Measurement of the polarization-transfer coefficient $K_y^{y'}$ of the fusion reaction $^2\mathrm{H}(\vec{d}, \vec{p})^3\mathrm{H}$ at $E_d = 58$ keV

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We measured the polarization-transfer coefficient $K_y^{y'}$ of the fusion reaction $^2\mathrm{H}(\vec{d},\vec{p}\,)^3\mathrm{H}$ at $E_d = 58$ keV at the laboratory reaction angle $\theta = 45°$. The result is compared with theoretical predictions based on Faddeev-Yakubovsky equations, calculated with and without inclusion of the Coulomb interaction, and a prediction based on a T-matrix parametrization of all available data of this reaction at energies below 500 keV.

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I. INTRODUCTION

With the three-nucleon system being (apart from a few remaining discrepancies such as the A_y puzzle of *dp* elastic scattering) well described by state-of-the-art Faddeev calculations [1] and with some progress in Faddeev-Yakubovsky calculations the interest in the four-nucleon system has grown appreciably in recent years. The theoretical situation before such calculations became available is described in detail in Ref. [2]. Like the three-nucleon system it is a suitable testing ground for modern meson-exchange nucleon-nucleon forces introduced into these calculations as well as for the effects of three- (and four-)nucleon forces. The A_y puzzle appears at least as severe in the $p + {}^3\mathrm{He}$ scattering as in the *dp* case [3,4]. Recent successes in *ab initio* calculations of levels of light nuclei assign a special role to the four-nucleon scattering system as intermediate between the two- and three-nucleon system and heavier light nuclei.

The four-nucleon systems have a number of features not found for three nucleons, which makes their study especially interesting. Some of them are existence of excited states, a complicated reaction mechanism, many channels in $[3 + 1]$ and $[2 + 2]$ configurations, and polarization effects much larger than for the $3N$ systems. The *dd* fusion reactions $^2\mathrm{H}(d,p)^3\mathrm{H}$ and $^2\mathrm{H}(d,n)^3\mathrm{He}$ play an important role in the big-bang element synthesis and primordial abundances (see, e.g., Ref. [5]) and in fusion-energy research where especially the idea of "polarized fusion" yields some remarkable consequences (see Refs. [6–8]).

Especially in this context of fusion energy, but also for general nuclear-physics considerations it is important to know the reaction mechanism of the *dd* reactions in detail. Different from the $^3\mathrm{H}(d,n)^4\mathrm{He}$ reaction and its mirror reaction $^3\mathrm{He}(d,p)^4\mathrm{He}$ which are dominated at low energies by a $\frac{3}{2}^+$ S-wave resonant state they need 16 complex transition matrix elements (MEs) in S-, P-, and D-waves for a complete description. Using all available data of these reactions below $E_d = 1.5$ MeV, parametrized by Legendre expansion coefficients, a set of MEs for each has been determined by direct fit [9–12]. This determination was practically model-independent. The only (well-founded) assumption entered was that the energy dependence of all transitions is entirely determined by the Coulomb penetrability. Therefore, the transition MEs could be factorized into calculated energy-dependent terms and energy-independent MEs thus allowing the combination of all data at different energies.

With these results predictions of all observables, especially of any unmeasured quantities, of both reactions can be performed. One such quantity is the "quintet-suppression factor" (QSF). This quantity (if $\ll 1$) would make a neutron-lean fusion reactor, based on the $^3\mathrm{He}(d,p)^4\mathrm{He}$ reaction, possible. It measures the possible suppression of $^2\mathrm{H}(d,n)^3\mathrm{He}$ neutrons by polarizing the fusion fuel (*dd* in the quintet state). The direct experimental determination of QSF would require a spin-correlation cross-section measurement at low energies such as 50 keV which has not been done so far. Whereas theoretical predictions for QSF vary widely, indirect determinations from the above analysis [12] as well as from multichannel R-matrix parametrizations [13] show that no neutron suppression occurs (see Fig. 1).

The present measurement of the vector-to-vector polarization-transfer coefficient (PTC) $K_y^{y'}$ was performed to provide additional *dd* reaction information on imaginary parts of ME products which were under-represented in the ME analysis of Ref. [12]. Polarization-transfer coefficients (PTCs) are suitable observables. Only one other experiment to determine PTCs at very low energies has been done so far [17] since the very low count rates present a serious difficulty. Katabuchi measured at an incident beam energy of 90 keV. The energy loss in his aluminum-backed deuterated-polyethylene $(\mathrm{CD}_2)_n$ targets resulted in an average reaction energy of $E_d = 68$ keV. Like in many other polarization-transfer experiments at higher energies he chose a primary scattering angle of $\theta = 0°$. In addition to a higher cross section, another advantage was a simplified determination of the transfer coefficient. He used only one detector for the second scattering, implying that he could not notice effects of the silicon crystal structure. These and other (new) results, when introduced in a new ME fit, are expected to corroborate the earlier results.

In Sec. II we briefly discuss the existing theoretical approaches to the $4N$ scattering system. Details of the experiment are given in Sec. III and the results in Sec. IV. We summarize in Sec. V.

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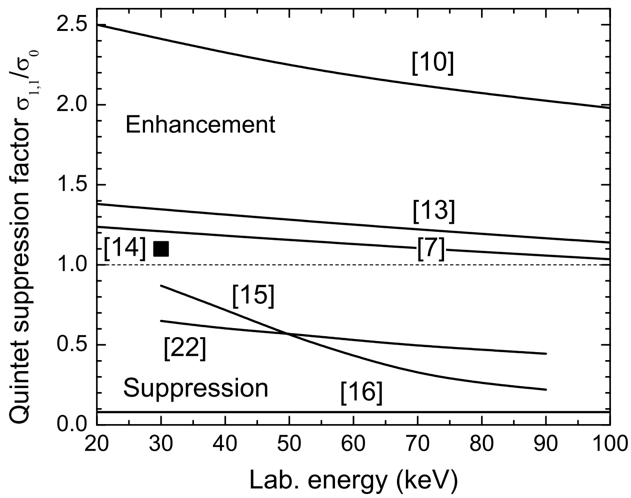

FIG. 1. Predictions and results from data parametrizations for the low-energy quintet-suppression factor of the $D(d,p)^3H$ reaction. Results for the $D(d,n)^3He$ reaction, not shown here, are 10% to 30% lower than for $D(d,p)^3H$. For comparison only one early DWBA prediction for $D(d,n)^3He$ is shown here [16]. Theoretical predictions have been published in the framework of four-body Faddeev-Yakubovsky equations [14,22] and DWBA [16], whereas data parametrizations have used T-matrix analysis [10], R-matrix analysis [7,13], and phase-shift analysis [15].

II. THEORY

Only very few attempts have been made at calculating the *dd* observables microscopically, i.e., based on realistic nucleon-nucleon (*NN*) potentials as input, especially at very low energies. The theoretical framework for such calculations are the Faddeev-Yakubovsky equations [18]. Examples are calculations by Fonseca [19], Gorbatov [20], and Uzu [21,22]. All calculations suffer from computational difficulties due to the complexity of the problem. Thus, the number of states taken into account and the treatment of the Coulomb interaction are insufficient, or only phenomenological *NN* potentials were used. However, improvements are underway [23]. In the future, also new approaches such as application of effective field theory approaches may be promising.

III. EXPERIMENT

A. Setup

The measurements were performed at the Cologne FN tandem Van de Graaff (VdG) accelerator facility. The purely vector-polarized deuterons were produced by the Cologne Lambshift source LASCO [24] in the SONA mode [25]. Due to the required very low deuteron energy the existing injector into the FN accelerator with a maximum voltage of 80 kV could be used to accelerate and focus the deuteron beam into an ORTEC 600 scattering chamber mounted in the injector beamline. Thus, continuous longtime operation of the entire experiment independent of and parallel to the FN tandem operation was possible. The beam with currents limited to 600 nA (on target) was focused into a beam spot of 3 mm diameter inside the scattering chamber.

The pure vector polarization p_y was achieved by performing one nonadiabatic (SONA) transition and ionization to D^- in a strong magnetic field of 18 mT. The polarization vector was precessed in a subsequent Wien filter into the vertical (lab) y axis. Using a Wien filter is not only useful to adjust the polarization direction at the target, but also–in combination with a magnet steerer–to deflect electrons which are accelerated from the ion source. The beam polarization was measured continuously by two detectors left and right at 115° using the fact that the $^2H(\vec{d},p)^3H$ reaction has the high vector-analyzing power of $A_y = 0.204 \pm 0.01$ at 58 keV, derived from an interpolation of data [13,26]. An average p_y value of 0.471 ± 0.023 (70% of the theoretical value) over the entire experiment has been achieved. Figure 2 shows the experimental setup including the primary and secondary (transfer) polarimeters.

B. Primary targets

In order to find the best primary target material for the given low-energy regime targets from different solid materials were compared. The high energy loss with the possibility of fast evaporation of deuterium had to be considered together with the nuclear density for maximum yield. Organic materials such as deuterated polyethylene and parapolyphenyl were excluded because of their limited thermal stability under beam conditions. Out of the other options (such as LiD) TiD_x targets with their superior thermal stability and high deuterium content were chosen. The titanium foil thickness was 0.3 $\frac{mg}{cm^2}$ so that the

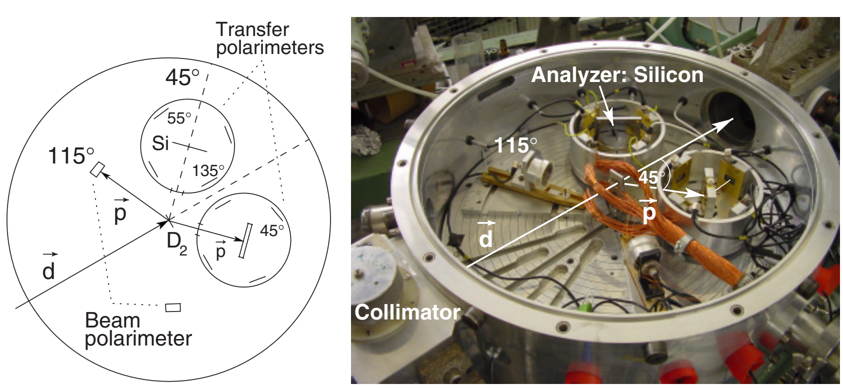

FIG. 2. (Color online) Setup in the scattering chamber: Two transfer polarimeters at $\theta = 45°$, the beam polarimeter detectors at $\theta = 115°$ and a Cu braid around the target.

beam was completely stopped. The deuterium was absorbed by heating the foils in a gaseous atmosphere to about 500°C. For this work a high deuterium content of about 10% by mass could be achieved. In order to determine the true reaction energy for the given injector beam energy of 78 keV a weighted average over the given thickness d of the target using the known total cross section $\sigma(E)$, obtained from the available global data set, as weighting factor was calculated. For each layer in steps of 1 μm the residual energy was determined by means of the program STOP [30], taking into account the stopping power of deuterated titanium. The relation

$$\langle E\rangle = \frac{\int_0^d \sigma_{\mathrm{tot}}(E(x)) \cdot E(x) dx}{\int_0^d \sigma_{\mathrm{tot}}(E(x)) dx} \tag{1}$$

yielded an average reaction energy of 58 ± 5 keV. The error is an estimate only, taking into account uncertainties in the target density and in the energy-loss calculations. In order to avoid carbon deposition and therefore an increase of target thickness by cracked hydrocarbon vapors in the scattering chamber a thick Cu braid cooled by LN_2 was mounted around the entire target region in conjunction with a good base vacuum of 2×10^{-6} mbar in the chamber.

C. Transfer polarimeters

Owing to the energy of the outgoing protons around 3 MeV where the effective analyzing power of polarimeters using proton scattering from ^{4}He or ^{12}C becomes quite small two polarimeters based on using natural Si as secondary targets were developed. One target (1) consisted of a single-crystal Si wafer with a thickness of (25 ± 3) μm, the other (2) of a ΔE transmission Si detector of thickness 18 μm.

For the optimization of the new polarimeters the variability of the adjustment of the detectors and the analyzer target proved to be advantageous. To achieve the same shapes of the spectra in the detectors left and right for the forward and backward direction, respectively, the two secondary Si targets were mounted perpendicular to the incident proton beam from the primary $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction under the lab angle $\theta = 45°$ left and right. As a result of a data evaluation and thereby the optimization of the figure of merit (FOM), the product of the square of the vector analyzing power and the cross section, the two sets of left and right transfer-polarimeter detectors were mounted under the angles $\theta_2 = 55°$ and 135° for polarimeter 1. The set at forward direction in polarimeter 2 had to be placed slightly off the optimal value, i.e., at $\theta_2 = 45°$. This was necessary because of the space taken by the transmission Si detector mount.

The absolute calibration with respect to effective analyzing power took place in the large ORTEC 2800 scattering chamber in a beamline at the FN tandem VdG accelerator with protons of the proper energies around 3 MeV incident directly on the polarimeters. The beam polarization was determined with the existing ^{4}He polarimeter in the Faraday cup of the scattering chamber at $\theta = 112°$ and $E_p = 12$ MeV, where the analyzing power is 1.0. The effects of the primary target (straggling and therefore beam spreading over the entrance aperture) were simulated by inserting a gold foil with a thickness

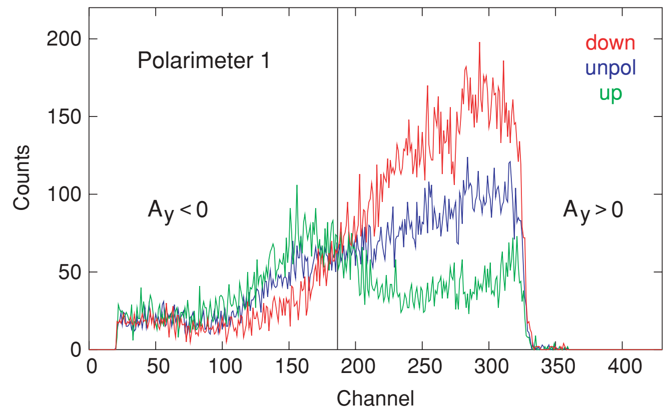

FIG. 3. (Color online) Effect of the polarization on the transfer-polarimeter spectra ($\theta_2 = 135°$).

of 2.6 μm in the beam path. Due to the high polarimeter efficiency the incident deuteron beam had to be reduced to ~pA. With the polarimeters in the beam line and therefore the additional straggling in the thick Si target this low current could not be measured in the cup behind the scattering chamber. Hence, two detectors were placed in the chamber to monitor the beam current and to allow a relative charge integration. Consequently, the beam polarization could not be measured simultaneously. The determination of the polarization component p_y was done by removing the polarimeters before and after the calibration, respectively. Runs with alternating up and down proton polarization as well as unpolarized runs were taken. By measuring the elastic p-Au scattering the runs could be normalized. The effect of the polarization is clearly visible in Fig. 3.

It is interesting that the strong angular dependence of the $\mathrm{Si}(p,p)$ analyzing power for the large acceptance angles of the polarimeter detectors with the Si targets leads to two spectral regions with opposite analyzing powers at backward angle ($\theta_2 = 135°$). When used in the transfer experiment they have to be evaluated separately. When the protons are detected at a backward angle, they are scattered many times more in the thick Si target than when detected in forward direction. This results in quite different shapes of the polarimeter spectra.

Up to now almost all measurements of $K_y^{y'}$ have been done at a scattering angle of $\theta = 0°$. In this case, there are simplifications in the determination of the PTC as well as a markedly higher cross section. Though the experiment and its analysis are simpler the measurement at other angles of the angular distribution is certainly important. For the polarimeters a very compact design was attempted such that two of them can be mounted in the small scattering chamber. Predictions for $K_y^{y'}$ and therefore suitable scattering angles exist [12]. Guided by these predictions and as a compromise between a scattering angle with a reasonable cross section and a position not too far away from the target a scattering angle of $\theta = 45°$ for both polarimeters was chosen. The efficiency of the two polarimeters was determined to be $\epsilon_1 = 3.9 \times 10^{-5}$ and $\epsilon_2 = 2.8 \times 10^{-5}$. Both values can be combined to give an relative effective FOM $A^2_{\mathrm{eff},1} \times \epsilon_1 = 3.01 \times 10^{-6}$ and

TABLE I. Efficiency and relative FOM of polarimeters–comparison between several analyzers.

Analyzer:	Efficiency	FOM	
^{28}Si			
	9.7×10^{-6}	1.88×10^{-6}	[17]
	3.8×10^{-6}	0.16×10^{-6}	[31]
	$\sim 12.5 \times 10^{-6}$	$\sim 2 \times 10^{-6}$	[34]
^{3}He, ^{4}He and ^{12}C			
	38×10^{-6}	16.2×10^{-6}	[27,28]
	1.4×10^{-6}	$\geqslant 0.4 \times 10^{-6}$	[29,30]

$A^2_{\mathrm{eff},2} \times \epsilon_2 = 0.64 \times 10^{-6}$. Table I shows a comparison with similar ^{12}C and He polarimeters [27,31] and testifies to the usefulness of Si as a polarimeter target in this energy region, see also [32–34].

One serious problem when using single-crystal Si targets proved to be the channeling of the scattered protons. This showed up as huge count-rate differences between left and right detectors even with unpolarized protons and could be resolved only by careful changes of orientation away from preferred crystal axes. For the analysis a small correction factor could be determined in the calibration.

D. Detectors

Si(Li) surface barrier detectors with an active area of 100 mm^2 and circular diaphragms with diameters of 9 mm were used as beam polarimeter detectors at a distance of 90 mm from the target. They were protected against secondary electrons and especially elastically scattered deuterons with 1 μm thick foils of Hostaphan (=PET = Mylar). The eight transfer-polarimeter detectors consisted of PIPS (Passivated Implanted Planar Silicon) Detectors with a thickness of 300 μm and an active area of 450 mm^2. To realize a compact design the detectors had a transmission mount with a radial microdot connector. By means of a proton beam with an energy relevant in the calibration the size of the diaphragms could be determined by an optimization between a count rate as high as possible and acceptable broadened shapes of the spectra. These detectors were used together with diaphragms of 16 × 10 mm^2 at a distance of 46 mm from the secondary Si targets. They were mounted together with these targets inside two cylindrical housings for each polarimeter for protection from secondary electrons and for good electrical shielding and ground. The distance between the primary and secondary targets was 102 mm.

E. Spectra

Figure 4 shows a typical spectrum of one of the beam-polarimeter detectors with 0.4 mC of D$^-$ on the target. Only the proton peak was used for determining p_y.

The combined (added) count rate of the left and right detector and the beam current on the (stopping) target as measured with a current integrator were used to distinguish the relative change of target thickness with time due to deuterium evaporation from changes of the beam current from the source. Thus it was established that the limitation of the beam current to less than 600 nA guaranteed that very little evaporation or sputtering from the target occured. A differential-cross section value of $\frac{d\sigma}{d\Omega} = (0.465 \pm 0.050)\ \frac{\mathrm{mb}}{\mathrm{sr}}$ at E$_d$ = 58 keV and $\theta = 115^\circ$ was used. For the result of the measurement presented here, no systematic current integration was necessary. Therefore, we can give an estimate only of the beam charge, delivered to the target during the effective beam time of about 30 d, of ∼0.7 C. The real experiment lasted at least one year, due to setting up and testing of all components.

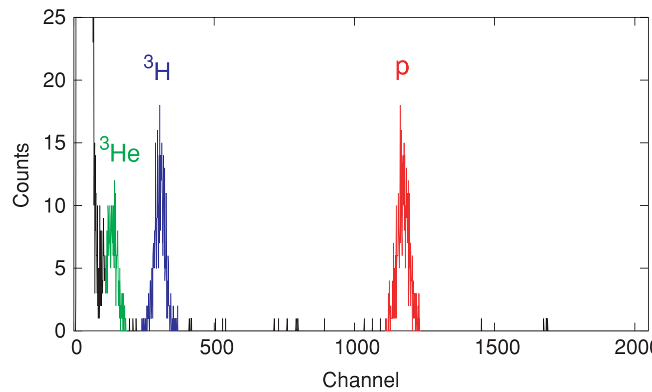

FIG. 4. (Color online) Typical spectrum at $\theta = 115^\circ$ after the primary reaction in one of the beam-polarimeter detectors.

The transfer-polarimeter spectra suffer from very low count rates and correspondingly some background. The source of this background is probably electronic noise and even cosmic radiation cannot be excluded. The known spectral shape from the calibration runs was employed to identify the peak regions of the doubly-scattered protons in the presence of some background. The peaks were analyzed by fitting a constant+exponential function to the background. Figures 5 and 6 show the resulting background-corrected spectra.

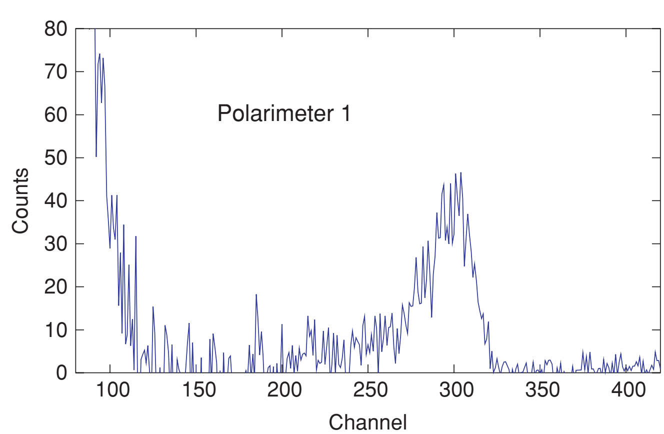

FIG. 5. (Color online) Background-corrected spectrum in polarimeter 1 in forward direction ($\theta_2 = 55^\circ$).

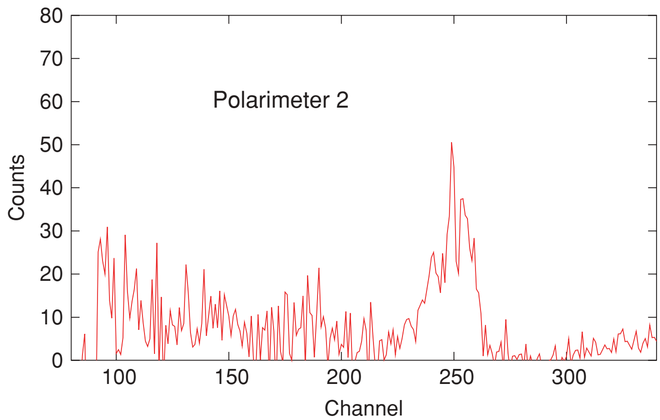

FIG. 6. (Color online) Background-corrected spectrum in polarimeter 2 in forward direction ($\theta_2 = 45^\circ$).

IV. RESULTS AND DISCUSSION

The cross section at backward angles was found to be one order of magnitude smaller than at forward angles. Due to the very low count rates and despite several months of effective beam time the statistics of the backward angle detectors was not good enough to be used for the present results. Thus, only forward detector spectra were analyzed.

The polarization-transfer coefficient was determined according to the equation

$$K_y^{y'} = \frac{p_{y'}\left(1 + \frac{3}{2}p_y A_y\right) - P^{y'}}{\frac{3}{2}p_y},$$

where p_y is the incident deuteron beam polarization, A_y the analyzing power of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction, $P^{y'}$ and $p_{y'}$ the outgoing proton polarization for incident unpolarized and polarized deuterons, respectively. The first of these quantities was determined simultaneously with the transfer measurement from the left-right asymmetry of the beam-polarimeter detectors (see Sec. III).

The second and third quantities were taken from the results of the transition ME fit (including energies up to 1500 keV) [12] with the program TUFXDD [35–38] because of their much smaller errors than those resulting from the present experiment. The numerical value for $\theta = 45^\circ$ (with a small variation over the aperture size of the polarimeter of ± 0.011) used here was

$$A_y = 0.074 \pm 0.040,$$

and for the outgoing polarization with unpolarized deuterons

$$P^{y'} = -0.045 \pm 0.020.$$

The variation of A_y is very small. A change of the average reaction energy of 3 keV implies a variation of 0.1% for this quantity, and a difference of 2% for the value of $P^{y'}$. The quantity $p_{y'}$ was determined in the present experiment by forming double ratios between left/right detectors and up/down polarization states leading to the final results:

$$K_y^{y'} = -0.005 \pm 0.183 \quad \text{(polarimeter 1)}$$

$$K_y^{y'} = -0.663 \pm 0.373 \quad \text{(polarimeter 2)}$$

$$K_y^{y'} = -0.132 \pm 0.164 \quad \text{(weighted average for polarimeters 1 and 2).}$$

The difference between the errors can be explained by the lower statistics in polarimeter 2. For this polarimeter a smaller entrance aperture and a somewhat larger distance from the target had to be chosen.

The result is compared to two different predictions: one is a four-body Faddeev-Yakubovsky calculation by Uzu with and without the Coulomb interaction [22] (see Fig. 7), the other the prediction from the T-matrix analysis using the results of Ref. [10] (see Fig. 8 from Ref. [17]).

Included in every comparison is the only other polarization-transfer coefficient measured at very low energies, $K_y^{y'}$ at $E_d = 90$ keV and $\theta = 0^\circ$ [17].

With regard to the theoretical calculations it is astonishing that the new PTC, the weighted average of the two polarimeters, is more consistent with the calculation without a Coulomb modification. In reactions of charged particles the Coulomb interactions can in general not be ignored. Certainly,

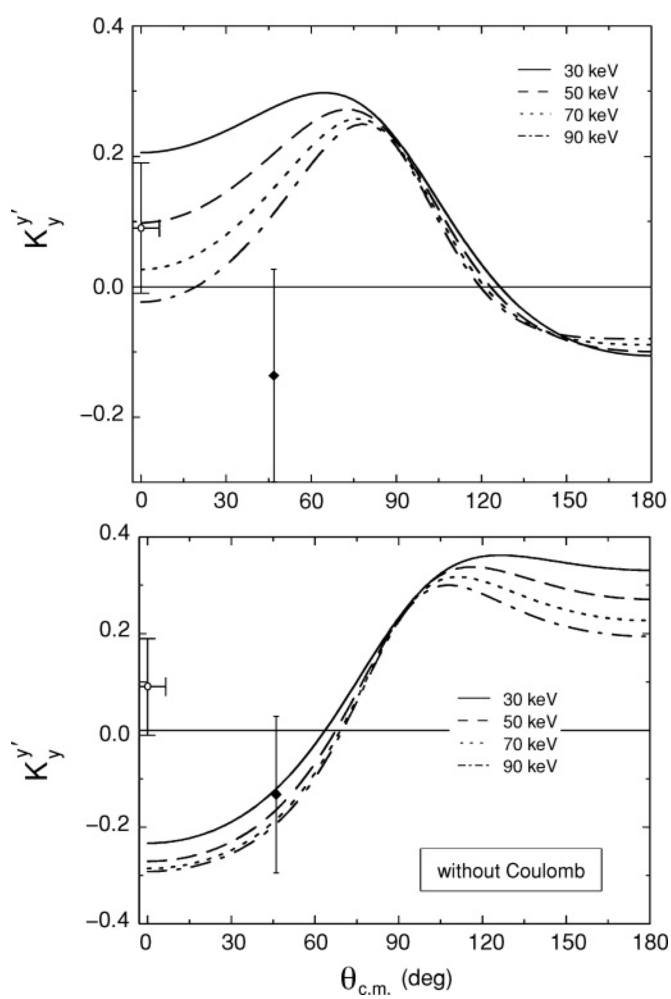

FIG. 7. Present result (filled) compared with Katabuchi's result (open circle) and calculations by Uzu–with and without Coulomb modification [22].

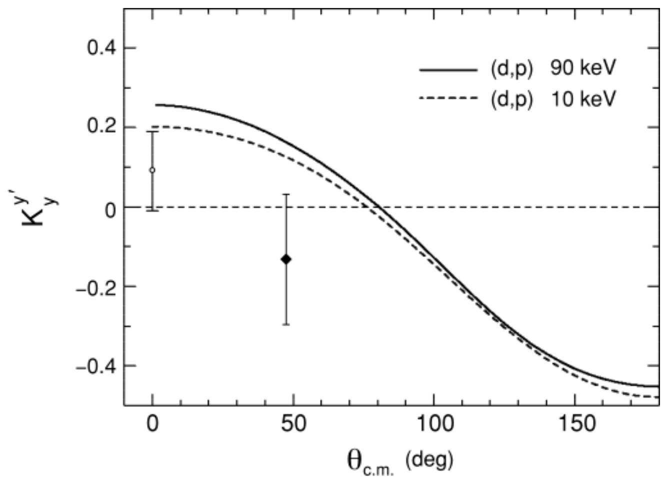

FIG. 8. Present result (filled) compared with Katabuchi's result (open circle) and predictions from the T-matrix analysis [17], which are using the MEs calculated by Lemaître [10].

the inclusion of this interaction succeeds only by means of an approximation. One has to take complicated asymptotic boundary conditions into consideration. Therefore, improved calculations will be very interesting [23]. The phenomenological matrix elements [10] predict both the present result and that of Ref. [17] reasonably well.

V. SUMMARY

The present paper gives the result of the measurement of the two-spin observable $K_y^{y'}$ in an energy range of interest for nuclear astrophysics as well as fusion energy research. This data point together with other recent data of the $^2\mathrm{H}(d,p)^3\mathrm{H}$ reaction in the low-energy region [39] will be entered into a new T-matrix fit in order to improve the quality (i.e., the errors and reliability) of that earlier ME determination [12]. Consequently the predicting capability of the resulting set of MEs will be improved as will be predictions on the quintet suppression factor discussed in the field of "polarized fusion."

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