CONF. 790847 --13

NUCLEON-NUCLEON RESONANCES

by

I. P. Auer

MASTER

DISCLAIMER

Prepared for
8th International Conference
on
High Energy Physics and Nuclear Structure
Vancouver, British Columbia, CANADA
August 13, 1979

UOTC-AUA-USDOE

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated under Contract W-31-109-Eng-38 for the
U. S. DEPARTMENT OF ENERGY

NUCLEON-NUCLEON RESONANCES⁺

Invited Talk Presented at
the 8th Int. Conf. on High-
Energy Physics and Nuclear
Structure, 13-17 August 1979
Vancouver, B.C., Canada
ANL-HEP-CP-79-24

I. P. Auer

High Energy Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439

Recent measurements of pp (and pd) total cross section with polarized beams and target have revealed unexpected structure.¹⁻⁴ One interpretation of the structure requires the existence of nucleon-nucleon resonances.⁵⁻⁶ Until recently such resonances have not been incorporated into the standard description of the nucleon-nucleon interaction, partly because neither compelling experimental evidence nor strong theoretical need required their existence. Until a few years ago a text book description⁷ of the status of nucleon-nucleon resonances was: "These are the easiest to observe and to investigate: there are none". Clearly, the existence of nucleon-nucleon resonances (or dibaryon resonance) would have a profound impact on our understanding of the fundamental nature and behavior of strongly interacting particles.

Since the appearance of the recent measurements and interpretations, controversy has arisen both to

1. the validity of the $\Delta\sigma_L$ data,⁸
2. the interpretation of the data in terms of nucleon-nucleon resonances⁹.

Since I have been mostly involved in obtaining the experimental data for the $\Delta\sigma_L$ measurements, I think it is best to address myself mainly to the first part of the controversy and concentrate on describing the experimental techniques related to these measurements. However before doing so let me briefly remind you of the total cross section data and their implication to nucleon-nucleon interaction.

In nucleon-nucleon interaction we have three parity non-violating total cross sections. Through the use of the optical theorem these cross sections can be expressed in terms of (s channel) helicity amplitudes.¹⁰

$$\sigma^{\text{Tot}} = 1/2[\sigma^{\text{Tot}}(\uparrow\uparrow) + \sigma^{\text{Tot}}(\uparrow\downarrow)] = 2\pi/k_{\text{cm}} \text{Im}[\phi_1(0) + \phi_3(0)]$$

$$\Delta\sigma_L = \sigma^{\text{Tot}}(\uparrow\uparrow) - \sigma^{\text{Tot}}(\uparrow\downarrow) = 4\pi/k_{\text{cm}} \text{Im}[\phi_1(0) - \phi_3(0)]$$

$$\Delta\sigma_T = \sigma^{\text{Tot}}(\uparrow\uparrow) - \sigma^{\text{Tot}}(\uparrow\downarrow) = 4\pi/k_{\text{cm}} \text{Im}[\phi_2(0)]$$

where:

$$\phi_1(t) = \langle ++ | \phi | ++ \rangle \quad \phi_4(t) = \langle +- | \phi | +- \rangle$$

$$\phi_2(t) = \langle ++ | \phi | -- \rangle \quad \phi_5(t) = \langle ++ | \phi | +- \rangle$$

$$\phi_3(t) = \langle +- | \phi | +- \rangle$$

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

⁺ Work supported by the U.S. Department of Energy.

Thus the measurements of the three cross sections at a particular energy uniquely define the imaginary part of the forward amplitudes of $\phi_1(0)$, $\phi_2(0)$ and $\phi_3(0)$ ($\phi_4(0) = \phi_5(0) = 0$).

From dispersion theoretic calculations (in conjunction with other data) the corresponding real parts of the forward amplitudes can also be obtained.

We should note however that the total cross section measurements provide basically only three data points at a particular energy. To determine the amplitudes uniquely at all angles we require data from other angle dependent observables over a wide angular range such as

$$d\sigma/d\Omega = d\sigma/d\Omega (0,0;0,0) = 1/2[|\phi_1|^2 + |\phi_2|^2 + |\phi_3|^2 + |\phi_4|^2 + 4|\phi_5|^2]$$

$$Pd\sigma/d\Omega = d\sigma/d\Omega (0,N;0,0) = \text{Im}[(\phi_1 + \phi_2 + \phi_3 - \phi_4)^* \phi_5]$$

$$C_{NN} d\sigma/d\Omega = d\sigma/d\Omega (N,N;0,0) = \text{Re}[(\phi_1^* \phi_2 - \phi_3^* \phi_4) + 2|\phi_5|^2]$$

$$C_{SS} d\sigma/d\Omega = d\sigma/d\Omega (S,S;0,0) = \text{Re}[\phi_1^* \phi_2 + \phi_3 \phi_4]$$

$$C_{SL} d\sigma/d\Omega = d\sigma/d\Omega (S,L;0,0) = \text{Re}[(\phi_1 + \phi_2 - \phi_3 + \phi_4)^* \phi_5]$$

$$C_{LL} d\sigma/d\Omega = d\sigma/d\Omega (L,L;0,0) = 1/2[-|\phi_1|^2 - |\phi_2|^2 - |\phi_3|^2 + |\phi_4|^2]$$

From the relative simplicity of the above expressions, we see that data from different observables at a fixed energy and angle can rather conveniently be related to the helicity amplitudes. However when angular momentum is important, as in the investigation of possible threshold or resonance effects, it's best to expand the various observables in terms of partial waves.

What makes the total cross section measurements especially attractive is that their dependence on partial waves is linear; while that of the other observables is more complicated. Thus generally an angle dependent observable such as the polarization parameter P is a ratio of two bilinear series.

This implies that for a general (angle dependent) observable the partial waves are strongly coupled while for the total cross section they are not. Furthermore certain linear combinations of these cross sections will only depend on some subset of all possible partial waves. Thus the knowledge of these (total) cross sections helps greatly to identify which particular waves are responsible for the energy dependence of the nucleon-nucleon interaction.

The spin averaged pp cross section (Fig. 1) increases sharply between 1.1 and 1.3 GeV/c beam momentum. All but the ($\Delta L = 2$) partial waves can contribute to σ_{tot} . Most of the structure is interpreted in terms of threshold effects. This contrasts sharply with respect to the π^+p cross sections which contain noticeable peaks corresponding to well established resonances.

Fig. 1 Measured pp Total Cross Section Up to $P_{\text{LAB}} = 6 \text{ GeV/c}$ (Ref. 11)

The $\Delta\sigma_L$ data (Fig. 2) has noticeably more structure than σ^{Tot} . The measurements were taken during several different running periods, and the corresponding data are represented with different symbols. Note that at some energies the measurements were repeated.

Fig. 2 Measured Total Cross Section Difference $\Delta\sigma_L(pp) = \sigma^{\text{Tot}}_{pp}(\uparrow) - \sigma^{\text{Tot}}_{pp}(\downarrow)$ Refs. 2-3. Error bars include both statistical and systematic errors. The dotted curve is drawn only to guide the eye.

The decomposition of cross sections in terms of $\sigma^{\text{Tot}}(\uparrow)$ and $\sigma^{\text{Tot}}(\downarrow)$ is shown in Fig. 3. The bump in $\sigma^{\text{Tot}}(\uparrow)$ at P_{LAB} of 1.5 GeV/c is most likely due to one or more spin triplet partial waves (with $J=L$, odd) such as: 3P_1 , 3F_3 , 3H_5 , etc. Structure is also evident in the $\Delta\sigma_L$ data. Since only the singlet partial waves (1S_0 , 1D_2 , 1G_4 , etc.) have positive coefficients, it is most likely that one or more of these partial waves contribute to the bump seen in Fig. 4 at 2 GeV/c beam momentum.

Fig. 3 Total pp Cross Sections for Longitudinal Spin States as Function of $\sigma^{\text{Tot}}(\uparrow) = \sigma^{\text{Tot}} + 1/2 \Delta\sigma_L$

Fig. 4 $(k^2/4\pi) \sigma_T(pp)$ as Function of Beam Momentum (Ref. 1)

During the $\Delta\sigma_L$ measurements we have also obtained some large angle $C_{LL}(A_{LL})$ data.¹² These data significantly influenced both Hoshizaki's⁶ and Arndt's¹³ phase shift analysis.

The dispersion theoretic calculations of $\phi_1(0) - \phi_3(0)$ amplitude by Grein and Kroll¹⁴ are shown in Fig. 5. The loop in the Argand diagram suggests the presence of a resonance.

Fig. 5 Argand Diagram of the $I=1$ (pp) Amplitude $\phi_1(0) - \phi_3(0)$. The imaginary part is from the $\Delta\sigma_L$ measurements.²⁻³ The real part is based on the dispersion theoretic calculations of Grein and Kroll.¹⁴

Other data such as σ_{el}^{Tot} and other spin dependent measurements also support the resonance interpretation.⁵

Hoshizaki performed a phase shift analysis on the basis of this and other elastic data from $P_{LAB} = 1.1$ to 3 GeV/c and obtained indication of diproton resonances in the 3F_3 (2.22 GeV) and 1D_2 (2.17 GeV) partial waves in Figs. 6a and 6b.

Figs. 6a and 6b Argand Diagrams of the 1D_2 and 3F_3 Partial Waves Respectively Based on Hoshizaki's Phase Shift Analysis.⁶ The background contributions to the partial wave amplitudes have been subtracted.

Arndt¹³ recently extended and revised his phase shift analysis up to 750 MeV for his energy independent analysis and to 850 MeV for his energy dependent analysis. In addition to the pp elastic $\Delta\sigma_L$ and $\Delta\sigma_T$ data, Arndt also made use of the dispersion relation calculations of Grein and Kroll. His analysis gives strong indication of resonance in the 1D_2 wave and is consistent with a resonance in the 3F_3 wave (Figs. 7a and 7b).

Figs. 7a and 7b Argand Diagram of the 1D_2 and 3F_3 Partial Waves Respectively Based on Arndt's¹³ Phase Shifts. The ellipses represent the errors in the real and imaginary parts of the amplitudes for energy independent solutions. The continuous curves represent the energy dependent solutions.

To fully describe the nucleon-nucleon interaction, we need to define not only the $I=1$ (pp) but also the $I=0$ amplitudes. The preliminary $\Delta\sigma_L(I=0)$ data obtained from $\Delta\sigma_L(pd)$ and $\Delta\sigma_L(pp)$ is shown in Fig. 8.

Fig. 8 Preliminary $\Delta\sigma_L(I=0)$ Data Derived From Measurements of $\Delta\sigma_L(pd)$ and $\Delta\sigma_L(pp)$. Errors indicate statistical uncertainties only. Systematic errors for preliminary data are ± 10 -20%.

Dispersion relation calculations¹⁴ based on the preliminary $\Delta\sigma_L(I=0)$ data show a counterclockwise loop in the Argand diagram suggesting resonance-like behavior.

EXPERIMENTAL TECHNIQUES OF $\Delta\sigma_L$ MEASUREMENTS

So far all the $\Delta\sigma_L(pp)$ and $\Delta\sigma_L(pd)$ have been collected at the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory in a total of approximately four months of polarized beam time.

The experimentalists involved in the $\Delta\sigma_L$ measurements were:

I. P. Auer	H. Halpern	H. Spinka	D. Underwood
A. Beretvas	D. Hill	N. Tamura	R. Wagner
E. Colton	K. Nield	G. Theodosiou	Y. Watanabe
R. Ditzler	B. Sandler	K. Toshioka	A. Yokosawa

The technique we used is the so called "good geometry transmission experiment". The basic idea is to measure the difference in the attenuation factor for the corresponding difference between $\sigma^{\text{Tot}}(\pm)$ and $\sigma^{\text{Tot}}(\mp)$ i.e.: $\Delta\sigma_L$ (Fig. 9).

Fig. 9 Experimental Setup for the $\Delta\sigma_L$ and the C_L Measurements. S0, S1U, S1D, S2L, S2R, BA2, BA3, BA4, R1-R6 and F1-F6 are scintillation counters. S1U, S1D and S2L, S2R are two pairs of segmented counters (up, down, left, right). BA2, BA3 and BA4 are hole counters. CH1 to CH7 are multiwire proportional chambers.

The function of the detector system was to measure accurately the total number of incoming and the total number of non-interacting particles transmitted by extrapolating the counts in the circular scintillators to zero solid angle.

$$R^{\pm} = \lim_{\Omega \rightarrow 0} \frac{N_i^{\pm}}{N_0^{\pm}} = \exp[-\alpha - 1/A(\sigma^{\pm} \pm |\vec{P}_B \cdot \vec{P}_T| \frac{\Delta\sigma_L}{2})]$$

where:

- $\vec{P}_B$ and $\vec{P}_T$ are the beam and target polarization vectors respectively.
- $\pm$ refers to the relative orientation of $\vec{P}_B$ and $\vec{P}_T$ antiparallel (+) or parallel (-).
- N_i refers to the number of particles (corrected for detection efficiency) transmitted through the i^{th} scintillator counter.
- N_0 refers to the number of incoming particles transmitted through the target.
- R refers to the ratio of noninteracting particles to the number of incoming particles.
- α refers to the spin independent attenuation factor due to target cryostat and container, plus all the non-hydrogenous material in the target.

$$\sigma^{\pm} = \lim_{\Omega \rightarrow 0} \sigma^{\pm}(\Omega) = \lim_{\Omega \rightarrow 0} \int_{\Omega}^{4\pi} (d\sigma/d\Omega)^{\pm} d\Omega$$

In addition to σ^{Tot} , $\sigma^{\pm}$ contains the Coulomb-nuclear interference (C-N) and the multiple scattering contributions. Strictly speaking $\sigma^{\pm}$ diverges but we will ignore this difficulty since all spin independent quantities cancel in the end, and only the spin dependent component of the C-N remains.

$$A = \frac{1}{N_A \rho L} \text{ is the target constant for the free protons } (\approx 2860 \text{ mb}).$$

$$N_A = \text{Avogadro's number} = 6.02 \times 10^{23}.$$

$$L = \text{target length} \approx 8 \text{ cm}.$$

ρ = density of free protons in target ($\sim .073 \text{ gm/cm}^3$).

To a very high degree of accuracy

$$\Delta\sigma_L = \frac{2A}{\vec{p}_B \cdot \vec{p}_T} \epsilon \quad \text{where: } \epsilon = \frac{R^+ - R^-}{R^+ + R^-}$$

The uncorrected $\Delta\sigma_L$ in addition to the nucleon-nucleon term contains the spin dependent part of the C-N term. Descriptions of how these corrections may be obtained for $\Delta\sigma_L$ (and $\Delta\sigma_T$) measurements are given in Ref. 15.

To detect a 1 mb effect in $\Delta\sigma_L$ with our experimental conditions, we needed to measure ϵ to an accuracy of $\sim 10^{-4}$. To estimate the overall error in $\Delta\sigma_L$, let us examine how well we know the experimental quantities that determine $\Delta\sigma_L$.

Statistical Errors

Considering an unambiguously identified incoming beam particle as a "trial" and a non-interacting particle as a "success", we may apply the binomial model to calculate the statistical error.

$$\sigma(N_0^\pm) = [N_0^\pm p^\pm(1 - p^\pm)]^{1/2} \quad \text{where: } p^\pm \cong \frac{N_i^\pm}{N_0^\pm} \cong R^\pm \text{ (probability for success)}$$

This yields, (after some simplifying assumptions such as:

$$N_0^\pm \cong \frac{N_0}{2} \quad R^\pm \cong R \quad N_i^\pm \cong \frac{N_i}{2} \text{ ,}$$

$$\sigma(\Delta\sigma_L) \cong \frac{2A}{\vec{p}_B \cdot \vec{p}_T} \left(\frac{1}{N_i} - \frac{1}{N_0} \right)^{1/2} = \frac{2A}{\vec{p}_B \cdot \vec{p}_T} \left(\frac{1-R}{RN_0} \right)^{1/2}$$

Typically in our experiments the statistical error ranged from 0.1 to 0.5 mb.

Systematic Errors

Target Constant A

- Generally we used a single target per running period within these intervals of time we believe that A was quite stable.
- The effective value of A may be reduced if some of the beam particles do not go through the total length of the target. This was only a small problem at high energies where the beam quality was good, but was potentially a serious problem at low energies where the beam quality was relatively poor.

To minimize the problem of large beam spot and divergence, we used several hole counters to veto part of the beam that could miss the target. We also checked the position of the beam with respect to the target by

- taking polaroid pictures of the beam just downstream of the target. (The outline of the target was visible on the picture.)
- continuously sampling beam tracks with the beam chambers (MWPC's) $\sigma(A)/A \cong 2-5\%$

Target Polarization

- The direction of $\vec{P}_T$ was well defined - no problem.
- The magnitude of $\vec{P}_T$ was monitored continuously with an NMR probe. The calibration constant which could drift slowly, was remeasured (by taking thermal equilibrium runs) at one or two week intervals.

$$\sigma(P_T)/P_T \approx 3-4\%$$

Beam Polarization

At extraction, the beam was vertically polarized. To obtain longitudinally polarized beam, $\vec{P}_B$ was precessed into the horizontal plane with a superconducting solenoid, then $\vec{P}_B$ was further precessed with a bending magnet in the horizontal plane until its direction became parallel (or antiparallel) to the direction of the beam.

- The direction of $\vec{P}_B$ was rather well known ($\approx 1^\circ$) from our knowledge of $\int B dz$ of the solenoid and last bending magnet used to precess $\vec{P}_B$ in the horizontal plane. At P_{LAB} of 1.47 GeV/c (where $|\Delta\sigma_L|$ was maximum) the asymmetry parameter was measured as a function of the nominal angle θ at between $\vec{P}_B$ and $\vec{P}_T$ (Fig. 10). On the basis of our measurements and the knowledge of our beam line we believe $\cos \theta \approx 1$.

Fig. 10 Total Cross Section Difference $\sigma_{tot}(\uparrow) - \sigma_{tot}(\downarrow)$ Data as Function of the Solenoid Current I . The solid curve $-16.5 \sin[\pi/2 (I/I_0)]$ mb is the expected value of the cross section difference at $P_{LAB} = 1.47$ GeV/c.

- The magnitude of $\vec{P}_B$ was continuously measured with two beam polarimeters (one located at the exit of the 50 MeV linac) during the initial stages of our measurements. Later when we suspected some energy dependent depolarization in the accelerator we installed in our beam line an additional polarimeter using a liquid hydrogen target. In addition to the beam depolarization problem, the uncertainties in P_B were further compounded due to a lack of accurate data for the analyzing power of our polarimeters.

$$\sigma(P_B)/P_B \approx 6\%$$

Determination of the Incident and Transmitted Flux

Both incident (N_0) and transmitted particles (N_1) were identified and counted with standard commercially available fast electronics. In order to make the identification unambiguous the instantaneous rate was generally kept below 1 MHz. Events were rejected if more than one incident particle was detected. Thus an event was vetoed if:

- a) The pulse height from a beam counter indicated the presence of more than one particle.
- b) Two segments of the same beam counter triggered. (We used two segmented beam counters up-down, left-right.)
- c) Two events were detected within an electronic window of width (20 - 50 ns), then both events were vetoed.

The transmission counters were only strobed if an incident particle was unambiguously identified. Efficiencies of the transmission counters were continuously monitored via the use of a highly redundant coincidence logic.

With our system no particle identification was made. The error due to this deficiency was estimated to be quite small, worst case 0.5 mb.

Some legitimate events were rejected because sharply back-scattered particles would mistakenly be identified as an off centered beam particle and vetoed by one of the hole counters. The error due to these back-scattered events compared to other types of errors appear to be negligible.

The overall performance of the detector system was also checked (in a somewhat crude way) at several energies by measuring the attenuation difference between a target containing CH_2 and a target containing an identical amount of carbon nuclei (per unit area) only. This way we could check our measured values of $\sigma^{\text{Tot}}(p, \text{CH}_2) - \sigma^{\text{Tot}}(p, \text{C})$ against the already measured values $\sigma^{\text{Tot}}(p, p)$. These measurements still need to be analyzed more carefully but initial indications are that our detector system performed as expected.

Spurious Asymmetries

The axial symmetry of our experimental setup provided the detector system a certain amount of stability against small departures in the nominal beam conditions. To some extent the longitudinal beam and target polarization provided similar benefits.

An essential feature of the ZGS running conditions was that the polarization was reversed every spill (2-5 seconds), thus slowly varying effects, such as variation of detector efficiencies and target polarization, were greatly reduced. To further reduce systematic effects the target polarization was also reversed every 2-4 hours.

The magnitude of the spurious asymmetries was monitored periodically by taking zero polarization target runs. During actual data taking certain online calculations provided additional means of monitoring spurious asymmetries.

Beam Momentum

From the known characteristics of the accelerator and the beam transport, I believe the beam momentum is known to better than 2%. Of course there is an additional energy spread of 20-30 MeV due to the energy loss of the beam through the target.

Estimated Errors

Statistical ± 0.1 to ± 0.5 mb

Systematic

Beam Polarization	$\pm 6\%$
Target Polarization	$\pm 3-4\%$
Target Constant	$\pm 2-5\%$
Others	$\pm 1-3\%$
Total Systematic	$\pm 7-9\%$

ACKNOWLEDGEMENTS

These experiments would not have succeeded without the excellent technical support of the Argonne High Energy Physics and Accelerator Research Facilities staff. Several Argonne physicists, E. Berger, M. Derrick, T. Fields, K. Hidaka, C. Sorensen and G. Thomas though not directly participating in the measurements, gave very valuable help through their active interest and support. I thank R. Arndt, N. Hoshizaki and P. Kroll for communicating the results of their calculations prior to publication.

REFERENCES

- 1) W. deBoer et al., Phys. Rev. Lett. 34 (1975) 558.
E. K. Biegert et al., Phys. Lett. 73B (1978) 235.
- 2) I. P. Auer et al., Phys. Lett. 67B (1977) 113.
I. P. Auer et al., Phys. Lett. 70B (1977) 475.
I. P. Auer et al., Phys. Rev. Lett. 41 (1978) 354.
- 3) H. Spinka, Proc. of the III Int'l. Symp. on High Energy Physics With Polarized Beams and Targets, Argonne, 1978 (American Institute of Physics) p. 382.
- 4) D. Underwood et al., Washington Spring SPA Meeting 1979.
- 5) K. Hidaka et al., Phys. Lett. 70B (1977) 479.
A. Yokosawa, Proc. of the Meeting on Exotic Resonances, Hiroshima, Japan (1978) HUPD-7813.
K. Hidaka and A. Yokosawa to be published in Surveys in High Energy Physics, Harwood Academic Publishers, Ltd., London, England (1979).
- 6) N. Hoshizaki, Progress of Theoretical Phys. Vol. 60 (1978) 1796.
N. Hoshizaki, Progress of Theoretical Phys. Vol. 61 (1978) 129.
- 7) R. Omnes, Introduction to Particle Physics, Wiley-Interscience (1971) p. 173.
- 8) D. V. Bugg, Proc. of the III Int'l. Symp. on High Energy Physics With Polarized Beams and Targets, Argonne, 1978 (American Institute of Physics) p. 362.
D. V. Bugg, Rutherford Labs. Report RL-79-013 (1979) 1.
- 9) S. Minami, Phys. Lett. 74B (1978) 120.
C. Hollas, Paper 3E18, submitted to this proceeding.
- 10) M. Jacob and G. C. Wick, Ann. Phys. 7 (1959) 404.
M. L. Goldberger et al., Phys. Rev. 120 (1960) 2250.
- 11) E. Bracci et al., Compilation of Cross Section III p and $\bar{p}$ Induced Reactions CERN/HERA 73-1.
- 12) I. P. Auer et al., Phys. Rev. Lett. 41 (1978) 1436.
- 13) R. A. Arndt (Private Communication and Nucleon-Nucleon Program from Virginia Polytechnic Institute, Blackburg, Virginia.
- 14) W. Grein and P. Kroll, Nucl. Phys. B137, (1978) 173.
- 15) Y. Watanabe, Phys. Rev. D19 (1979) 1022.
W. Grein and P. Kroll, University of Wuppertal Preprint WUB 79-4 (1979).
- 16) E. Colton et al., Nucl. Inst. and Meth. 151 (1978) 85.

* Westfield College, London, England.