles played by nucleonic and mesonic degrees of freedom.

The deuteron analyzing powers A_y^d and A_{yy} are measured using a vector and tensor polarized deuteron beam with its spin perpendicular to the scattering plane. Then the cross section can be written as

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{d\sigma_o(\theta)}{d\Omega}\left(1 + \frac{3}{2}p_z A_y^d + \frac{1}{2}p_{zz}A_{yy}\right). \qquad (1)$$

Here σ_o is the unpolarized cross section and θ the center-of-mass (c.m.) angle of the deuteron-photon system. The vector and tensor polarizations of the beam, p_z and p_{zz}, have to be measured absolutely before the analyzing powers can be extracted.

The deuteron beam energy was chosen as 29 MeV and 45 MeV. At around 30 MeV the beam energy dependence of $A_{yy}(\theta = 90^o)$ shows a maximum whereas at 50 MeV a zero crossing occurs as shown by both experimental data [9–15] and theory [2, 16]. The minimum of $A_{yy}(\theta = 90^o)$ is expected to be particularly sensitive to interference effects. As it will become clear when comparing the data to the theoretical results the tensor analyzing powers at these two energies show rather different sensitivities to the underlying physics.

The full angular dependence of the analyzing powers up to the extreme angles were measured which is important because of the different sensitivity to MEC's. In the energy range of 10-50 MeV the ^{1}H($\vec{\rm d}$,γ)^{3}He-capture process is dominated by the electric dipole transition (E1). Although MEC's can give large contributions to the E1-transition, they can be taken into account implicitly when performing calculations with operators derived using the Siegert's theorem [17]. The Siegert theorem treats the two-body currents in (part of) the electric transitions only and disregards them in the magnetic transitions completely. Therefore at medium angles where the E1-E1 transition dominates ($\propto \sin^2(\theta)$) it is expected that the Siegert theorem will provide a good description of the data. At the extreme angles in forward and backward direction the small M1 amplitude is enhanced by the E1 amplitude in the M1-E1 interference term. In the M1 transition MEC's can contribute up to 50 % [13].

2 Experimental details

The experiment was performed at the Philips injector cyclotron (maximum proton energy 72 MeV) of the Paul Scherrer Institute (PSI) in Villigen (Switzerland) where a polarized deuteron beam prepared in the PSI atomic beam ion source [18] was available. With the two strong and one weak field radio frequency (RF) -transition units the nuclear polarization was induced. Depending on the combination of active RF-units 4 polarization states with $p_z = \pm 1/3$ and $p_{zz} = \pm 1$ could be obtained in addition to the unpolarized beam (= 5 modes). To minimize systematic errors the modes were cycled through with a repetition rate of 0.3 Hz.

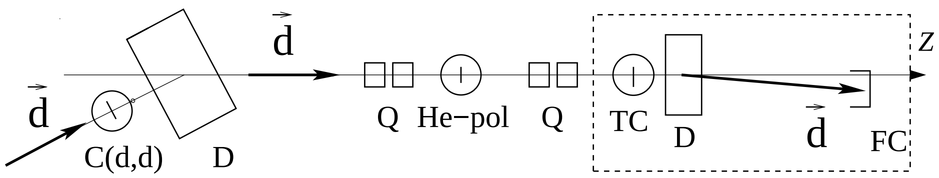

Figure 1: Schematic overview of the beam line in the experimental hall NE-C. Here C(d,d) - carbon scattering chamber, Q - quadrupole doublet, He-pol - ^{4}He-polarimeter, TC - target chamber, D - dipole magnet to separate ^{3}He and unscattered deuterons, FC - Faraday cup.

In fig. 1 a sketch of the experimental setup is shown. In a first a scattering chamber deuterons scatter elastically on a thin carbon foil and are detected using a fast scintillator. The signal relative to RF of the cyclotron gives online-information about the actual bunch structure of the beam. It was required to be less than 1.5 ns FWHM. After a dipole the deuterons passes a second scattering chamber which houses a polarimeter to measure the tensor and vector polarization of the beam. It consists of a ^{4}He cell of 0.5 bar and two passivated implanted planar silicon (PIPS) detectors which detect the recoil ^{4}He at $\theta_{cm} = 150^o$ left and right from the beam line. The PIPS detectors allow to discriminate between α particles and deuterons. At this angle the vector and tensor analyzing powers for elastic d-α scattering are high and precisely known [19]. Then the beam polarizations can be extracted in a similar to eq. 1. In average the polarizations were $p_z = 0.25$ and $p_{zz} = 0.65$, determined with accuracies of 2 -3%.

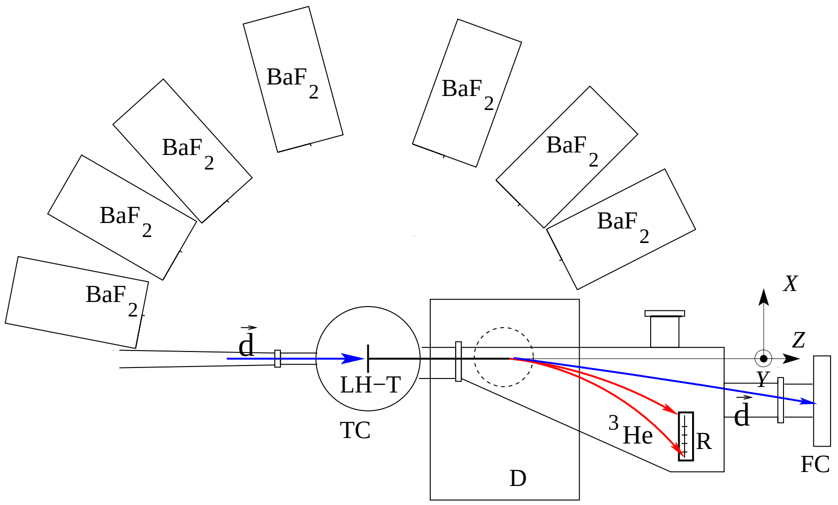

Figure 2: Schematic overview of the setup: LH-T - liquid hydrogen target, D - dipole magnet to separate ^{3}He and unscattered deuterons, R - recoil-detectors, FC - Faraday cup.

Behind the beam polarimeter the setup for the capture experiment is located. It is shown in more detail in fig. 2. The deuteron beam hits first the liquid hydrogen target (16 K at 0.25 bar) with a thickness of 14 mg/cm^2. The conical beam entrance tube allows also for measurements at extreme backward angles. The capture photons are detected in four BaF_2 crystals of dimension 8cm x 8cm x 25cm. This crystal was chosen for its excellent timing characteristic and the high density (4.89 g/cm^3) which leads to a good efficiency for photons and an acceptable energy resolution of about 16%. Further the short component allows to discriminate between photons and neutrons generated by background reactions. Both performances are crucial considering the high background rate from hadronic reactions (in particular neutrons from the break-up reaction). In addition the crystals were shielded against background with 5 cm Pb on top, bottom and side as well as 5 cm Bor-plastic in the front.

The recoil ^{3}He particles are detected in a segmented plastic scintillator of 1.2 mm thickness. The thickness is chosen such that ^{3}He is stopped but protons and deuterons pass through. This helps distinguishing these particle types. The ^{3}He recoil in a cone between 0.4^o and 2.6^o degrees. Without the C-shaped dipole it would be not possible to separate them from the deuteron beam downstream. The strength of the magnetic field was chosen such that the ^3He were separated from the deuteron beam by 10^o. Simulations were performed to determine the path of the particles.

Finally a Faraday cup (FC) stopped the beam and measured the current for each polarization state.

3 Analysis and Results

The main challenge of the data analysis is to single out the few capture events from a huge background due to hadronic reactions. The signal to noise ratio (S/N) could be increased to one by a hardware coincidence (time window 25 ns) between the detected photon, the recoiling ^3He and the RF of the cyclotron. After applying several 2-dimensional software cuts S/N was larger than 25. For a more detailed description of the software cuts see refs. [20, 21]. After applying all possible cuts the γ energy spectrum of the

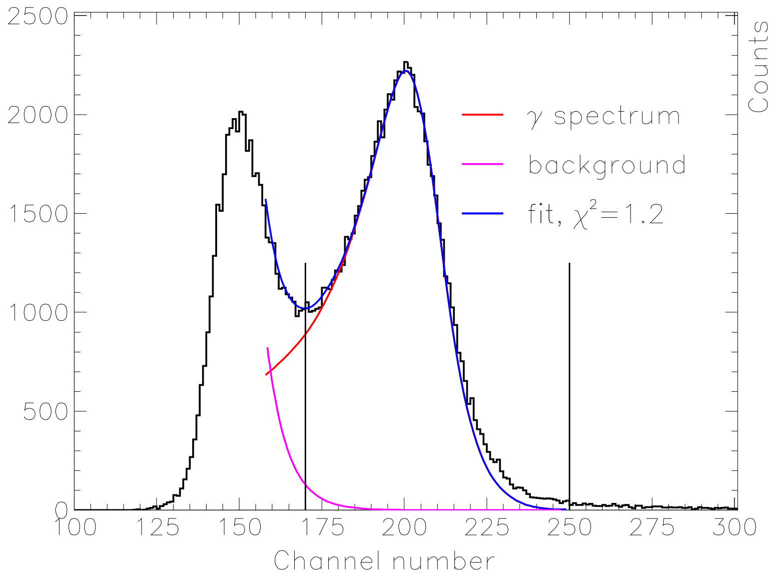

Figure 3: Final γ energy spectrum of the short component in BaF_2. Indicated are the integration limits set for the signal. Further the fit of the response function to the data is shown as well as the decomposition into background (magenta) and signal (red).

short component of BaF_2 obtained is shown in fig. 3. Also indicated are the integration limits from which the final asymmetries are derived. The asymmetries are diluted by the remaining background from the low energy photons leaking into the region of the integration limits. The final result has to be corrected for and therefore the background has to be determined. For this a fit function for the region between the integration limits is needed, i.e. a response function of BaF_2 for photons of about 20 MeV must be known.

For this determination an additional experiment with monoenergetic γ-rays was performed at the Physics Institute of the University of Basel. Monoenergetic 20 MeV γ-rays were produced in a ^{3}H(p,γ)^{4}He reaction with a 1 MeV proton beam provided by a Cockcroft-Walton accelerator. The detector was placed at 110 deg close to the maximum of the angular distribution of the photons in a similar geometry as in the $\vec{d}-p$-capture experiment. The measured short component of the BaF_2 response function plus an exponential function representing the background were folded with a Gaussian and fitted with the peak position, the amplitude, the width of the Gaussian and the exponent of the exponential function as free parameters. The result of such a fit is shown in fig. 3. The background determined in this way contributes at maximum 4.6%. In addition it was verified that the background is unpolarized. Further various systematic checks were done to determine the systematic error. The resulting total systematic errors vary between 0.00044 and 0.00113 as compared to the statistical errors of 0.00187 to 0.00470.

4 Comparison to theory

The present data together with previous data taken at the same deuteron energies are compared to calculations from the Bochum-Krakow group [22] ,the Pisa group [23] and the Hannover-Lisbon group [24]. The calculations are all exact in the sense that they provide a full solution of the Schrödinger equation for a realistic nucleon-nucleon interaction for both the ground- and continuum states. The techniques applied in the calculations by the three groups are quite different. The Hannover-Lisbon group solves the Alt-Grassberger-Sandhas equation in momentum space via a Chebychev expansion of the two-baryon transition matrix. As N-N potential the CD-Bonn potential is used which is extended to include the excitation to a (static) Δ. The latter produces an effective three-body force. The CD-Bonn + Δ extension is as exact as CD-Bonn as it is also fitted to the experimental two-nucleon data up to 350 MeV [25]. The Pisa group solves the three-body Schrödinger equation in coordinate space by variational methods. The wave function is expanded by pair-correlated hyperspherical harmonics. The Bochum-Krakow group solves the Faddeev equation in momentum space. The Pisa and the

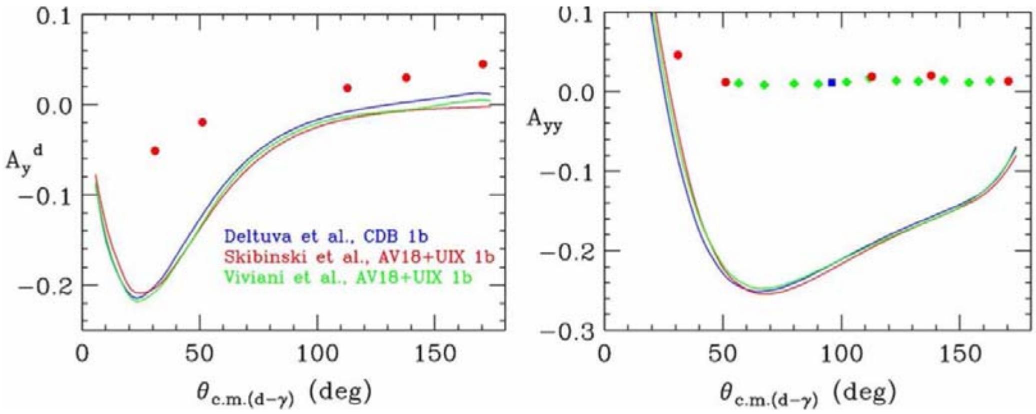

Figure 4: A$_y^d$ (left) and A$_{yy}$ (right) for 45 MeV incident deuteron energy as a function of the center-of-mass angle between deuteron and outgoing γ. Data of the present experiment (•) together with the data by Anklin et al [14] (○) and Jourdan *et al.* [13] (□) are compared to the one-body-calculations by Deltuva *et al.* (blue), Skibinski *et al.* (red) and Viviani *et al.* (green). The last two calculations also include the three-body force.

Bochum-Krakow group are using the Argonne V18 potential combined with the Urbana IX three-body force.

The data shown in the following are from the present experiment and from Anklin *et al.* [14] (○) and Jourdan *et al.* [13] at incident deuteron energies of 29 and 45 MeV. The data themselves have non-visible error bars and are therefore also able to distinguish tiny effects. All three data sets are in

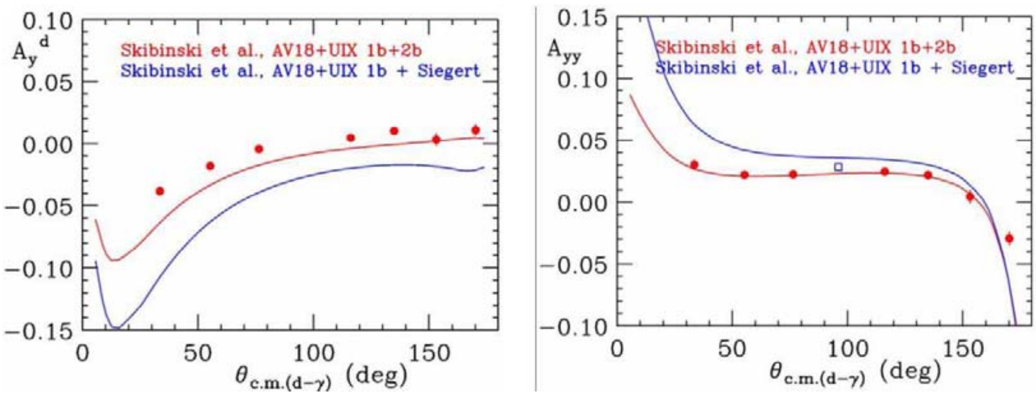

Figure 5: Similar to figure 4 but for 29 MeV. Here the data are compared to the calculations by Skibinski *et al.* with an explicit treatment of the exchange currents (red) and within the Siegert approach (blue).

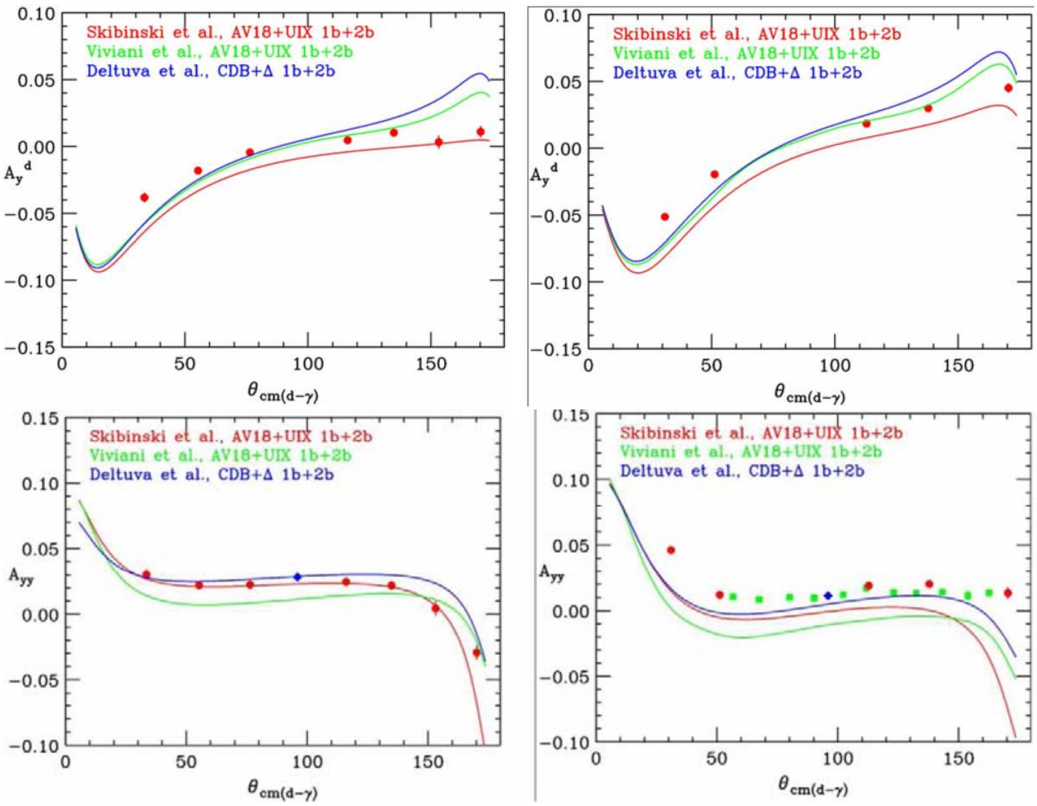

Figure 6: A_y^d (top) and A_{yy} (bottom) for 29 MeV (left) and 45 MeV (right). Data are the same as in fig. 4. They are compared to the calculations with the explicit treatment of the exchange currents and two- and three-body currents: Marcucci/Viviani *et al.* (green), Skibinski *et al.* (red) and Deltuva *et al.* (blue).

good agreement with each other. In fig. 4 the results for 45 MeV from the three theoretical groups are shown for the case of neglecting the two-body currents. The large deviation from the data demonstrates the importance of two-body currents. In contrast they contribute only 15% in the unpolarized cross section. Even though the calculations use different potentials, the CD-Bonn and the Argonne V18, the difference between the results are small. The calculations of the Bochum-Krakow and the Pisa group contain in addition the Urbana IX as three-body force. It seems already here that the effect of the three-body force is small. For an explicit comparison see below. The results at 29 MeV show the same features as at 45 MeV and therefore they are not shown here (s. ref. [20] for a more detailed comparison).

In sec. 1 the application of the Siegert theorem to the case of the cap-

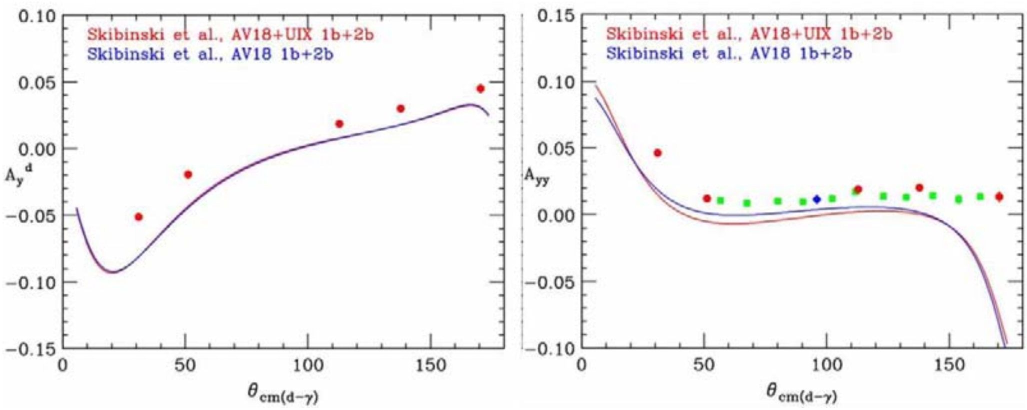

Figure 7: The data (s. fig. 4) for E = 45 MeV are compared to the calculations by Skibinski *et al.* with one- and two-body currents only (blue) and with the Urbana IX as three-body force in addition (red).

ture reaction was discussed. The Bochum-Krakow group provided calculations where the two-body currents are approximated by the Siegert theorem (modified version in momentum space s. [2]), i.e. MEC's are neglected in the magnetic currents, and with an explicit treatment of MEC's using the Riska prescription [26]. While it was previously thought that the Siegert theorem would describe the data correctly at medium angles where the E1 transition is dominant, this is not the case as shown in fig. 5. On the other hand explicitly taking into account π and ρ currents via the Riska description improves the theoretical description of the data a lot.

In fig. 6 the calculations of the three groups including two- and three-body currents are shown. Whereas the Hannover-Lisbon and Bochum-Krakow group take the Riska prescription for the π and ρ exchange currents the Pisa group uses exchange currents for the π, ρ, ω and σ currents consistent with the Argonne V18 potential [23]. In this case current conservation is preserved. Further the excitation to a Δ as well as point Coulomb interaction are taken into account. For the tensor analyzing power at 29 MeV satisfactory agreement with the data is achieved. However, particularly at 45 MeV a deviation from the data at small and large angles is apparent.

The effect of the three-body force was studied by Skibinsky *et al.* for 45 MeV beam energy. As shown in fig. 7 its effect is small and the large discrepancy to the data at backward angles for A_{yy} remains unchanged.

A similar discrepancy presented a long standing puzzle in the 0 deg cross section of the *two-body* photodisintegration. Cambi, Mosconi, and Ricci [7] solved this puzzle demonstrating the importance of the relativistic spin-orbit contribution.

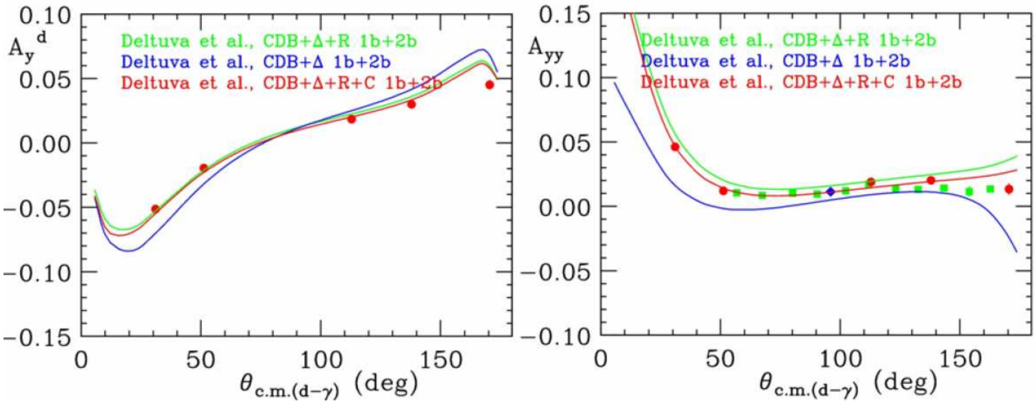

Figure 8: Comparison to the calculations by Deltuva *et al.* with two- and three-body currents (blue), plus relativistic corrections (green), and plus added Coulomb corrections (red).

Deltuva *et al.* included a relativistic correction of the order $(k/m_N)^2$ in the current operator [24]. Here k is the nucleon momentum and m_N the nucleon mass. This calculation, shown in fig. 8, is in very good agreement with the data and also describes A$_{yy}$ at backward angles for the first time. In addition the effect of the Coulomb interaction was studied. Inclusion of the Coulomb interaction into a calculation in momentum space is not straightforward as in configuration space. This problem was solved by using a screened Coulomb potential [16]. A benchmark calculation between the Pisa and Hannover-Lisbon group was performed for verification of the procedure [27]. The effect of the Coulomb interaction at 45 MeV is small (s. fig. 8).

5 Summary

Precise data for the vector and tensor analyzing powers, A$_y^d$ and A$_{yy}$, have been measured at a deuteron beam energy of 29 and 45 MeV in a wide angular range for the capture reaction ^{1}H($\vec{\mathrm{d}}$,γ)^{3}He. These energies were chosen because at 29 MeV A$_{yy}$ has a maximum whereas at 45 MeV it is close to the zero crossing.

The data were compared to exact calculations of three groups, the Hannover-Lisbon, the Bochum-Krakow and the Pisa group [22–24] which use different approaches and potentials. The calculations are in general in good agreement with each other, in particularly when only one-body currents are included. Calculations disregarding the two-body currents are in large disagreement with the data demonstrating the sensitivity of the data to MEC. Further-more the treatment of the MEC's using the Siegert theorem, i.e. by neglecting the MEC's in the magnetic part completely, is not sufficient to describe the data. While the sensitivity to the three-body force and the Coulomb interaction is small, relativistic corrections have to be included to get a satisfying agreement for A_{yy} at 45 MeV and backward angles.

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