[8]M. Buenerd *et al.*, Phys. Lett. 102B, 242 (1981).
[9]R. D. Stokstad *et al.*, Phys. Rev. C 20, 655 (1979).
[10]G. R. Satchler, personal communication.
[11]G. R. Satchler, in *Proceedings of the International Conference on Reactions between Complex Nuclei, Nashville, Tennessee, 1974*, edited by R. L. Robinson, F. R. McGowan, J. B. Ball, and J. H. Hamilton (North-Holland, Amsterdam, 1974), Vol. II, p. 171.
[12]M. E. Brandan, in Proceedings of the International Conference on Selected Aspects of Heavy Ion Reactions, Saclay, 1982 (unpublished), p. 76.
[13]J. G. Cramer and R. M. DeVries, Phys. Rev. C 22, 91 (1980).
[14]R. Schaeffer, in *Nuclear Physics with Heavy Ions and Mesons*, Proceedings of the Les Houches Summer School, Session XXX, edited by R. Balian, M. Rho, and G. Ripka (North-Holland, Amsterdam, 1978), p. 69.

Spin Correlation for *pp* Elastic Scattering at $\theta_{\text{c.m.}} = \pi/2$ in the Energy Region of Dibaryon Resonances

T. S. Bhatia, G. Glass, J. C. Hiebert, R. A. Kenefick, L. C. Northcliffe, and W. B. Tippens
Texas A & M University, College Station, Texas 77843

and

J. G. J. Boissevain, J. J. Jarmer, and J. E. Simmons
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

G. E. Tripard
Washington State University, Pullman, Washington 99164

and

D. Fitzgerald, J. Holt, and A. Mokhtari
University of California, Los Angeles, California 90024
(Received 14 June 1982)

Precise measurements are reported of the spin-correlation parameter A_{NN} for 500–800 MeV *pp* elastic scattering at $\theta_{\text{c.m.}} = \pi/2$. While not reproducing the large value of A_{NN} reported earlier at 697 MeV, the data show a pronounced maximum in the 90° triplet-to-singlet ratio near the location of the reported $^3F_3$ dibaryon resonance. In contradiction with an earlier report, structure is not found in the moduli of the singlet and triplet amplitudes.

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In studies of the spin dependence of nucleon-nucleon scattering at the zero-gradient synchrotron (ZGS), Yokosawa and co-workers[1] found a striking structure in the total-cross-section differences for longitudinal initial spin states, $\Delta\sigma_L$, in *pp* scattering. Hidaka *et al.*[2] have interpreted this as a manifestation of an $I=1$ $^3F_3$ dibaryon resonance. Hoshizaki's single-channel fits to his set of phase shifts[3] indicated the existence of the diproton resonances $^1D_2$ (2.17 GeV) and $^3F_3$ (2.22 GeV). Recent analyses by Arndt *et al.*[4] have also shown sharp energy variations for the $I=1$ $^1D_2$ and the $^3F_3$ phases in the 2.08–2.25 GeV region. A recent experiment[5] at the Clinton P. Anderson Meson Physics Facility (LAMPF) has corroborated the earlier ZGS $\Delta\sigma_L$ data. Whereas the correctness of the $\Delta\sigma_L$ data is no longer in doubt, convincing proof for the existence of these resonances is still lacking. For instance, several theoretical analyses have shown that, although it seems to be compatible with resonances of the type that have been suggested, the existing limited data base does not demand such resonances.[6,7] High-precision measurements of some carefully chosen set of observables may remove this ambiguity. Measurements of the energy dependence of the spin-correlation parameter, A_{NN}, for *pp* elastic scattering at $\theta_{\text{c.m.}}=\pi/2$ are especially important since together with measurements of $d\sigma/d\Omega(90°)$, they uniquely determine the modulus of the singlet amplitude. (See MacGregor, Moravcsik, and Stapp, or Beretvas, Ref. 7.)

The importance of polarization measurements for *pp* elastic scattering at 90° has been emphasized, most recently by Goldstein and Moravcsik.[7] In a recent experiment at LAMPF we have measured the angular distributions of the spin-correlation parameter A_{NN} for *pp* elastic scattering at 500, 600, 650, 700, 733, and 800 MeV incident proton energies. In this paper the results for $\theta_{\rm c.m.} = 90°$ are reported. We find the triplet dominance at 1.34 GeV/*c* to be much less strong than reported earlier.[8]

The polarized proton beam from LAMPF was focused onto a dynamically polarized proton target. The momentum of the scattered protons was measured with a magnetic spectrometer and the corresponding recoiling protons were detected in a multiwire proportional chamber array (see Fig. 1). The polarization of the proton beam, typically ~0.80, in a direction normal to the scattering plane, was continuously monitored with a polarimeter consisting of up-down and left-right monitor systems. All eleven detectors, four for left-right and seven for up-down systems, viewed a 3.2-mm-thick CH_2 target. Only the left-right component of the polarimeter is shown in Fig. 1. The sum of up plus down yields was used as the primary-beam intensity monitor. The sum of left plus right yields and an ion chamber provided independent checks on the primary monitor. The typical beam intensity was ~1 pA. The polarized proton target consisted of ~1-mm-diam beads of propanediol ($C_3H_8O_2$) doped with Cr(V). The cryostat containing the target cell, 20 mm diam × 40 mm long, immersed in liquid ^{3}He, was placed in a normal (vertical) uniform magnetic field (2.5 T). A beam profile monitor

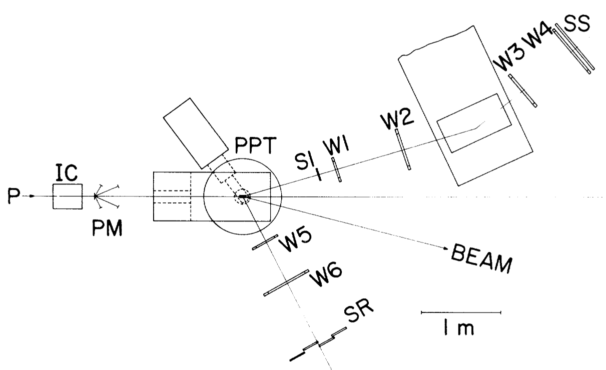

FIG. 1. Experimental setup. Only the left-right component of the beam-line polarimeter monitor (PM) is shown. Scintillators: S1, SS, SR; wire chambers: W1–W6; ion chamber: IC.

was used periodically to monitor fluctuations of the spot size and position. The incident-beam polarization direction was reversed at the source every 2–3 min. No beam motion correlated with spin reversal was observed. The target polarization was also reversed twice in a four-run cycle (↑↓↓↑), which took 5–6 h. Absolute beam polarization was determined by the "quench ratio" method, a technique which is capable of polarization calibration to ±0.4%.[9] In this experiment the accuracy of the beam polarization measurement was ~1%. Absolute target polarization was obtained by using improved NMR techniques.[10] Typical target polarization was ~0.80 and was measured to within 2%.

Measurements of the time of flight, scattering angle, and momentum of the scattered protons together with the direction and velocity of the conjugate recoiling charged particle permitted a nearly complete separation of the signal from the background due to quasielastic scattering from the nonhydrogenous component of the polarized target (background was typically 3%–5% of the signal). The shape of the quasielastic scattering was obtained by taking data with the propanediol beads replaced by hollow graphite beads of approximately the same density.

A check on the accuracy of the measurement of the scattering angle was provided when the analyzing power for *pp* elastic scattering near 90° (where A must equal zero) was extracted. The result obtained was $A(89.9°) = 0.003 \pm 0.005$ for 800-MeV *pp* elastic scattering. From the values obtained for *pp* analyzing powers near 90° it is determined that the angle measurement is accurate to ±0.1°.

The results of these measurements of $A_{NN}(90°)$ are given in Table I and shown in Fig. 2 in com-

TABLE I. Spin-correlation parameter A_{NN}(90° c.m.) for $pp \to pp$ at 500–800 MeV. Overall normalization uncertainty of 3% is not included. The error ΔA_{NN} is the standard deviation from the mean of several measurements.

T_p (MeV)	A_{NN}	ΔA_{NN}
500	0.497	0.005
600	0.606	0.004
650	0.672	0.007
700	0.715	0.005
733	0.744	0.005
800	0.684	0.004

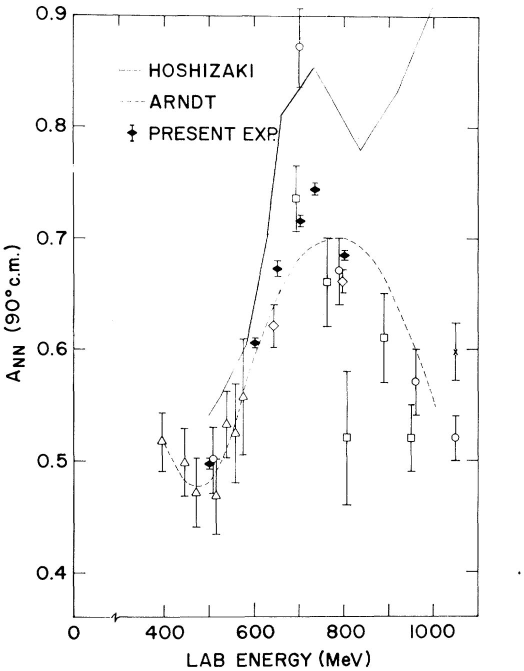

FIG. 2. Spin-correlation parameter $A_{NN}(90°)$ for pp elastic scattering. The error bars shown for the present work are the standard deviation from the mean of several measurements while for the rest of the data only statistical errors are given. The previous data shown are as follows: circles, Ref. 8; triangles, Ref. 11; diamonds, Ref. 12; squares, Ref. 13; crosses, Ref. 14. The result of Arndt *et al.* (dashed curve) is obtained from their SP82 solution whereas Hoshizaki's prediction (solid line) is from Ref. 3.

parison with those of previous measurements.[8,11-14] The error bars shown in Fig. 2 for all data sets except the present work are statistical. For the present LAMPF work shown in Table I and Fig. 2, the error bars are the standard deviation from the mean of many (typically eight) measurements. The overall normalization error, mainly due to possible errors in beam and target polarization measurements, of 3% is not included. Our data show a peak value at 733 MeV which implies $\sigma_t/\sigma_s = 6.8$. Near 500 MeV our A_{NN} value is ~5% larger than the value quoted by Besset *et al.*[11] Similarly near 650 and 800 MeV we find that $A_{NN}(90°)$ is ~4% larger than the corresponding values reported by McNaughton *et al.*[12] Both the Besset *et al.* (396–578 MeV) and the previous LAMPF (647 and 796 MeV) measurements[12] differed from our measurements in that they were carried out with an experimental setup which did not include a magnetic spectrometer and thus lacked a momentum measurement for the scattered protons. At 500 and 800 MeV the ZGS results, also obtained with a magnetic spectrometer in the detection system, agree remarkably well with the present measurements. We find striking disagreement with the ZGS measurement[8] at 1.34 GeV/c (697 MeV) which gave $A_{NN}(90°)$ of 0.872 ± 0.035, implying triplet-to-singlet ratio $\sigma_t/\sigma_s = (1+A_{NN})/(1-A_{NN}) \sim 15$, whereas our value at 700 MeV (0.715 ± 0.005) leads to $\sigma_t/\sigma_s = 6$. Because A_{NN} for pp elastic scattering exhibits very little angular dependence near 90° c.m. in the energy range of this experiment, differences in averaging over angles in the two measurements will not account for this discrepancy at 700 MeV.

The principal sources of error in this experiment are the normalizations of beam and target polarizations. As a check of these normalizations, a substantial amount of data were taken for 800-MeV pp scattering at $\theta_{c.m.} \sim 48°$, where the analyzing power is a maximum. Measurements of the analyzing powers $A(p_{pol}p)$ and $A(pp_{pol})$ for 800-MeV pp scattering at 48° c.m. agreed with each other and with the previous high-precision LAMPF measurement[9] to within ~3% relative.

Figure 2 also shows the predictions of the energy dependence of $A_{NN}(90°)$ from the phase-shift analysis (PSA) of Hoshizaki[3] and from a recent PSA of Arndt *et al.* (SP82). The present data are not included in the data base of the PSA program of Arndt *et al.* whereas the ZGS data[8] are included. The present results which show a smooth increase from ~0.51 at 500 MeV to ~0.74 at 733 MeV are clearly not in agreement with the predictions of Hoshizaki's PSA, in which the existence of the $^1D_2$ and $^3F_3$ resonances was emphasized. The energy variations of $A_{NN}(90°)$ from 500 to 733 MeV can be understood qualitatively by considering the results of our measurements of the spin correlations for the pion production channels in the 500–800 MeV energy range. The preliminary results show that A_{NN} for the $pp \to d\pi^+$ reaction is large and negative at all energies in the angular range covered in this experiment. Similarly, our preliminary value of A_{NN} for the $pp \to np\pi^+$ reaction at 650 and 800 MeV for two kinematic settings is large and negative[15]; to our knowledge, this is the only spin-correlation measurement for this dominant inelastic channel.[16] The total cross section for the $d\pi^+$ channel peaks to ~3 mb at ~620 MeV whereas that for the $np\pi^+$ channel increases from ~0 at 500 MeV to ~19 mb at ~900 MeV. Large negative values of A_{NN} imply that the pion production proc-

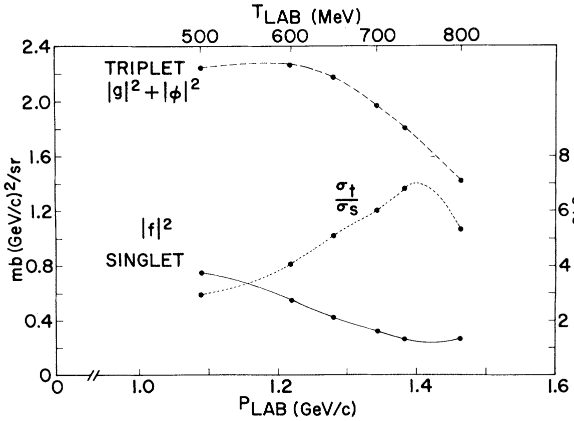

FIG. 3. Energy dependence of the singlet amplitude $|f|^2$ (solid curve) and the total triplet amplitude $|g|^2 + |\varphi_3|^2$ (dashed curve). Curves are drawn merely to guide the eye. The dotted curve showing the triplet-to-singlet ratio is derived from the solid and dashed curves.

esses are taking place predominantly from antiparallel spin configurations of the initial pp system. Thus, as the pion production cross section rises as the energy increases above 500 MeV, the elastic pp channel will reflect a relative decrease in the spin-antiparallel contribution, thereby causing an increase in $A_{NN}(90°)$.

For pp elastic scattering, only three independent amplitudes survive at $\theta_{c.m.} = \pi/2$ because of the symmetry properties and identity of the particles. An important feature of such a scattering process is that a subset of observables uniquely determines a subset of the amplitude parameters.[7,17] For example, in the notation of Ref. 17, the modulus of the singlet amplitude $|f|^2$ and the sum of the moduli of the triplet amplitudes, $|g|^2 + |\varphi_3|^2$, can be obtained from $d\sigma/dt\,(90°)$ and $A_{NN}(90°)$ as follows:

$$|f|^2 = \frac{2q^4}{\pi}\frac{d\sigma}{dt}\,(1 - A_{NN}),$$

$$|g|^2 + |\varphi_3|^2 = \frac{2q^4}{\pi}\frac{d\sigma}{dt}\,(1 + A_{NN}).$$

Using our values of $A_{NN}(90°)$ and $d\sigma/dt\,(90°)$ from the phase-shift parametrization of Arndt *et al.*, which fits the data[18] well, one can determine the energy dependence of the singlet amplitude $|f|^2$ and the sum of the triplet moduli $|g|^2 + |\varphi_3|^2$. Such a procedure shows no structure in the moduli (see Fig. 3), in direct contradiction with the conclusions of Svarc, Bajzer, and Furic.[17] Nevertheless the 90° triplet-to-singlet ratio, σ_t/σ_s, also given in Fig. 3, shows a distinct peak at 733 MeV. The sharp decrease in the triplet modulus is interesting and warrants more experimental and theoretical input.

Arndt[19] has pointed out that the angular distributions of A_{NN}, which will be discussed in a later paper, will constrain the PSA much further and are expected to have a substantial impact on the question of the dibaryon resonances.

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[1]I. P. Auer *et al.*, Phys. Lett. 67B, 113 (1977), and Phys. Rev. Lett. 41, 354 (1978); A. Yokosawa, Phys. Rep. 64, 47 (1980).

[2]K. Hidaka *et al.*, Phys. Lett. 70B, 479 (1977).

[3]N. Hoshizaki, Prog. Theor. Phys. 60, 1976 (1978), and 61, 129 (1979).

[4]R. A. Arndt, L. S. Roper, B. J. VerWest, R. Clark, R. A. Bryan, and P. Signell, to be published; R. Bhandari, R. A. Arndt, L. D. Roper, and B. J. VerWest, Phys. Rev. Lett. 46, 1111 (1981).

[5]I. P. Auer *et al.*, Phys. Rev. D 24, 2008 (1981).

[6]B. J. VerWest, Phys. Rev. C 25, 482 (1982); Ian Duck, Phys. Lett. 160B, 267 (1981).

[7]M. H. MacGregor, M. J. Moravcsik, and H. P. Stapp, Annu. Rev. Nucl. Sci. 10, 291 (1960); A. Beretvas, Phys. Rev. 171, 1392 (1968); G. R. Goldstein and M. J. Moravcsik, Phys. Rev. D (to be published).

[8]D. A. Bell *et al.*, Phys. Lett. 94B, 310 (1980).

[9]M. McNaughton *et al.*, Phys. Rev. C 23, 1128 (1981); P. R. Bevington *et al.*, Phys. Rev. Lett. 41, 384 (1978).

[10]J. G. J. Boissevain and W. B. Tippens, Los Alamos Report No. LA9429 MS, 1982 (unpublished).

[11]D. Besset *et al.*, Nucl. Phys. A345, 435 (1980).

[12]M. McNaughton *et al.*, Phys. Rev. C 23, 838 (1981), and 25, 2107 (1982).

[13]V. A. Efimovyh *et al.*, Phys. Lett. 99B, 28 (1981).

[14]A. Lin *et al.*, Phys. Lett. 74B, 273 (1978).

[15]W. B. Tippens *et al.*, Bull. Am. Phys. Soc. 27, 46 (1982); J. E. Simmons *et al.*, Bull. Am. Phys. Soc. 27, 47 (1982), and to be published.

[16]There is significant disagreement between the Kloet-Silbar and the Mandelstam [W. Kloet and R. Silbar, Nucl. Phys. A346, 346 (1981); S. Mandelstam, Proc. Roy. Soc. London, Ser. A 244, 491 (1958)] predictions of the total reaction cross-section ratio $\sigma_t^{\,r}/\sigma_s^{\,r}$ for the pion production process. Our measurements seem to substantiate the Kloet-Silbar predictions.

[17]A. Svarc, Z. Bajzer, and M. Furic, Nucl. Phys. A370, 468 (1981).

[18]K. Abe *et al.*, Phys. Rev. D 12, 1 (1975); D. T. Williams *et al.*, Nuovo Cimento 8A, 447 (1972); M. G. Albrow *et al.*, Nucl. Phys. B23, 445 (1970).

[19]R. A. Arndt, private communication.