R. Levy for their help in part of the experimental work and N. Benczer-Koller for helpful discussions. The help of Eng. B. Feldman, L. Sapir, Y. Yurman, and their colleagues with the technical aspects of this work is gratefully acknowledged. This work was supported, in part, by the Israel–United States Binational Science Foundation.

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Investigation of Noncentral Proton-Proton Interaction at Low Energy

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(Received 26 March 1979)

The analyzing power of proton-proton scattering has been measured at 6.14 MeV in the angular range $7.5 \leq \theta_{lab} \leq 20°$ with an accuracy of $\pm 3 \times 10^{-4}$. Phase shifts are deduced from an analysis of the cross-section and polarization data. The spin-orbit and tensor P-wave phase-shift combinations are determined in a model-independent way to be $\Delta_{LS} = 0.139° \pm 0.31°$ and $\Delta_T = -0.488° \pm 0.023°$.

The study of the proton-proton interaction is one of the most fundamental problems in nuclear physics. In the low-energy region ($E_p \leq 10$ MeV), where the S-wave scattering is dominant, most efforts have been made to measure the differential cross section with high accuracy.[1-6] In this energy region the P-wave contribution to proton-proton scattering is small and comes mainly from the interference of Coulomb and nuclear amplitudes. It has been shown by Sher, Signell, and Heller[7] that the S-wave phase shift and the central P-wave phase-shift combination $\Delta_c = \frac{1}{9}[\delta(^3P_0) + 3\delta(^3P_1) + 5\delta(^3P_2)]$ can be extracted from low-energy differential–cross-section data. For a determination of the noncentral P-wave phase-shift combinations $\Delta_T = \frac{5}{72}[-2\delta(^3P_0) + 3\delta(^3P_1) - \delta(^3P_2)]$ and $\Delta_{LS} = \frac{1}{12}[-2\delta(^3P_0) - 3\delta(^3P_1) + 5\delta(^3P_2)]$, additional polarization measurements are necessary. Recent high-precision analyzing-power measurements have been performed at 10 MeV (Ref. 8) and 16 MeV.[9] It was the aim of the present investigation to continue these measurements to lower energies and to extract the P-wave splitting and hence the noncentral P-wave phase-shift combinations Δ_T and Δ_{LS} in an unambiguous way. In this Letter we present an analyzing-power measurement at 6.14 MeV accurate to $\pm 3 \times 10^{-4}$.

The experiment was performed with the polarized proton beam of the Universität Erlangen Lamb-shift source and the 6-MV model EN tandem accelerator. The beam polarization (60–65%) was monitored continuously with a ^{4}He polarimeter mounted behind the Faraday cup. Since a measurement at extreme forward angles was in-

TABLE I. Experimental values of the analyzing power for proton-proton scattering at 6.141 MeV.

$\theta_{c.m.}$ (deg)	$10^4 A(\theta)$
15	-5.0 ± 4.0
20	-9.1 ± 2.9
25	-9.1 ± 2.7
30	-9.4 ± 3.3
35	-6.4 ± 2.8
40	-3.3 ± 3.6

TABLE II. Phase shifts and deduced magnitudes for p-p scattering at 6.141 MeV, in degrees [$A_{\rm Erl.}$, our analyzing power measurement; $\sigma_{\rm Hegl.}$, cross-section measurement at 5.957 MeV by Hegland *et al.* (Ref. 3). $\sigma_{\rm Slob.}$, cross section measurement at 6.141 MeV by Slobodrian *et al.* (Ref. 1)].

	Unfloated Cross Section		Floated Cross Section [a]	
	$A_{\rm Erl.}, \sigma_{\rm Hegl.}$	$A_{\rm Erl.}, \sigma_{\rm Slob.}$	$A_{\rm Erl.}, \sigma_{\rm Hegl.}$	$A_{\rm Erl.}, \sigma_{\rm Slob.}$
$^1S_0$	55.19±0.05	55.55±0.08	54.66	55.83
$^3P_0$	1.65±0.16	1.64±0.28	1.73	1.61
$^3P_1$	−1.14±0.04	−1.19±0.07	−1.11	−1.20
$^3P_2$	0.31±0.03	0.27±0.05	0.34	0.26
$^1D_2$ [b]	0.065	0.069	0.065	0.069
χ^2	39.8	6.7	34.1	6.3
Δ_c	−0.021±0.027	−0.062±0.049	0.009	−0.073
Δ_{LS}	0.139±0.031	0.137±0.55	0.129	0.141
Δ_T	−0.488±0.023	−0.494±0.042	−0.494	−0.491

[a] The errors are the same as in columns 1 and 2.
[b] The $^1D_2$ phase was fixed by one-pion exchange.

tended, we used the supersonic H_2-gas jet of a windowless gas target.[10] The target arrangement for this measurement is shown in Figs. 1 and 3 of Ref. 10. The target thickness obtained for an entrance pressure of 20 bars was about 10 μg/cm^2. The angular acceptance of the detectors was 0.1 msr for $\theta_{\rm lab}=7.5°$ and 1.25 msr for $\theta_{\rm lab} \geq 10°$. The observed spectra showed a flat and unstructured background on the low-energy side, and a prominent peak and a smaller peak due to scattering on hydrogen and on gas contaminants, respectively. A typical spectrum at $\theta_{\rm lab}=7.5°$ is shown in Fig. 13 of Ref. 10. The result at $\theta_{\rm lab}=5°$, which has been mentioned in a preliminary report of this investigation,[11] has been dropped since the two peaks partly overlap. Since the experiment is very sensitive to variations in position and direction of the incident beam, correlated with the spin reversal, the polarization was switched on and off with a frequency of 100 Hz. This was achieved by the use of a weak magnetic field between the Sona coils of the Lamb-shift source; this has no effect on the beam position. In addition to this the position of the polarized beam was stabilized with a fast feedback system. The results of this measurement are shown in Table I. The errors listed there originate mainly from statistics, but additional errors due to the beam polarization measurement, the background subtraction, and a possible analyzing power (upper limit) of the background are included. This latter error source affects mainly the value at 7.5°. For more details of the experimental arrangement and of the data reduction procedure, and for error discussions we refer to Bittner[12] and a forthcoming paper.

Our polarization data were analyzed simultaneously with the 6.141-MeV cross sections of

TABLE III. Experimental and theoretical noncentral p-wave combinations Δ_{LS} and Δ_T.

	E_p (MeV)	Experiment [a]	Bonn potential (Ref. 16)	Graz potential (Ref. 18)	Regge-pole theory (Ref. 17)
Δ_{LS} (deg)	6.14	0.139±0.031	0.055	−0.044	0.055
	10.0	0.31±0.11	0.128	−0.021	0.134
Δ_T (deg)	6.14	−0.488±0.023	−0.650	−0.456	−0.553
	10.0	−0.812±0.055	−1.131	−0.910	−1.030

[a] This work (6.14 MeV) and the results of Hutton *et al.* (Ref. 8) (10 MeV).

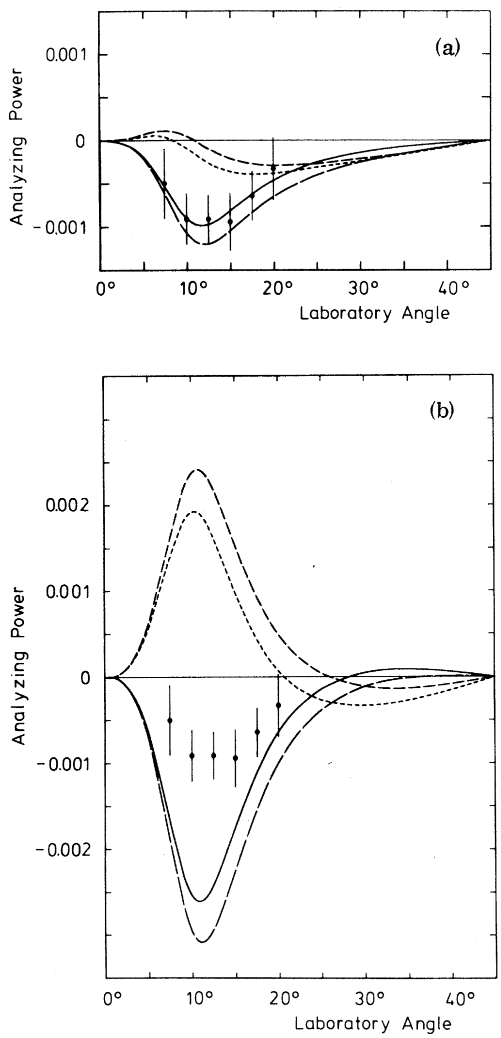

FIG. 1. Analyzing power for proton-proton scattering at 6.14 MeV. (a) Theoretical curves for dominating tensor force ($\Delta_{LS}=0.139°$, $\Delta_T=0.488°$). (b) Theoretical curves for dominating spin-orbit force ($\Delta_{LS}=0.704°$, $\Delta_T=0.270°$). Solid line: $\Delta_{LS}>0$, $\Delta_T<0$; short-dashed line: $\Delta_{LS}<0$, $\Delta_T>0$; long-dashed line: $\Delta_{LS}>0$, $\Delta_T>0$; dotted line: $\Delta_{LS}<0$, $\Delta_T<0$.

Slobodrian *et al.*[1] (set BGS) as well as with the 5.957-MeV cross sections of Hegland *et al.*[3] using a phase-shift program of Watari.[13] The $^1S_0$- and ^3P_J-wave phase shifts were used as fit parameters, while the phase shifts for $L \geq 2$ and the mixing parameters were fixed by the one-pion-exchange model. The phases, corrected for the effect of vacuum polarization, are of the electric-nuclear type of Sher, Signell, and Heller.[7] In a recent publication by Knutson and Chiang[14] it has been shown that electromagnetically induced spin-dependent potentials have virtually no effect on the analyzing power in low-energy proton-proton scattering and thus a neglect of such effects in the analysis seems to be appropriate. The results of the fit to our polarization data and the different cross-section data are shown in Table II together with the corresponding χ^2 and the derived magnitudes Δ_c, Δ_{LS}, and Δ_T. For a better comparison with the results of other *p-p* analyses the errors are calculated in the usual way from the error matrix. Another error estimate derived from the half widths of the likelihood functions, which have Gaussian shape, resulted in larger errors by about a factor of 2–3 (see Ref. 12). To check whether the extracted parameters are sensitive to the absolute cross-section normalization, the latter was also allowed to be floated with the results shown in columns 3 and 4 of Table II. A comparison of the "unfloated" and the "floated" analysis shows that mainly the $^1S_0$ phase shift and to some extent the central *P*-wave combination Δ_c are affected by this procedure. The important fact is that both the tensor and spin-orbit *P*-wave combination Δ_T and Δ_{LS} are nearly insensitive to this different treatment of the cross section. The reason for this is that the analyzing power, which is fitted simultaneously with the cross section, primarily depends on Δ_T and Δ_{LS}, whereas the cross section is insensitive to both magnitudes. When the $^1D_2$-wave phase shift was allowed to be varied, the χ^2 was improved slightly, Δ_{LS} and Δ_T were nearly not affected, and the change of the $^1S_0$ phase shift and of Δ_c were within the error listed in Table II.

Our measurement is shown in Fig. 1 compared with curves predicted by eight different *P*-wave phase-shift combinations which all describe the differential cross section $\sigma_{\text{Hegl.}}$ equally well. The curves in Fig. 1(a) correspond to a dominating tensor force ($|\Delta_{LS}/\Delta_T|=0.29$), while the curves in Fig. 1(b) are in accordance with a dominating spin-orbit force ($|\Delta_{LS}/\Delta_T|=2.61$). This ambiguity concerning the relative strength of spin-orbit and tensor forces in low-energy proton-proton scattering, which has been already mentioned by Slobodrian *et al.*,[1] can be clearly resolved by our analyzing-power measurement. This is because the sign and amplitude of $A_y(\theta)$ are mainly determined by Δ_{LS}. The four curves in each figure correspond to different signs of Δ_{LS} and Δ_T, while the $^1S_0$ phase-shift and the central *P*-wave combination Δ_c are kept fixed. Our conclusion from this analysis is that the well-known fourfold ambiguity[15] concerning the sign of Δ_{LS} and Δ_T can be resolved only partly by an analyzing-power measurement. The negative Δ_{LS} [upper curves in Fig. 1(a)] can be ruled out by our measurement, whereas the sign of Δ_T cannot be determined unambiguously. The solid curve in Fig. 1(a), calculated with the best-fit parameters of Table II, column 1, corresponds to a repulsive tensor force ($\Delta_T < 0$) and to a weak attractive spin-orbit force ($\Delta_{LS} > 0$). The noncentral P-wave combinations Δ_{LS} and Δ_T obtained from this analysis at 6.14 MeV and from Hutton *et al.*[8] at 10 MeV are compared with predictions from potential models in Table III. For the long-range behavior the Bonn potential[16] and the Regge-pole theory[17] underestimate the spin-orbit force and overestimate the tensor force, whereas the Graz potential[18] predicts a wrong sign for the LS force, but gives a good description for the tensor force.

We thank G. Graw and W. Haeberli for stimulating discussions, W. Watari for furnishing the computer code, K. Holinde and L. Mathelitsch for calculating the phase shifts of the Bonn potential and the Graz potential, respectively, and we thank K. Frank, J. Jordan, H. Löh, K. Rüskamp, W. Schuster, K. Spitzer, W. Stach, and P. Urbainsky for their help in data taking.

This work was supported by the Deutsche Forschungsgemeinschaft.

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