Polarization transfer coefficient $K_y^{y'}$ for n-p scattering at 15.8 MeV

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The polarization transfer coefficient $K_y^{y'}$ has been measured for neutron-proton scattering at $E_n = 15.8$ MeV and $\theta_{\mathrm{c.m.}} = 132.4°$. Using a quasimonoenergetic polarized neutron beam produced via the $^2\mathrm{H}(d,n)^3\mathrm{He}$ reaction, and a liquid-helium proton polarimeter, a value of $K_y^{y'} = 0.160 \pm 0.020$ has been obtained which is appreciably smaller than the predictions of all realistic, meson-based N-N potentials but agrees well with the result of an earlier measurement at 17.4 MeV. [S0556-2813(98)06208-6]

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The measurement reported here was part of a program at the Institut für Strahlen- und Kernphysik (ISKP) of the University of Bonn to investigate the nucleon-nucleon (N-N) tensor force by means of polarized neutron scattering. For n-p scattering below 20 MeV, the three most important phase-shift parameters are $^1S_0$, $^3S_1$, and the $^3S_1 - {}^3D_1$ mixing parameter ε_1 which is related to the strength of the isoscalar tensor force. While in general the last few years have seen considerable progress in the phase-shift parametrization of N-N scattering data, there is still some ambiguity concerning ε_1, best illustrated by a comparison of the most recent phase-shift analyses [1,2] which differ most noticeably in their results for ε_1. The reason is that, due to its nature as a spin-spin interaction, the tensor force is difficult to measure, and only a few scattering observables are sufficiently sensitive to allow its accurate determination at least in principle; they all involve the measurement of the polarization of two of the reaction partners. Among these, the spin-correlation parameters A_{yy} and A_{zz}, the total cross section differences $\Delta\sigma_L$ and $\Delta\sigma_T$, and the polarization transfer coefficient $K_y^{y'}$ are the most promising ones. While not many such experiments have been performed, some of the most accurate ones have produced contradictory results, especially at energies below 20 MeV [3,4]. We have therefore repeated one of our own measurements of $K_y^{y'}$ [5] under improved experimental conditions with the hope to clarify the situation in this low-energy domain.

The experiment was performed at the ISKP cyclotron at the University of Bonn. The setup was basically the same as described in Refs. [5,6] so that only a brief account will be given here. A vector-polarized deuteron beam of 400 nA average intensity was focused into a high-pressure, LN_2-cooled deuterium-gas target. The main difference compared with [5] was that now the quasimonoenergetic neutrons produced via the $^2\mathrm{H}(d,n)^3\mathrm{He}$ reaction were used whereas before, the high-energy part of the breakup continuum from the $^2\mathrm{H}(d,n)pd$ reaction had been employed. The obvious advantage was that cleaner experimental conditions were thus obtained which facilitated the data analysis and reduced systematic errors. Also, since due to the positive Q value of the $^2\mathrm{H}(d,n)^3\mathrm{He}$ reaction the same neutron energy could be obtained with a lower energy of the primary deuteron beam, there was less room background and the count rates in the various detectors were reduced, resulting in a much smaller number of accidental coincidences. At a pressure of 25 bars, the collimated neutron beam had an intensity of 7×10^5/s, with an average energy of 15.8 MeV, and an energy spread of 3.5 MeV.

The polarization of the n beam was measured *via* n-α scattering. Two ΔE-E detector telescopes, each consisting of a thin scintillator foil and a Si-surface-barrier detector, were placed inside a scattering chamber filled with He gas at a pressure of 1 bar. Recoil α's were detected at $\pm 24°$, corresponding to the well-known maximum in the n-α analyzing power at $\theta_{\mathrm{c.m.}} = 132°$. The efficiency of this polarimeter was only 10^{-8} which was, however, sufficient to determine the *average* beam polarization over all data runs with a statistical accuracy of better than 1%. More details about the performance of this polarimeter can be found in Ref. [7]. A fast ^{12}C polarimeter was used to optimize and monitor the performance of the polarized-ion source. The intensity and energy distribution of the neutron beam were measured by means of a proton-recoil-telescope placed behind the beam polarimeter.

A schematic diagram of the scattering chamber containing the proton polarimeter is shown in Ref. [6]. For the present experiment, the target consisted of a CH_2 disc of 1.5 mm thickness and 25 mm diameter, attached to the upstream side of a 300 μm thick NE 104 scintillator foil housed in a V-shaped Al reflector and viewed by an RCA 4516 photomultiplier. The proton polarimeter was completely symmetric with respect to the neutron beam. Recoil protons emitted from the CH_2 target were scattered from two identical, cylindrical liquid-helium targets placed at laboratory angles of $\pm 22.4°$ on either side of the n beam, and detected in two 80 cm^2 scintillator detectors (''E detectors''). The liquid-He

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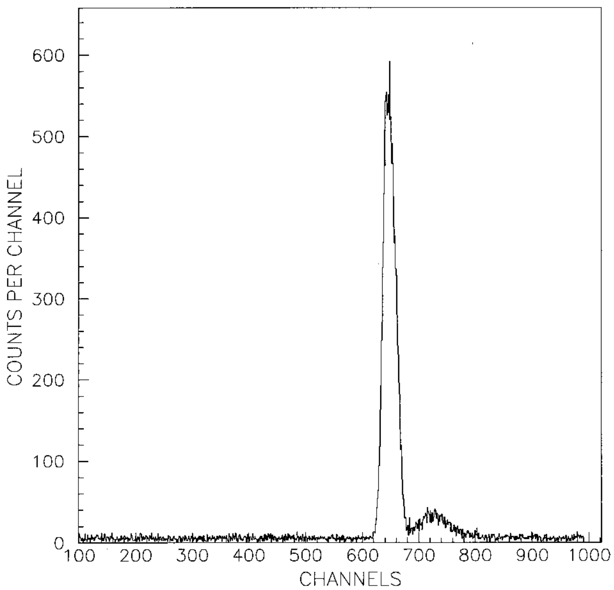

FIG. 1. Time-of-flight spectrum between the CH_2 target and one of the E detectors of the proton polarimeter, after a window was set to select the quasimonoenergetic part of the neutron beam. The origin of the small satellite to the right of the main peak is explained in the text.

containers were fabricated from 30 μm thick Al foil and bonded with an epoxy-type adhesive.[1] They were 40 mm high and 10 mm in diameter, and surrounded by heat shields made from 15 μm Al foil. The LHe vessels were coated on the inside with 100 μg/cm^2 of the wavelength shifter diphenylstilbene (DPS); each target was viewed from below through a quartz window by an RCA 4516 photomultiplier attached to a 90° deviating prism. The scintillator thickness of the E detectors was reduced from 8 mm in the original setup [5,6] to 1.6 mm, which helped to further reduce the number of accidentals considerably.

For each side of the polarimeter, the pulse heights of all detectors were recorded together with the times-of-flight from the CH_2 target to the LHe scatterer (TOF_{12}) and to the E detector (TOF_{13}). In addition, the TOF of the incoming neutrons was measured relative to the rf of the accelerator so that the quasimonoenergetic part of the n beam could be separated in the off-line analysis. Finally, the spin state of the deuteron beam, which was reversed every 5 s at the ion source, was recorded for each event.

A typical TOF_{13} spectrum is shown in Fig. 1. It can be seen that the accidental background is very low. The small structure to the right of the main peak is due to events in which the proton, after producing the start signal in the target scintillator, was detected in the LHe scatterer only, while the recoiling neutron was scattered back from the far wall of the target chamber and registered in the E detector. In order to determine the number of true coincidences in which a neutron was detected in one of the E detectors, a separate background run had to be made because most such events could not be separated by their TOF. This was the case, e.g., if the recoiling neutron backscattered in the target itself, or if a neutron was scattered into the LHe and from there into the E detector while the recoil proton provided the start signal in the scintillator foil. For this background run, the E detectors were covered with Al plates so that they could not see any charged particles. Although Monte Carlo simulations indicated that such coincidences would constitute not more than a few percent and produce mainly small pulse heights in the E detectors, they had to be investigated carefully because of the relatively large polarization of the neutrons involved.

For the data reduction, a proton asymmetry a_p was defined which takes advantage of the special symmetry of our experimental setup. Denoting with L_+, L_-, L_0, R_+, R_-, and R_0 the count rates in the left and right E detector with the beam polarization ''up,'' ''down,'' and zero, respectively, we write [6]

$$a_p = \frac{2L_0R_0(L_+R_- - L_-R_+)}{L_+L_-R_0^2 + L_0R_0(L_+R_- + L_-R_+) + R_+R_-L_0^2}, \quad (1)$$

which for point geometry transforms into

$$a_p = -(p^+ + p^-)A \quad (2)$$

with

$$A = (A_y^{np} - A_y^{p\alpha}K_y^{y'})/(1 - A_y^{p\alpha}A_y^{np}). \quad (3)$$

For the beam polarimeter, the asymmetry was defined correspondingly as

$$a_n = -(p^+ + p^-)A_y^{n\alpha}. \quad (4)$$

A_y^{np}, $A_y^{p\alpha}$, and $A_y^{n\alpha}$ are the analyzing powers for n-p, p-α, and n-α scattering while p^+ and p^- denote the absolute values of the neutron polarization with spin ''up'' and ''down,'' respectively. Thus in the asymmetry, which is independent of the number of beam particles, solid angles, and efficiencies, only the *sum* of the two polarizations appears, and a_p as well as a_n are zero for an unpolarized beam. As explained in Ref. [6], a short run with an unpolarized beam was necessary because p^+ and p^- were not exactly the same. It follows from Eqs. (2) and (4) that the task was to measure the sum of the neutron polarizations $(p^+ + p^-)$, and to determine A which plays the role of a ''combined'' analyzing power resulting from the successive n-p and p-α scatterings. Using Eqs. (2), (3), and (4), $K_y^{y'}$ then becomes

$$K_y^{y'} = \left[-\frac{a_p}{a_n} A_y^{n\alpha}(1 - A_y^{p\alpha}A_y^{np}) + A_y^{np} \right] \Big/ A_y^{p\alpha}. \quad (5)$$

Of course, Eq. (5) cannot be used directly to extract $K_y^{y'}$ from the measured data. Due to the extended geometry of the experiment with thick targets and large solid angles, all analyzing powers are average quantities, and because out-of-plane scattering was appreciable the effective beam polarization had a small x component. Nevertheless, the formulas can serve to show the basic connections between the various quantities, and to estimate errors.

[1] Araldit AW 116 with hardener HV 953 U, manufactured by Ciba-Geigy, distributed by AGS Chemie GmbH, Obertshausen, Germany.

The actual data analysis was performed by means of Monte Carlo simulations in which all details of the experiment were taken into account, especially the finite geometry and beam energy spread, straggling, multiple scattering, and background reactions. Using for $K_y^{y'}(E,\theta)$ the predictions of the charge-dependent CD-Bonn potential [8], an asymmetry was calculated according to Eq. (1) and compared to the measured one. This procedure was repeated with somewhat smaller or larger values for $K_y^{y'}$ until the calculated and measured asymmetries agreed. The value of $K_y^{y'}$ at the *average angle and energy* of the experiment was then taken as the ''experimental'' result. This is, of course, model dependent in principle because the same quantity $K_y^{y'}$ which is to be determined must be used as input for the simulations and, necessarily, certain assumptions have to be made with respect to the angular and energy dependence of $K_y^{y'}$. To assure that the result does not depend on the particular potential model used to calculate $K_y^{y'}(E,\theta)$, the simulations were repeated with the predictions of the Paris potential [9] instead of CD-Bonn; the differences were found to be negligible. This is not surprising because all potential models predict essentially the same *qualitative* behavior for $K_y^{y'}(E,\theta)$, i.e., in particular, the same basic shape for the angular distributions. The final result for the n-p polarization transfer coefficient at $E_n = 15.8$ MeV and $\theta_{\mathrm{c.m.}} = 132.4°$ was

$$K_y^{y'} = 0.160 \pm 0.020 \pm 0.004,$$

where the first error of one standard deviation is due to statistics and the second one comprises all systematic errors and the normalization uncertainty.

The total error is almost completely due to counting statistics in the proton polarimeter while systematic errors and the statistics in the beam polarimeter played only a minor role. For p-α scattering, $A_y^{p\alpha}$ was calculated using several different sets of phase shifts [6]; the results all agreed within 1%. On the other hand, the uncertainty in A_y^{np} is relatively large, but its absolute value is small. This parameter was calculated with the phase shifts of Ref. [1], and its contribution to the error of $K_y^{y'}$ was also estimated at 1%. For the beam polarimeter, the n-α phases of Stammbach and Walter were used [11]; the absolute error of its effective analyzing power was 1.3%. Since out-of-plane scattering was significant in the proton polarimeter, the beam polarization had a noticeable x component which could produce a small asymmetry even with $K_y^{y'} \equiv$ zero. Consequently, $K_x^{x'}$ was also needed in the simulations. Calculations with different predictions for $K_x^{x'}$ showed, however, that its influence on the extracted value of $K_y^{y'}$ was well below 1%. The most important correction which had to be made by means of Monte Carlo simulations was for double scattering involving the Al walls and heat shields of the LHe targets. Its overall effect was to reduce the asymmetry by $3.5 \pm 1.0\%$ while double scattering in the LHe itself contributed only 0.8%. The removal of neutron events, as determined from the background run, increased the statistical error by 8% (relative) for a threshold of 0.7 MeV in the E detectors, while the error from the subtraction of accidental background was negligible. Due to its Q value of -12.6 MeV, the $^{12}C(n,p)^{12}B$ reaction could not contribute to the background in any significant way.

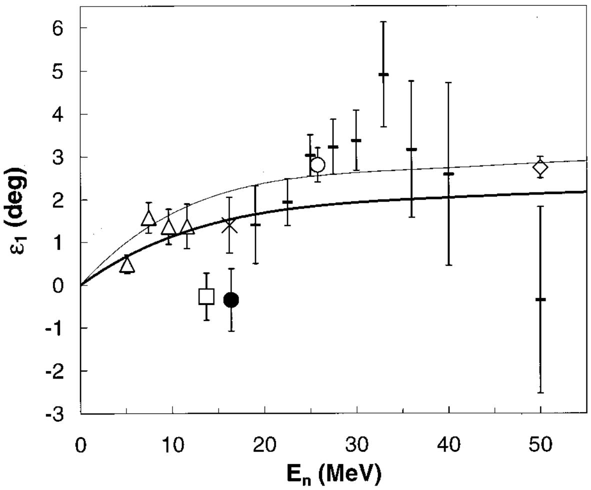

FIG. 2. Summary of the experimental situation with respect to ε_1 in the energy range up to 50 MeV. The full circle is the result of the present work combined with Ref. [5], the open circle is from our $K_y^{y'}$ measurement at 25.8 MeV [6]. The additional values of ε_1 are from work by other authors: triangles ($\Delta\sigma_T$) Ref. [4], square [$A_{yy}(90°)$] Ref. [3], cross ($\Delta\sigma_T - \Delta\sigma_L$) Ref. [15], diamond ($A_{zz}$ and $\Delta\sigma_L$) Ref. [17]; the horizontal bars are from a single-parameter phase-shift analysis of the $A_{yy}(90°)$ data from Ref. [16]. Also shown are the phase-shift predictions PWA93 by Stoks *et al.* [1] (thick line), and SM97 by Arndt *et al.* [2] (thin line). The prediction of the CD-Bonn potential [8] essentially coincides with PWA93.

The new value for $K_y^{y'}$ at 15.8 MeV is in perfect agreement with our previous result, which was $K_y^{y'} = 0.155 \pm 0.026$ [5], obtained at the same angle at $E_n = 17.4$ MeV. Both values are significantly smaller than predicted by any realistic N-N potential model [8,10,12]. According to the CD-Bonn potential [8], e.g., one should expect $K_y^{y'} = 0.199$ at 15.8 MeV and 0.195 at 17.4 MeV. Since the energy dependence of $K_y^{y'}$ is rather weak we can combine the two results to get an average value $K_y^{y'} = 0.158 \pm 0.016$ for a mean energy $E_n = 16.4$ MeV, which is more than two standard deviations below the corresponding CD-Bonn prediction.

In order to obtain a value for the mixing parameter ε_1 from our results for $K_y^{y'}$, a single-parameter phase-shift analysis was performed. For this purpose, the interactive computer code SAID [13] was used together with a program adapted from Ref. [14]. We started with the phase shifts of the CD-Bonn potential [8] which are very similar to those obtained in the Nijmegen multienergy partial-wave analysis (PWA) [1] and fit the world N-N data up to 350 MeV with a near-perfect normalized $\chi^2 = 1.03$. Varying only the phase parameter ε_1 to reproduce our average experimental value of $K_y^{y'} = 0.158 \pm 0.016$ at $E_n = 16.4$ MeV, we obtained $\varepsilon_1 = -0.36° \pm 0.73°$ while the CD-Bonn potential predicts $\varepsilon_1 = 1.50°$ and the Nijmegen PWA gives $\varepsilon_1 = 1.56°$. Fitting the two individual values of $K_y^{y'}$ separately, the results were $\varepsilon_1 = -0.37° \pm 0.93°$ at $E_n = 15.8$ MeV, and $\varepsilon_1 = -0.34° \pm 1.18°$ at $E_n = 17.4$ MeV. The results of such a simple analysis should be realistic nevertheless because the other phase shifts to which $K_y^{y'}$ is sensitive—especially the phases $^1S_0$ and $^3S_1$—are well determined experimentally [1,2]; the uncertainties in these parameters are estimated to contribute to the error of ε_1 only at the level of $\pm 0.1°$. Also, contrary to most spin-correlation experiments where ε_1 is strongly correlated with the $^1P_1$ phase shift, the spin-transfer coefficient $K_y^{y'}$ has almost no sensitivity to this parameter in our case. Thus, our result for $K_y^{y'}$ unambiguously translates into a value of ε_1 at energies around 16 MeV which is considerably smaller than the predictions of modern N-N phase-shift analyses and potential models (see Fig. 2). It is in agreement with the result of a related study by Schöberl *et al.* [3] who also obtained a very small ε_1 from a measurement of the n-p spin correlation parameter A_{yy} at $E_n = 13.7$ MeV and $\theta_{\mathrm{c.m.}} = 90°$, where the correlation between ε_1 and $^1P_1$ also vanishes. On the other hand, measurements of $\Delta\sigma_T$ and $\Delta\sigma_L$ at energies below 20 MeV [4,15] did not produce ε_1 values smaller than predicted, and the existing data between 25 and 60 MeV [6,16,17,18] all appear to support uncomfortably large values of ε_1 which cannot be reproduced by realistic meson-based N-N potentials, either [19]. A final answer to this puzzle can only come from additional experiments.

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