



# Absence of spin dependence in the final state interaction of the $\vec{d}p \rightarrow {}^3\text{He}\eta$ reaction



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## ABSTRACT

The deuteron tensor analysing power  $T_{20}$  of the  $\vec{d}p \rightarrow {}^3\text{He}\eta$  reaction has been measured at the COSY-ANKE facility in small steps in excess energy  $Q$  up to  $Q = 11$  MeV. Despite the square of the production amplitude varying by over a factor of five through this range,  $T_{20}$  shows little energy dependence. This is evidence that the final state interaction causing the energy variation is not influenced by the spin configuration in the entrance channel. The weak angular dependence observed for  $T_{20}$  provides useful insight into the amplitude structure near threshold.

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It has been known for many years that measurements of the total cross section for the  $pd \rightarrow {}^3\text{He}\eta$  or  $dp \rightarrow {}^3\text{He}\eta$  reaction show very anomalous results near threshold [1–4]. In terms of the excess energy  $Q = W - M_{{}^3\text{He}} - M_\eta$ , where  $W$  is the total centre-of-mass (c.m.) energy, the cross section jumps to its plateau value already for  $Q < 1$  MeV. It was suggested that this effect is due to a strong

final state interaction (FSI) between the  $\eta$  and the  ${}^3\text{He}$  that might even lead to a quasi-bound  $\eta$ -nuclear state [5]. Fits to the most detailed data set have been made that show a pole in the  $\eta^3\text{He}$  elastic amplitude for  $|Q| < 0.5$  MeV [3]. Support for this pole assumption also comes from the study of the variation of the angular dependence of the cross section with  $Q$  [6].

If the threshold behaviour is due to an  $\eta^3\text{He}$  FSI then this should manifest itself in broadly similar ways for different entrance channels. The new photoproduction data on  $\gamma^3\text{He} \rightarrow \eta^3\text{He}$  show a steep rise in the first 4 MeV excess energy bin above threshold [7], though their resolution or statistics were not sufficient to determine the pole position with high precision.

In the  $dp \rightarrow {}^3\text{He}\eta$  reaction it is possible to access the  $s$ -wave  $\eta^3\text{He}$  system from either the total spin  $S = \frac{3}{2}$  or the  $S = \frac{1}{2}$  initial states and the differences will influence measurements of the deuteron tensor analysing power  $T_{20}$  of the  $\vec{d}p \rightarrow {}^3\text{He}\eta$  reaction.

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**Table 1**

Nominal values of the vector and tensor polarisations of the deuterons provided by the ion source for the three polarisation modes. Also shown are the average tensor polarisations  $p_{zz}^{\text{ANKE}}$  measured through the ramp using the  $\vec{d}p \rightarrow \{pp\}_s n$  reaction. The values quoted for  $p_z^{\text{LEP}}$  were measured at the injection energy of 75.6 MeV with the low energy polarimeter [10] for a sample of deuterons.

Mode	$p_z^{\text{ideal}}$	$p_{zz}^{\text{ideal}}$	$p_z^{\text{LEP}}$	$p_{zz}^{\text{ANKE}}$
1	+1/3	−1	$+0.244 \pm 0.032$	$−0.62 \pm 0.05$
2	−1	+1	$−0.707 \pm 0.026$	$+0.67 \pm 0.05$
3	+1	+1	$+0.601 \pm 0.027$	$+0.22 \pm 0.05$

The pure *s*-wave FSI hypothesis would require that the value of  $T_{20}$  should remain constant as a function of energy even though the corresponding unpolarised cross section varies. This approach to the comparison of the effects of the entrance channel on the FSI is very appealing because the detection system is independent of the deuteron beam polarisation and many of the systematic effects cancel.

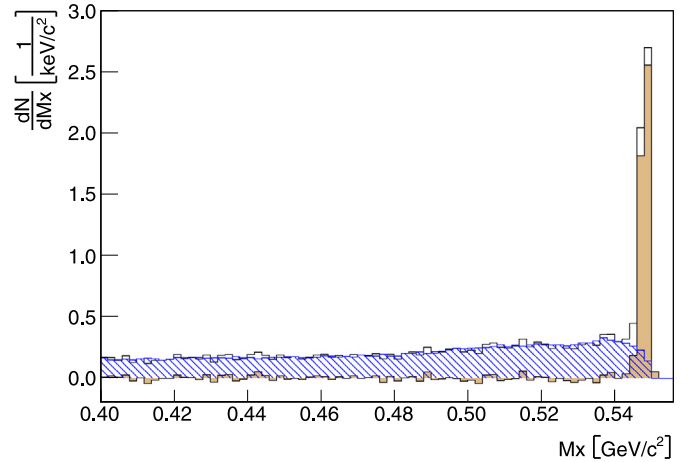
The only  $T_{20}$  measurement in this reaction was carried out at four energies close to threshold at Saclay [1], reaching up to  $Q \approx 5$  MeV. Over the limited energy range their values of  $T_{20}$  were consistent with being constant, though the results were not compelling. We have therefore remeasured this observable in greater detail and over a wider energy range.

The ANKE magnetic spectrometer [8] is located at an internal target station of the COoler SYnchrotron (COSY) of the Forschungszentrum Jülich. Only the forward detection system was used in the present experiment and this has full geometric acceptance for the  $\vec{d}p \rightarrow {}^3\text{He} \eta$  reaction at the energies investigated up to  $Q = 11$  MeV. With an unpolarised deuteron beam incident on a hydrogen cluster-jet target [9], this facility was already used to measure the unpolarised cross sections at 192 values of the excess energy [3]. Since the same system was also used when repeating the experiment with a polarised deuteron beam, much of the experimental discussion will here be focussed on the polarisation effects.

Polarised  $D^-$  ions are produced by colliding atomic deuterium with a caesium beam. A series of permanent sextupole magnets and radio frequency transition units is then used to enhance further the occupation numbers of the desired polarisation state [10]. The negatively charged ions are then pre-accelerated to the injection energy but, before entering the COSY ring, they are stripped of their electrons when passing through a carbon foil.

Three different polarisation modes plus one unpolarised mode for polarimetry were provided by the ion source. The modes were arranged to provide different vector ( $p_z$ ) and tensor ( $p_{zz}$ ) polarisations, alternating with each beam injection, in order to be able to compare them and investigate systematics. The polarisations refer to an axis that is perpendicular to the accelerator plane, being conventionally labelled by *z* in the source frame. Though the nominal values of the beam polarisations are shown in Table 1, these are idealised numbers and the actual ones are better determined in the experiment itself. The procedure for doing this will be discussed later and the mean values of the measured  $p_{zz}$  are shown in the table. It is seen here that the tensor polarisation for mode 3 was about a third of that of mode 2 so that it is clear that one or more of the hyperfine transitions in this mode were not operating as desired. The results presented in this letter are therefore based upon the data taken with modes 1 and 2 plus the unpolarised mode.

Also shown in Table 1 are the values of the vector polarisation measured with the low energy polarimeter at the 75.6 MeV injection energy. Though the deuterons are unlikely to lose any polarisation through the acceleration, we cannot guarantee that the



**Fig. 1.** Missing-mass distribution of the  $\vec{d}p \rightarrow {}^3\text{He} X$  at an excess energy of 3 MeV with respect to the  $\eta$  threshold (black line). Data taken below the threshold (blue line) were transformed to this energy and fitted to the data in the 0.4 GeV/c<sup>2</sup> to 0.52 GeV/c<sup>2</sup> missing-mass region. After subtracting the background, only a clean (brown shaded) missing-mass peak remains. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

source was completely stable such as to make these values valid throughout the whole experiment.

The beam was continuously ramped from a deuteron beam momentum of 3.118 GeV/c up to 3.185 GeV/c over a 300 second cycle. While the beam momentum is only known with an uncertainty of  $\Delta p/p \approx 10^{-3}$  from macroscopic measurements, the study of the  ${}^3\text{He}$  momentum ellipse from the  $\vec{d}p \rightarrow {}^3\text{He} \eta$  reaction allows the production threshold to be determined with much better precision [3]. The momentum range then corresponds to an excess energy of  $-5$  MeV to  $+11$  MeV. The below-threshold data were taken for the evaluation of the background.

Several hardware triggers were installed to filter out unwanted background events and thus minimise the dead time. A high threshold trigger, which was designed mainly for the primary reaction, selected events with a high energy loss in the hodoscopes of the forward detection system. This eliminated most of the charge-one protons and deuterons. A second trigger, which looked for events where there was an energy loss in one of the first two layers of the forward hodoscopes, was prescaled by a factor of 1024. The associated data were used for luminosity and polarisation determinations. A final trigger stored information on the experimental conditions (e.g. beam intensity and event rates) which, for instance, are necessary to estimate the dead time of the data acquisition.

The  ${}^3\text{He}$  nuclei were detected in the ANKE forward detection system and the  $\eta$  mesons reconstructed through the missing-mass peak. The shape of the missing-mass spectra depends mainly on the characteristics of the spectrometer and changes little over small steps in beam energy. Analysing the subthreshold data as if they were taken above the  $\eta$  production energy, they can be used to provide an accurate description of the background below the  $\eta$  missing-mass peaks. This procedure, which was already used successfully for the unpolarised data [3], is illustrated in Fig. 1. This technique was applied for all the energy bins and polarisation modes used in the data analysis.

The tensor polarisation of the deuteron beam was determined from the study of the  $\vec{d}p \rightarrow \{pp\}_s n$  reaction that was measured simultaneously through the ramp. For this purpose, events with two protons in the forward detection system were analysed. If the two proton system  $\{pp\}_s$  is at low excitation energy, typically  $E_{pp} < 3$  MeV, the tensor analysing power signal is very strong and can be predicted with high accuracy in the required energy

range [11,12]. The vector analysing power is, as expected [13], consistent with zero [14]. The tensor polarisation could therefore be determined at the same energies as those used for the main reaction. However, there are no depolarising resonances for deuterons in the COSY energy range and so the values of the polarisations could also be checked at the standard beam energy of 1.2 GeV [14] in each cycle. Any deviations observed here were very small and would affect the mean value of  $T_{20}$  by less than 0.02 while not influencing the energy or angular dependence of the observable.

For a two-body or quasi-two-body reaction, the ratio of the numbers of polarised to non-polarised events becomes

$$\frac{N^\uparrow}{N^0} = C_n (1 + \sqrt{3} p_{zz} i T_{11}(\theta) \cos \phi - \frac{1}{2} p_{zz} [T_{20}(\theta)/\sqrt{2} + \sqrt{3} T_{22}(\theta) \cos 2\phi]), \quad (1)$$

where  $\phi$  is the azimuthal angle,  $i T_{11}$  the (spherical) vector analysing power, and  $T_{20}$  and  $T_{22}$  two components of the tensor analysing power [15].

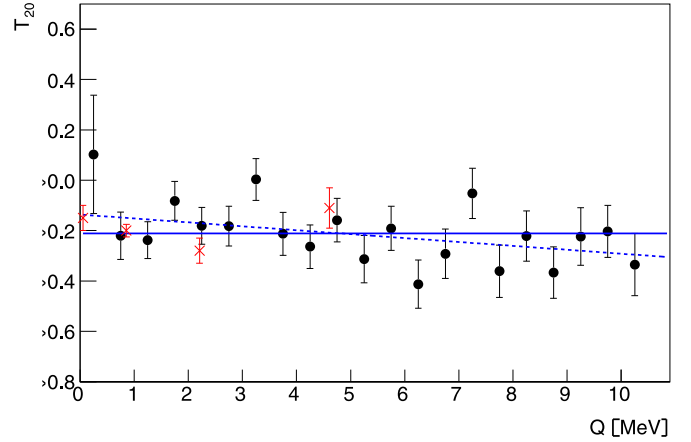
Since the  $T_{20}$  tensor signal is the strongest and has no dependence on the azimuthal angle, the relative luminosity of the polarised to unpolarised modes  $C_n$  must be determined accurately. Though this could be estimated from the beam current transformer (BCT) signal, the most precise measurement is found by counting simultaneously the numbers of spectator protons registered in the forward detection system with a Fermi momentum  $p_{\text{spec}} \leq 60$  MeV/c. These rates are largely unaffected by the beam polarisation [12] and we did not find any significant change in the values of  $C_n$  when reducing the cut to 40 MeV/c. Not only does this method account for the different luminosities but, since they were obtained using the same hardware trigger, the dead-time effects are also included. Furthermore, the geometrical acceptances are identical for the polarised and unpolarised modes.

Eq. (1) is used with the  $\bar{d}p \rightarrow \{pp\}_s n$  data to determine the values of  $p_{zz}$  for each mode in terms of the known values of  $T_{20}$  and  $T_{22}$  [12]. It is also used to extract values of  $T_{20}$  for the  $\bar{d}p \rightarrow {}^3\text{He} \eta$  reaction, using precisely these values of  $p_{zz}$ . However, the  $\bar{d}p \rightarrow \{pp\}_s n$  reaction is not sensitive to the vector polarisation of the beam and alternative solutions, such as the study of the quasi-free  $\bar{n}p \rightarrow d\pi^0$  [16], are strongly affected by the background conditions. We are therefore forced to use the values of  $p_z^{\text{LEP}}$  quoted in Table 1 when extracting  $i T_{11}$ , though these polarisations were not measured throughout the whole run.

Unfortunately, it was found during the analysis that, due to a defective scintillation counter in the third forward hodoscope layer, there was not a complete angular acceptance for the  $\bar{d}p \rightarrow {}^3\text{He} \eta$  reaction across the full range of excess energies. The data were therefore grouped into 10 bins in  $\cos \theta$  and 4 bins in  $\phi$  in such a way that  $\int \cos 2\phi d\phi = 0$  for each  $\cos \theta$  bin. This eliminates any possible contributions arising from  $T_{22}$ .

At the low excess energies studied in this experiment, the vector analysing power signal is proportional to  $\sin \theta \cos \phi$ . Using only those angular regions with full azimuthal acceptance allowed the values of  $i T_{11}$  to be determined from the  $\cos \phi$  dependence. The results of the fits confirmed that  $|i T_{11}| \lesssim 0.04$  for  $Q \leq 10$  MeV. One slight caveat here is that this analysis does rely on the values of  $p_z^{\text{LEP}}$  quoted in Table 1 and these were not determined for all the data-taking runs.

Having extracted the vector polarisation asymmetries for all  $\theta$  and  $Q$ ,  $T_{20}$  could then be determined from Eq. (1) over the whole  $\cos \theta$  range for each energy. The values obtained for polarisation modes 1 and 2 are consistent within  $2\sigma$  and the results found by averaging over the polarisation modes and all  ${}^3\text{He}$  c.m. angles are shown in Fig. 2. Since the data were taken over a continuous ramp, the binning in  $Q$  is somewhat arbitrary and the 0.5 MeV used



**Fig. 2.** The tensor analysing power  $T_{20}$  (black circles) measured for the  $\bar{d}p \rightarrow {}^3\text{He} \eta$  reaction in 0.5 MeV bins in the excess energy  $Q$ . The solid and dashed lines are, respectively, constant and linear fits to these data. Also shown are the four points (red crosses) measured at Saclay [1]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

here was chosen to match the statistics. The results are largely in agreement with those measured at Saclay [1].

The ANKE data shown in Fig. 2 are consistent with a constant value of  $T_{20} = -0.21 \pm 0.02 \pm 0.05$ , which has a reduced  $\chi^2$  of 1.34. Here the first error is statistical and the second systematic. The latter arises mainly from uncertainties in the beam polarisation, the relative flux normalisation, the geometry, and the contribution from  $i T_{11}$ .

Allowing  $T_{20}$  to have a linear dependence on  $Q$  leads to a marginal improvement in the description of the data with

$$T_{20} = (-0.14 \pm 0.04) + (-0.02 \pm 0.01) Q, \quad (2)$$

where  $\chi^2/\text{NDF} = 1.17$  and here and in other fits  $Q$  is measured in MeV.

It was shown [3,4] that for  $Q > 4$  MeV there is a significant but linear dependence of the unpolarised  $\bar{d}p \rightarrow {}^3\text{He} \eta$  differential cross section on  $\cos \theta$ , where  $\theta$  is the c.m. polar angle of the  ${}^3\text{He}$  with respect to the deuteron beam direction. The statistics are, of course, much higher for the unpolarised cross section than for the polarised data presented here because of the greater strength of the unpolarised beam, the low values of  $T_{20}$  and  $p_{zz}$ , and the fact that the data are spread over four polarisation modes. In order to quantify the angular dependence of  $T_{20}$ , we have determined the asymmetry in  $\cos \theta$  for each energy bin by defining an asymmetry parameter through

$$\alpha = dT_{20}/d\cos \theta|_{\cos \theta=0}. \quad (3)$$

The resulting values of  $\alpha$  are shown versus  $Q$  in Fig. 3.

The asymmetry parameter reflects interferences between odd and even  $\eta$  partial waves so that it is an odd function of the  $\eta$  c.m. momentum  $p_\eta$  which must vanish at threshold. The data shown in Fig. 3 are compatible with zero for all  $Q$  and the best fit that is linear in  $p_\eta$  is given by  $\alpha = (0.0002 \pm 0.0005) p_\eta$ , where  $p_\eta$  is measured in MeV/c. Only statistical errors are quoted here and  $\chi^2/\text{NDF} = 1.19$ . There is therefore no sign of any  $s$ - $p$  interference, despite the unpolarised cross section showing a significant non-isotropy [6].

At low energies, or at arbitrary energies in the forward and backward directions, the spin dependence of the production amplitude can be written in terms of two independent scalar amplitudes  $A$  and  $B$  [17]:

$$f = \bar{u}_{{}^3\text{He}} \hat{\mathbf{p}}_p \cdot (A \boldsymbol{\varepsilon}_d + i B \boldsymbol{\varepsilon}_d \times \boldsymbol{\sigma}) u_p, \quad (4)$$

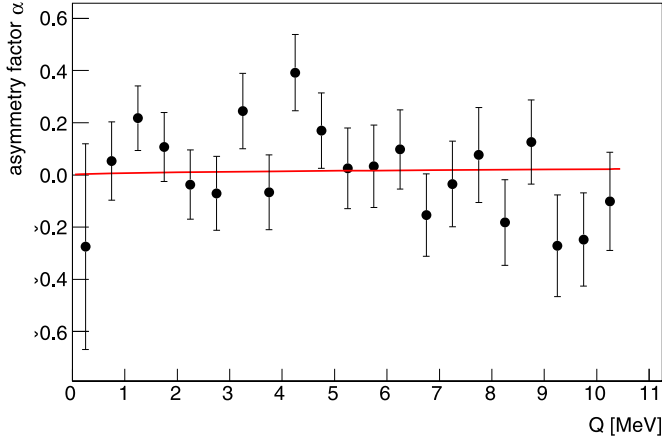


Fig. 3. The variation of the asymmetry factor  $\alpha$  of Eq. (3) with  $Q$  and fitted as a function of the  $^3\text{He}$  c.m. momentum.

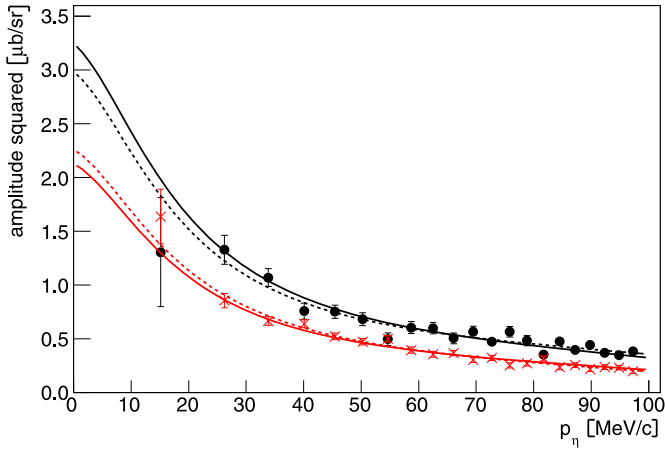


Fig. 4. Angular averages of  $|A|^2$  (black circles) and  $|B|^2$  (red crosses) in 0.5 MeV bins in  $Q$  deduced from the current  $T_{20}$  measurements and the previous ANKE unpolarised cross section results [3]. The solid lines assume that  $T_{20}$  has the constant value of  $-0.21$ , whereas the dashed ones include possible effects from the slope in  $Q$  given by Eq. (2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

where  $u_{^3\text{He}}$  and  $u_p$  are Pauli spinors,  $\epsilon_d$  is the polarisation vector of the deuteron, and  $\hat{p}_p$  the direction of the incident proton beam in the c.m. frame. The differential cross section and the deuteron tensor analysing power may then be written as:

$$\frac{d\sigma}{d\Omega} = \frac{p_\eta}{3p_p} (|A|^2 + 2|B|^2) \quad \text{and} \quad T_{20} = \sqrt{2} \frac{|B|^2 - |A|^2}{2|B|^2 + |A|^2}. \quad (5)$$

Though the slope in the differential cross section [3,4] shows that the amplitudes contain small contributions from  $p$  waves for  $Q \gtrsim 4$  MeV, these will not significantly affect the extrapolation to the pole and so it is still useful to evaluate the average values of  $|A|^2$  and  $|B|^2$  as functions of  $Q$ , and this is done in Fig. 4. For this purpose the parameterisation of the unpolarised  $dp \rightarrow ^3\text{He} \eta$  cross section has been taken from our earlier measurements [3].

Clearly, if the angular average of  $T_{20}$  remains energy-independent, the same has to be true for the ratio of  $|A|^2/|B|^2$ , despite both amplitudes being subject to the strong FSI that leads to the violent behaviour shown in Fig. 4. The linear fit in Eq. (2) gives

$$|B|^2/|A|^2 = (0.75 \pm 0.06) - (0.014 \pm 0.014)Q. \quad (6)$$

If such a variation exists then it is likely to be on an energy scale of perhaps  $0.75/0.014 \approx 50$  MeV rather than the less than 1 MeV

associated with the  $\eta^3\text{He}$  final state interaction. Initial state interactions or the reaction mechanism itself might lead to changes on this scale but one would need much firmer data before speculating further.

In general six invariant amplitudes are required to describe the  $dp \rightarrow ^3\text{He} \eta$  reaction [18] and an unambiguous amplitude analysis would require very complex polarisation measurements. Attempts were made in Ref. [6] to extend the description of the unpolarised cross section given by Eq. (4) to include the effects of  $p$  waves. For this purpose only two of the five possible  $p$ -wave structures were retained. In the absence of reliable  $iT_{11}$  data the decomposition is very ambiguous and the main features of our data could be well described by the ansatz:

$$A = A_0 [\text{FSI}(p_\eta) + \alpha p_\eta \cos \theta + \beta p_\eta^2 (3 \cos^2 \theta - 1)/2], \\ B = B_0 [\text{FSI}(p_\eta) + \alpha p_\eta \cos \theta + \beta p_\eta^2 (3 \cos^2 \theta - 1)/2], \quad (7)$$

where the FSI factor only influences the  $s$ -wave term. By taking  $B$  to be proportional to  $A$  in terms of both  $p_\eta$  and  $\theta$ , it follows immediately that  $T_{20}$  would be independent of both variables despite the differential cross section developing a significant anisotropy at high  $p_\eta$  [3,4]. The observed linearity of the cross section with  $\cos \theta$  [3,4] could then arise from a cancellation of the interference between the  $\eta$   $s$  and  $d$  waves and the square of the  $p$  waves.

In the  $A + B$  model the vector analysing power vanishes but there is the possibility of a non-zero  $iT_{11}$  in the extended model where two more spin amplitudes  $C$  and  $D$  are introduced [6]. Our result that  $|iT_{11}| \lesssim 0.04$  is clearly not in contradiction with the  $A + B$  hypothesis outlined here.

In summary, we have measured the tensor analysing power  $T_{20}$  for the  $\bar{d}p \rightarrow ^3\text{He} \eta$  reaction in 0.5 MeV steps in excess energy. The near constancy of the angle-summed data support strongly the belief that the rapid variation of the amplitudes with energy near threshold is due to an  $s$ -wave final state interaction that is common to the two different spin states in the entrance channel. This is consistent with the fact that fits to the unpolarised cross section data [3] yield a pole at such a low value of  $|Q|$ . This would not have been the case if the amplitudes  $A$  and  $B$  had poles at very different values of  $Q$ .

The lack of any obvious forward/backward asymmetry in  $T_{20}$ , which contrasts strongly with that observed for the cross section, gives information on the spin structure of the scattering amplitude. Our data are consistent with the assumption that only the amplitudes  $A$  and  $B$  are important and that they have similar angular dependence. This might help in the development of models for the  $dp \rightarrow ^3\text{He} \eta$  reaction.

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