# BOSON PRODUCTION IN $p$-$p$ COLLISIONS AT 12.3 BeV/$c$*

H. L. Anderson, S. Fukui,† D. Kessler, K. A. Klare, M. V. Sherbrook, and H. J. Evans
The University of Chicago, Chicago, Illinois

and

R. L. Martin
Argonne National Laboratory, Argonne, Illinois

and

E. P. Hincks
Carleton University and National Research Council, Ottawa, Canada

and

N. K. Sherman
McGill University, Montreal, Canada

and

P. I. P. Kalmus
Queen Mary College, London, England
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Single-arm missing mass (MM) spectrometers have been used by several groups to study inelastic $p$-$p$ scattering.[1-5] Peaks were observed at the positions of known nucleon isobars and interpreted as arising from reactions of the type $p+p\rightarrow p+N^*$. By adding a second spectrometer arm it becomes possible to identify three-body final states. In particular, if both the final-state protons are measured, a plot of the invariant missing mass will show peaks for those channels in which a neutral boson is the unobserved third particle.

In an initial attempt to carry out such a study we used the automatic spark-chamber system recently developed at the University of Chicago[6,7] and measured simultaneously two positive particles produced by 12.3-BeV/$c$ protons in a hydrogen target. The experimental setup consisted of two spectrometer arms, one of which detected the forward-scattered proton at an angle of $5.0\pm0.5$ deg and four-momentum transfers $0.8\leq -t\leq 1.3$ (BeV/$c$)$^2$, and the other of which accepted positively charged particles at an angle around 35° and low momentum (1.2-2.8 BeV/$c$). The particles detected in the first arm were always assumed to be protons, and the particles in the second arm were identified as protons or $\pi^+$ with the help of a gas Čerenkov counter and time-of-flight measurements.

This paper is an account of the results obtained. In particular, it will be shown that the MM spectra of the reactions

$$p+p\rightarrow p+p+\mathrm{MM}, \tag{1}$$

$$p+p\rightarrow p+\pi^+ +\mathrm{MM} \tag{2}$$

have considerable structure and permit a relatively large fraction (more than $\frac{1}{4}$) of the events detected in our configuration to be ascribed to well-defined reactions. The most striking of these reactions is $p+p\rightarrow p+p+\omega^0$, which accounts for about 6% of reactions of type (1).

The spectrometer was set up as shown in Fig. 1 in the external proton beam area of the zero-gradient synchrotron (ZGS) at the Argonne National Laboratory. The trajectories of the particles incident on the liquid-hydrogen target (4 in. diameter, 12 in. long) were not ob-

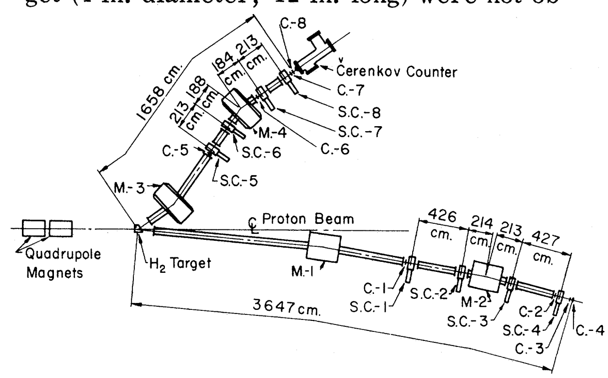


FIG. 1. Experimental layout. C1-C3 and C5-C7 are $\frac{1}{4}$-in.-thick scintillation counters for triggering; C4 and C8 are 2-in.-thick scintillation counters for time-of-flight measurement. SC1-SC8 are spark chambers; M1-M4 are bending magnets.

served; therefore, the beam was carefully adjusted to be as parallel to the axis with as little angular spread at the target position as possible. Each spectrometer arm consisted of a pair of magnets and four spark chambers as shown in Fig. 1. The intervening spaces were filled with helium bags to reduce the multiple scattering. For single-arm events the chambers were triggered by a threefold coincidence of counters 1, 2, 3 or 5, 6, 7. For two-arm events a sixfold coincidence was required. Counters 4 and 8 were used to measure the time difference between the arrival of the two particles at the ends of the arms. In addition, a gas Čerenkov counter of 250-cm effective length (containing 600 lb. of Freon-13B1 gas at 150 psi) was used in the low-momentum arm to differentiate between pions and protons.

Each spark chamber was viewed by a Vidicon camera with a mirror system that put both the horizontal and the vertical view on the Vidicon screen. The spark coordinates were digitized using a 10-Mc/sec clock and the data recorded on magnetic tape. Auxiliary data, such as the event number, pulse number, real time, monitor counts, magnet currents, Čerenkov pulse, and time of flight were also recorded for each event. The time needed for recording one event, including erasing of the Vidicon image, was about 115 msec. With the long beam spills (up to 400 msec) available during this run it was possible to record as many as 3 events per pulse. If no two-arm event was being recorded, a one-arm trigger would be accepted during the last 10 msec of each pulse. The laboratory solid-angle acceptances were 31 $\mu$sr in the high-momentum arm and 225 $\mu$sr in the low-momentum arm. Typically, the number of protons per pulse was $10^{10}$ and yielded 0.8 one-arm events and 0.3 to 1.0 two-arm events. Our data are based on $4.6\times10^{14}$ proton traversals of the 2.02 g/cm$^2$ liquid-hydrogen target.[8] The chamber construction and associated electronics have been described before[6] and a more detailed account of the system will be published shortly.[7]

The magnetic tapes were analyzed on an IBM-7094 computer, in general within 24 h. The analysis consisted in reconstructing a track from the digital readout, fitting a trajectory through each set of four chambers and second bending magnet, and tracing back through the first magnet to the target. The program then computed the kinematical quantities: momenta, angles at emission, location of interaction in the target, time of flight, etc. The computer programs and selection criteria for "good" events will be described elsewhere.[7]

The precision of momentum measurement was about $\pm\frac{1}{4}\%$ at 10 BeV in the high-momentum arm and $\pm0.1\%$ at 2 BeV in the low-momentum arm. Systematic errors of up to $\pm0.1\%$ were possible due to insufficient knowledge of the magnetic fields. Multiple scattering limited the precision of the determination of the emission angle at the target to $\pm0.3$ mrad for the high-momentum particle and $\pm1.5$ mrad for the low-momentum particle. The intersection of the two trajectories within the target could be established within 1.5 cm. The angular spread of the incoming beam was measured and found to be $\pm1$ mrad. The momentum spread of the incoming beam was not determined directly, but is estimated to be better than $\pm1\%$. From these uncertainties the calculated error of the missing mass squared turned out to be $\Delta(\mathrm{MM}^2)\approx0.030$ BeV$^2$ for Reaction (1) and 0.050 BeV$^2$ for Reaction (2). These compare well with the observed widths in the actual measurements (see Fig. 3).

The one-arm MM spectra in our experiment are similar to those obtained by the Brookhaven group[4] for comparable energy and momentum transfer. Figure 2 shows one of our spec-

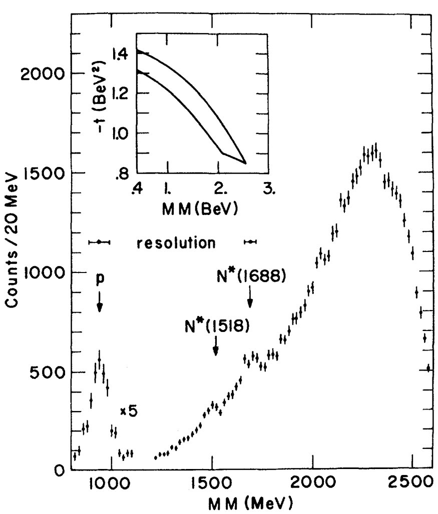


FIG. 2. Missing-mass spectrum for protons detected in the high momentum arm. The total number of events is 55 588. The spectrum shown was obtained at a magnetic field $B_0 = 15.7$ kG in M1 and M2. The corresponding spectrometer acceptance in the momentum-transfer missing-mass plane for the high-momentum arm is shown in the inset.

Table I. Differential cross sections at 12.3 BeV/$c$.

| Process | $-t$ ($\mathrm{BeV}^2$) | $\partial\sigma/\partial t$ ($\mu\mathrm{b/BeV}^2$) |
|---|---|---|
| $p+p\to p+p$ | 1.31 | $7.3\pm1.5$ |
| $p+p\to p+N^*(1518)$ | 1.17 | $1.4\pm0.4$ |
| $p+p\to p+N^*(1688)$ | 1.13 | $3.7\pm0.9$ |

tra where the elastic peak and peaks corresponding to the $N^*(1518)$ and $N^*(1688)$ can be clearly seen. The corresponding cross sections are given in Table I. The principal error in the isobar production cross section comes from the uncertainty in the background subtraction. Note that the other known isobars in the mass range covered by our experiment do not seem to contribute appreciably.

In our arrangement the identifiable two-body processes constitute only 2% of the events. Much more structure is evident in the two-arm events. We divided our events into "pion events" ($p+p\to p+\pi^++\mathrm{MM}$) and "proton events" ($p+p\to p+p+\mathrm{MM}$) according to whether the coincidence was accompanied by a Čerenkov pulse or not. In addition, all events which did not have the proper timing corresponding to this identification were rejected. This eliminated most cases where the Čerenkov pulses due to pions have been missed or where protons accompanied by knock-on electrons produced Čerenkov pulses and were mistakenly identified as pions. In addition, the timing restriction rejected $K^+$ events and reduced the background due to accidentals.

The MM spectra for "pion events" and "proton events" are shown in Fig. 3. The data shown include that from three different settings in the low-momentum arm ($B_0=13.5$, 16.6, and 17.8 kG), but with the same magnet setting in the high-momentum arm ($B_0=15.7$ kG). The figure also shows the contribution of accidentals to the MM spectra. The distribution of accidentals was obtained by combining one-arm events at random and normalizing to the number of events in the region of nonphysical missing masses. In the data shown 25% of the events are accidentals.

The spectrum for "pion events" is relatively simple. The main feature is a prominent neutron peak corresponding to the reaction $p+p\to p+n+\pi^+$ and containing about 50% of all "pion events" above the background of accidentals. Above the peak is a broad distribution of higher missing masses about which little can be said because of the poor statistics, but the shape of the curve suggests some contribution of $N^*(1236)$.

The MM spectrum from "proton events" shows a prominent $\pi^0$ peak corresponding to the reaction $p+p\to p+p+\pi^0$. This is given in greater detail in the inset to show the resolution capabilities of our arrangement. In addition, the spectrum has the following features: The two-pion edge is as steep as the instrumental

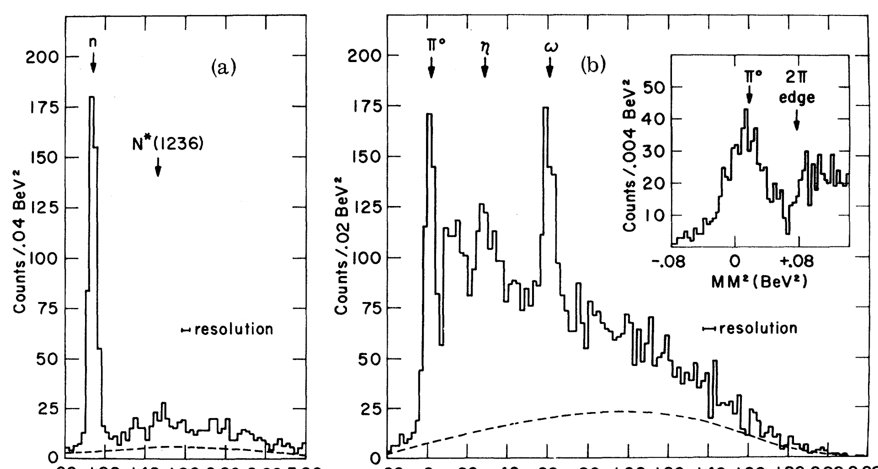


FIG. 3. (a) Total missing-mass square spectrum of events of the type $p+p\to p+\pi^++\mathrm{MM}$. Total number of events is 1234. The dashed line shows the calculated contribution of accidental coincidences ($311\pm44$ events). The horizontal bar indicates the computed resolution. (b) Total missing-mass square spectrum of $p+p\to p+p+\mathrm{MM}$. Total number of events 6331, calculated accidentals $1659\pm245$.

resolution allows. This suggests some enhancement in the di-pion state near threshold. However, because of the uncertainties in the threshold behavior of the two- and three-pion production, it is not clear that the broad peak in the vicinity of 400 MeV is due to a $\sigma$ resonance. The evidence for such a resonance has not been decisive,[9] although good arguments for its existence have been put forward.[10,11] We observe a peak centered at the $\eta^0$ mass. The shape appears to be anomalous, but this could be an effect of statistics. The most striking feature of the spectrum is the narrow peak at 780 MeV. The width, full width at half-maximum = 50 MeV, corresponds to the experimental resolution. The position of the peak and its narrow width identify it with the $\omega^0$ and the reaction as $p+p \to p+p+\omega^0$. There seems to be no appreciable production of the $\rho^0$. The dominance of $\omega^0$ over $\rho^0$ production in $p$-$p$ collisions has been noted by others.[12] No significant features are evident at masses higher than the $\omega^0$ mass. The decreasing acceptance of the spectrometer and increasing fraction of accidentals at our setting made the observation of higher resonances more difficult.

We denote by the subscripts 1 and 2 the particles detected in the high-momentum and low-momentum arms, respectively, and by $m_3$ the mass of the remainder. The vector momentum $\vec{p}_1$ establishes the invariant mass $m_{23}$ and the square of the four-momentum transfer $-t$ of the recoiling system. The $m_{23}$ distribution within the $\omega^0$ peak shows no significant correlation, suggesting that the $\omega^0$ is produced directly rather than as a decay product of a nucleon isobar. From our data the same can be said of the $\pi^0$, $\pi^+$, and $\eta^0$ production.

We calculated the differential cross section for boson production by using the $m_{23}$ distribution in the neighborhood of the peak for a background subtraction. Table II gives the values of

$$\partial^3\sigma/\partial m_{23}{}^2 \partial t \partial\Omega_2{}^b$$

for the values of $m_{23}$, $t$, and $\cos\theta_2{}^b$ accessible in our experiment. The superscript $b$ refers to the center of mass of the whole system. The cross section is generally highest near the threshold value of $m_{23}$ and decreases for increasing values of this quantity.

In all the identified reactions, the bosons seem to be produced directly and not as a decay product of nucleon isobars. This indicates that, where $t$ is not small, direct boson production competes effectively with pion production via nucleon isobars at high energy. Moreover, a given boson is seen most readily near the threshold value of $m_{23}$. We hope to use this feature in looking for more massive bosons.

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Table II. Differential cross section for boson production in $p$-$p$ collisions at 12.3 BeV/$c$. $\partial^3\sigma/\partial m_{23}{}^2\partial t\partial\Omega_2{}^b$ in $\mu$b/sr BeV$^4$ is given for various boson-nucleon final states as a function of $m_{23}$ for values of $-t$ and $\theta_2{}^b$ close to those indicated. To show the relative behavior only the statistical errors are given. Systematic effects contribute an uncertainty of about ±25% to the absolute values.

| $m_{23}$ (BeV) | $-t$ (BeV$^2$) | Boson-nucleon final state $p\pi^0$ | $p\pi^+$ | $p\eta^0$ | $p\omega^0$ |
|---|---|---|---|---|---|
| 1.5 | 1.18 | 7.2 ± 0.7 | | | |
| 1.6 | 1.15 | 2.2 ± 0.3 | | | |
| 1.7 | 1.12 | 1.4 ± 0.2 | 1.3 ± 0.2 | 1.1 ± 0.4 | |
| 1.8 | 1.09 | 1.1 ± 0.2 | 1.7 ± 0.1 | 0.75 ± 0.28 | |
| 1.9 | 1.06 | 1.1 ± 0.2 | 1.3 ± 0.1 | 0.33 ± 0.19 | 1.8 ± 0.4 |
| 2.0 | 1.02 | 0.75 ± 0.14 | 0.69 ± 0.09 | 0.39 ± 0.19 | 0.91 ± 0.29 |
| 2.1 | 0.98 | 0.58 ± 0.13 | 0.51 ± 0.08 | 0.32 ± 0.15 | 0.65 ± 0.23 |
| 2.2 | 0.94 | 0.28 ± 0.08 | 0.25 ± 0.06 | 0.02 ± 0.11 | 1.0 ± 0.2 |
| 2.3 | 0.90 | 0.17 ± 0.07 | 0.05 ± 0.03 | | 0.53 ± 0.16 |
| 2.4 | 0.86 | 0.13 ± 0.07 | | | 0.30 ± 0.12 |
| 2.5 | 0.84 | | | | 0.02 ± 0.09 |
| | $\langle\theta_2{}^b\rangle$ | −132° | −117° | −135° | −135° |

cially A. Glowacki and C. Testin, for their help in setting up the experiment and providing the proton beam for our use. We are indebted to Dr. Roland Winston for the design of an efficient light funnel in our Čerenkov counter.[13]

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†Present address: Nagoya University, Department of Physics, Nagoya, Japan.

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## OBSERVATION OF THE $B$ MESON IN THE REACTION $\bar{p}+p \to \omega^0+\pi^++\pi^-$†

C. Baltay, J. C. Severiens,* N. Yeh, and D. Zanello‡
Columbia University, New York, New York, and Brookhaven National Laboratory, Upton, New York
(Received 16 December 1966)

The $B$ meson, decaying into $\omega^0+\pi^\pm$, has been observed in $\bar{p}p$ annihilations at rest in the reaction $\bar{p}+p\to\omega^0+\pi^++\pi^-$. The mass and width of the $B$ meson as observed in this reaction are $M=1200\pm20$ MeV and $\Gamma=100\pm30$ MeV.

Evidence for an $\omega\pi$ resonance at 1220 MeV, called the $B$ meson, was first reported by Abolins et al.[1] in 1963. Since then evidence for both charged states of the $B$ meson, decaying via $\omega^0\pi^\pm$, has been obtained in a number of experiments.[2] Recently, however, the interpretation of the enhancement in the $\omega\pi$ mass spectra as a resonant state has been questioned.[3,4]

The purpose of this note is to present evidence for the production of the $B^\pm$ meson in the annihilation of antiprotons at rest in hydrogen. The details of the experimental procedure and analysis have been published.[5]

The present study is based on 16 934 events of the type

$$\bar{p}+p\to\pi^++\pi^++\pi^-+\pi^-+\pi^0. \tag{1}$$

Figure 1 shows a fit of a Gaussian plus a second-order polynomial for background to the $\pi^+\pi^-\pi^0$ effective-mass spectrum from Reaction (1) in the region 650 to 950 MeV. The best fit, centered at $M_\omega=783.4\pm0.7$ MeV, with $\sigma=19.9$ MeV, corresponds to 3221 events of the two-step process

$$\begin{array}{l}\bar{p}+p\to\omega^0+\pi^++\pi^- \\ \quad\ \ \llcorner\!\!\to \pi^++\pi^-+\pi^0.\end{array} \tag{2}$$