Neutron-Proton Spin-Correlation Parameter A_{zz} at 68 MeV

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(Received 3 December 1990)

We report a first measurement of the spin-correlation parameter A_{zz} in neutron-proton scattering at 67.5 MeV. The results, obtained in the angular range $105° \leq \theta_{c.m.} \leq 170°$ with typical accuracies of 0.008, are highly sensitive to the $^3S_1$-$^3D_1$ mixing parameter ϵ_1. A phase-shift analysis based on the current world data yields a value of ϵ_1 significantly higher than predicted by modern potential models.

PACS numbers: 21.30.+y, 13.75.Cs, 13.88.+e, 25.10.+s

One of the long-standing problems in our understanding of the fundamental nucleon-nucleon interaction is the poor knowledge of the isoscalar tensor force. This force mixes states with different angular momenta $L=J\pm 1$ (with J the total angular momentum). It is directly related to the $^3S_1$-$^3D_1$ mixing parameter ϵ_1 in neutron-proton scattering and the D-state admixtures of light nuclei.

Since the binding energies of few-nucleon systems are highly sensitive to the isoscalar tensor force, the poor knowledge of ϵ_1 has important implications concerning the accuracy of binding-energy calculations, and the question of whether nuclear binding energies can quantitatively be understood in terms of two-nucleon forces. Exact calculations of the triton binding energy show that without three-body forces the measured binding energy can only be reproduced for a weak tensor force.[1] The binding energy of nuclear matter as well depends strongly on the isoscalar tensor interaction.[1]

For the study of non-nucleonic degrees of freedom of nuclei a precise knowledge of S-D transitions is also a prerequisite. The contribution of mesonic degrees of freedom to electromagnetic form factors of the $A=2,3$ systems—the observables most sensitive to these degrees of freedom—is of nearly equal size, but of opposite sign as the effects of the S-D transition. A determination of the former requires reliable information on the latter.

The problem[2,3] with ϵ_1 is a twofold one: (a) only higher-order spin observables such as spin-correlation or spin-transfer parameters in n-p scattering are sensitive to ϵ_1; these quantities are difficult to measure; (b) these observables in most cases are also sensitive to the other poorly determined quantity, the $^1P_1$ phase. As a result, the values of ϵ_1 and $^1P_1$ which have been extracted from phenomenological phase-shift analyses (PSA) exhibit large uncertainties. A more accurate determination of ϵ_1 in the energy region relevant for nucleons in nuclei ($k_F^2/2m \sim 35$ MeV) thus would be of high interest.

Condition (a) requires precise experiments in which the spins of at least two of the reaction partners are measured. Recently, measurements have been performed for the spin-correlation coefficient A_{yy} between 18 and 50 MeV.[4] The present Letter reports the first measurement below 400 MeV of the spin-correlation parameter $A_{zz}(\theta)$, the observable most sensitive to ϵ_1.[2]

Condition (b) calls for the measurement of complementary quantities to pin down other phases, especially $^1P_1$. In order to reduce the amount of ambiguity in a PSA we have measured the differential cross section, the analyzing power A_y,[5] and the spin-dependent total cross section $\Delta\sigma_L$ in addition to $A_{zz}(\theta)$.

The experiment was performed at the Paul-Scherrer Institut (PSI) injector cyclotron. Figure 1 shows our setup, part of which has been described in Refs. 6 and 7.

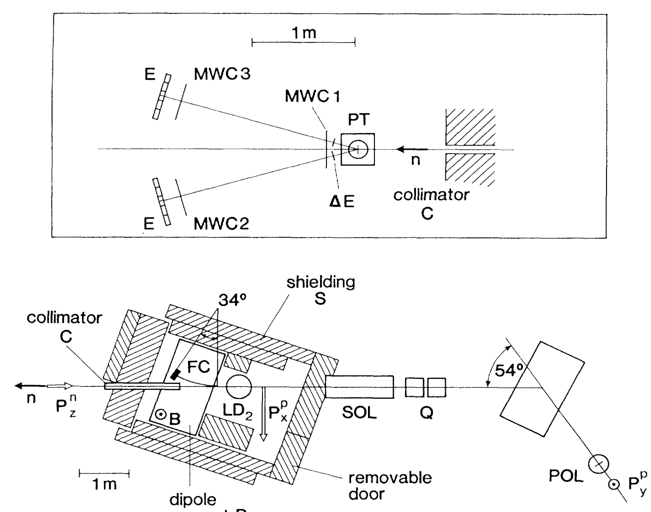

FIG. 1. Experimental arrangement, showing the proton polarimeter POL, the spin precession solenoid SOL, the liquid-deuterium LD_2 target, the dipole magnet D, the Faraday cup FC, and the neutron collimator C with the shielding S. Inset: The scattering setup in more detail, the polarized target PT, the multiwire chambers MWC_j, $j=1,2,3$, and the thin plastic (ΔE) and the thick plastic detector array (E).

Protons of 72 MeV and beam intensity of 2 μA were focused into the polarimeter, where the polarization of the incident beam (P_y^p) was measured continuously via elastic scattering from a thin carbon foil. Subsequently, the beam passed through a solenoid where the proton spin was precessed into the horizontal plane (P_x^p). The proper setting of the solenoid current was determined by means of a plastic detector which recorded the zero crossing of P_y^p via elastic proton scattering from a carbon foil mounted in the production chamber. The neutron production target, 1 cm of liquid deuterium, produced a quasimonoenergetic neutron beam of 2×10^5/s cm^2 by the reaction D(p,n)2p at 0°. The polarization for neutrons in the high-energy peak ($\sim$2.3 MeV FWHM) was $|P_x^n|\sim0.37$. The beam spot position on target was measured continuously by a secondary-electron-emission monitor and stabilized via feedback to steering magnets. The dipole magnet deflected the proton beam into the Faraday cup and precessed the polarization of the neutrons produced at 0° into the longitudinal direction (P_z^n). The production target and Faraday cup are surrounded by a steel-and-concrete shielding with a 1.5-m-long collimator to form the neutron beam. Neutron beam profile measurements showed that the beam was centered on the polarized target and that 90% of the flux was contained within a diameter of 18 mm. Beyond 25 mm diameter the flux had dropped to 0.3% of the flux in the central region.

The polarized target consisted of a 20-mm×20-mm ×3-mm-thick slab of a frozen butanol (95%) and water (5%) mixture, doped with 1% porphyrexide and contained in a thin-walled copper cell.[8] A ^{3}He cryostat kept the temperature at 0.5 K. A longitudinal field of 2.5 T was provided by a superconducting split coil magnet. The protons were dynamically polarized by irradiation with microwaves of 70.2 GHz (for positive polarization) and of 70.6 GHz (for negative polarization). This allowed us to flip the target polarization of typically $P_z^T=0.6$ without changing any other parameter. The proton polarization was measured every 20 min by observing the NMR signal produced in a pickup coil embedded in the butanol. Periodically, the polarization was calibrated by measuring the "natural" polarization at equilibrium obtained at a given temperature without microwave irradiation. The temperature was determined from the ^{3}He vapor pressure directly above the target cell.

The experiment was based on the detection of recoil protons which were observed with an array of plastic scintillators and multiwire proportional chambers (see inset in Fig. 1). A valid event was defined by a coincidence between a ΔE detector and any one of the corresponding E detectors. The time difference between ΔE and the cyclotron rf signal determined the neutron energy needed to correct for the energy dependence of the n-p cross section and of the D(p,n)2p polarization transfer coefficient.[9] The time and pulse-height information of the ΔE and E counters allowed us to identify protons. The coordinates in the multiwire chambers were used to determine the proton trajectories.

In addition, spectra were recorded of the polarimeter detector energy signals and of the time jitter of the incident protons with respect to the 50-MHz cyclotron rf signal, measured by an additional detector in the polarimeter.[6]

In the off-line analysis cuts were made to accept only protons with trajectories originating from the region of intersection of neutron beam and target, produced by neutrons within the high-energy peak of the spectrum. The background ($\leq$ 25%) under the $p(n,p)n$ peak, produced by (n,p) reactions on target material other than hydrogen, was measured using a dummy target of $C_4H_{0.5}O$, contained in an identical cell as the butanol. Using pure graphite as a dummy target yielded similar background spectra.

A_{zz} was finally computed using

$$A_{zz}=\frac{1}{P_z^T|P_z^n|}\frac{N^+-N^-}{N^++N^--2N_b}, \qquad (1)$$

where N^+ (N^-) is the yield corresponding to an incident neutron beam with helicity + (−). N_b is the corresponding yield of the background under the hydrogen peak. Both yields were dead-time corrected and normalized to the Faraday-cup integrated charge. Density variations in the liquid-deuterium target were found to be slow and were eliminated by flipping the proton spin every 10 s.

The final results include a correction for finite geometry ($\leq$ 3%) and for the effect of the magnetic field on the proton trajectories ($\Delta\theta_{\text{c.m.}}\leq0.8°$).

Suitable count-rate combinations (see, e.g., Refs. 10 and 11) were used to obtain an upper limit on a possible transverse polarization component $P_y^n/P_z^n\leq0.015$; the resulting effects cancel largely by averaging over the two target spin orientations. A small correction ($\leq$ 0.005) was applied for the effect of a horizontal component $P_x^n/P_z^n=0.01$, which was caused by setting the spin-precession dipole for the neutron energy peak and not for the average energy in the final analysis ($\Delta E\simeq1$ MeV).

The internal consistency of the data was studied by several means: (a) The analysis was performed with two different cuts on the neutron energy spectrum. This allowed us to check the proper treatment of the energy dependence of the effective neutron polarization. The two results were in excellent agreement. (b) Equation (1) was evaluated for both signs of the target polarization separately. No systematic differences were found. (c) Part of the data was taken with the overall phase of the neutron spin reversed by reversing the magnetic field of the solenoid; no difference was observed. (d) The distribution of the A_{zz} values of as many as 66 individual 1-h runs was found to be completely statistical.

The results are shown in Fig. 2 together with predictions of the Bonn-potential[1] and Paris-potential[12] models as well as of the PSA's discussed below. The errors represent the root-square sum of the statistical and the systematic errors discussed above. The data are subject to an additional normalization uncertainty of 6%, due to the calibration uncertainties of the polarizations of the neutron beam (4%) and of the target (4%). No clear preference for either the Bonn or the Paris potential is observed (the Paris-potential prediction is almost identical to that of the Bonn potential A mentioned below). The data agree better with the Paris potential near the zero crossing, but are lower at smaller angles, whereas the Bonn prediction is 7% too large on average.

The results, together with our new A_y data[5] at the same energy and the results for $d\sigma/d\Omega$ and A_{yy} by the Karlsruhe group,[4,13] were added to the world database (omitting the erroneous[14] Harwell σ_T and $d\sigma/d\Omega$ data[15,16]) and analyzed by means of Arndt's PSA code.[17] The phases were assumed to be linear over the energy range studied (32–68 MeV). We searched all phases with $L \leq 2$ (except ${}^3D_3$), including ${}^1F_3$, the mixing parameters $\epsilon_1, \epsilon_2, \epsilon_3$, and a free normalization parameter for every experiment. The other partial waves were taken from the Bonn potential; using other parametrizations such as the Paris or Nijmegen[18] potential did not change the results. Similarly, varying the energy dependence of the phases or fixing some of the less significant phases on the Bonn predictions had negligible effect. The ${}^1S_0$ pp phase was taken from the Paris potential; the charge splittings for the higher $T=1$ phases could be determined in a stepwise χ^2 minimization and were found to be similar to the ones of the most recent complete PSA.[19] The final total χ^2 (np and pp data) was 506 for 488 degrees of freedom. Figure 2 includes the new fit as well as the 1989 50-MeV single-energy fit[17] without the new data. For better presentation in the figure the new fitted curve has been multiplied by the renormalization factor 0.941 required by the analysis. This is within the 6% normalization error given above.

In general, the predictions of the most recent meson-theoretical models, the Bonn[1] and the Paris[12] potentials, are close to our solution. The most significant difference occurs for ϵ_1, presented in Fig. 3. The error bar on the new value of ϵ_1 represents the diagonal element of the error matrix which also coincides with the parameter latitude given by the usual "$\chi^2_{\min}+1$" criterion for simultaneous variation of all other parameters.

The impact of the new data is shown by the striking reduction, by a factor of 3, of the uncertainties in ϵ_1 and ${}^1P_1$. The improvement is mainly due to the addition of the A_{zz} data. The value of ϵ_1 ($2.9° \pm 0.3°$) is significantly higher than the predictions of the potential models and of Arndt's 1987 analysis.[19] One should bear in mind that this value is closely linked to the value of ${}^1P_1$. More positive values of ${}^1P_1$—determined by cross-section data—require larger values of ϵ_1 in order to fit A_{zz}. Although the new value of ${}^1P_1$ ($-9.4° \pm 0.2°$) is much more negative than the recent value of Ref. 19 ($-4.1° \pm 0.6°$) and essentially removes the notorious discontinuity at 50 MeV caused by the Harwell data, it is still more positive than the Bonn ($-10.5°$) and Paris ($-10.9°$) predictions. Fortunately, A_{zz} and A_{yy} represent complementary data sets in the sense that the signs of the correlation between ϵ_1 and ${}^1P_1$ are opposite. Using both data sets thus tends to eliminate a possible bias

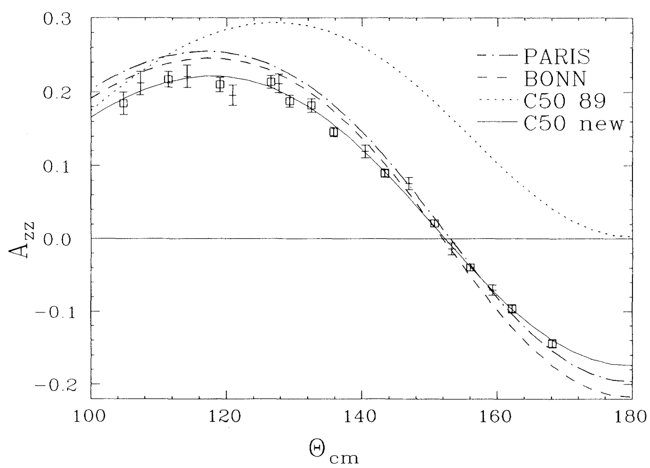

FIG. 2. Our results for A_{zz} at 67.5 MeV compared with the predictions of the Bonn (dashed) and Paris (dash-dotted) potentials. Our new phase-shift fit (multiplied by the fitted renormalization factor 0.941) is given by the solid line; the old C50 SP89 (Ref. 17) fit by the dotted line. The different symbols for the data represent the results of two independent run periods.

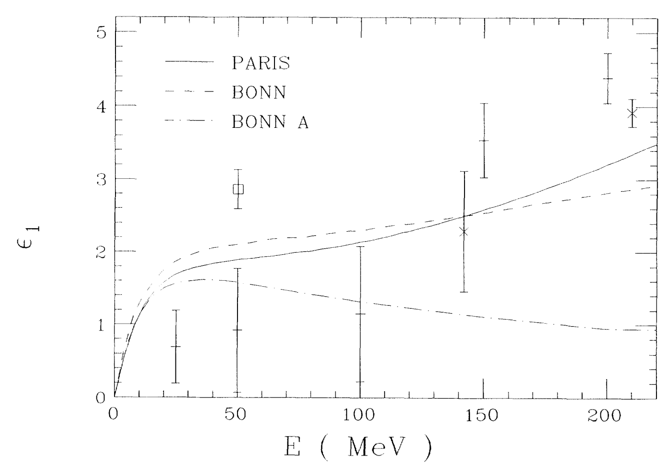

FIG. 3. ϵ_1 as a function of energy. Curves represent the predictions of the Bonn (dashed), Paris (solid), and Bonn A (dash-dotted) potentials. Single-energy PSA results are given by the square (this work), horizontal bars (Ref. 19), and crosses (Ref. 20).

in the determination of ϵ_1 which would be caused by the correlation to a potentially wrong value of $^1P_1$. Our new value of ϵ_1 is in line with a recent PSA,[20] including new data above 200 MeV, where ϵ_1 values much larger than predicted by the Bonn potential were obtained.

The value we find for ϵ_1 is significantly higher than that given by modern N-N potentials. The discrepancy is largest with respect to the one-boson-exchange approximation Bonn A (Ref. 1) (see Fig. 3) which is characterized by a weak tensor force. This relativistic momentum-space potential was recently shown to essentially explain the binding energy of the triton[1] and three-nucleon continuum observables[21] without need for three-body forces. The other Bonn potentials as well as the Paris potential do not allow this because of their stronger tensor force. The present results which were derived directly from nucleon-nucleon scattering indicate that an even stronger tensor force is required to explain the behavior of ϵ_1. Whether this is in conflict with the results of Ref. 21 can only be clarified by a detailed study of the uncertainties entering into the three-nucleon calculation of Ref. 21 concerning the neglect of Coulomb forces and of possible three-body-force–off-shell effects.

We would like to thank Professor R. A. Arndt for his assistance with the analysis code and the Karlsruhe group for providing their data prior to publication. We appreciate the support with the multiwire chambers by the University of Neuchatel. This work was supported by the Swiss National Science Foundation.

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