Dimuon Production by Neutrons

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A very narrow resonance with a mass of 3.1 GeV/c^2 is observed in the reaction $n+\mathrm{Be}\to\mu^+ +\mu^- +X$. The total cross section for this process, as well as its $P_\perp^2$ and x distribution, are given.

This Letter describes measurements of dimuon production in the reaction

$$n+\mathrm{Be}\to\mu^+\mu^- +\text{anything}. \qquad (1)$$

The experiment was performed at the Fermi National Accelerator Laboratory with neutrons of approximately 250 GeV energy. We report the observation of an enhancement in the dimuon mass distribution at 3.1 GeV/c^2. In the production of massive muon pairs in nucleon-nucleon collisions in the experiment of Christenson *et al.*[1] at the Brookhaven National Laboratory alternating-gradient synchrotron, the differential cross section in the dimuon effective mass appeared to exhibit a "shoulder" above 3 GeV/c^2. Recently a strikingly narrow mass peak was reported at 3.1 GeV/c^2 by Aubert *et al.*[2] in the reaction $p+\mathrm{Be}\to e^+e^- +$anything.

In the preceding Letter[3] we have reported the photoproduction of this narrow resonance at 3.1 GeV/c^2. The neutron experiment used the same detectors but differed from the photon experiment in two respects. First, the 34 m of liquid deuterium was emptied and 3.8 cm of Pb was placed upstream in the neutral-beam line, thereby selectively attenuating the photons. The neutral beam was then predominantly neutrons. Secondly, the multiwire proportional chamber, $P1$, was moved 75 cm downstream in order to insert an absorber, 61 cm of Be followed by 183 cm of Fe, into the beam. It attenuates reaction products other than muons and reduces the decay path for pions produced in the target to 150 cm. This improves the experimental sensitivity to Reaction (1).

The first 60 cm of neutron absorber is subdivided into twelve layers of 6-mm-thick plastic scintillator, interspersed with 4.4-cm-thick sheets of steel, which are viewed by a single phototube. This calorimeter was calibrated in a 50-GeV pion beam and found to have a resolution of ±25%. It is used at low intensities to determine the incident-neutron energy spectrum.

Figure 1 shows the energy spectrum unfolded from the pulse-height distribution of the calorimeter. The spectrum of photons surviving the 3.8 cm of Pb is also shown for the corresponding number of proton interactions in the primary target.

Because of the additional absorber, analysis of these experimental data differs from that described in the preceding Letter. Only four proportional chambers downstream of the absorbers are used to measure the direction and momentum

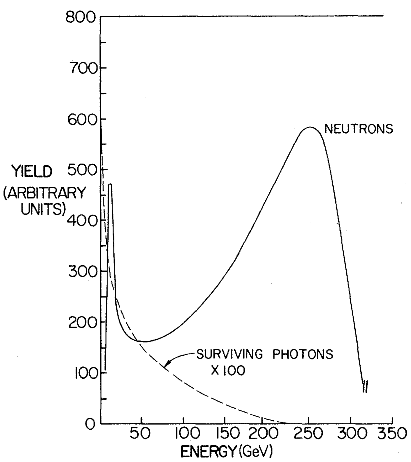

FIG. 1. Neutron energy spectrum (raw distribution of neutron calorimeter pulse height) with the spectrum of surviving photons superimposed.

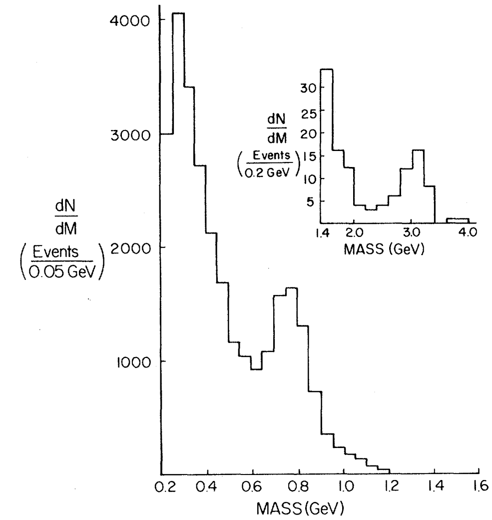

FIG. 2. Invariant-mass distribution of pairs of muons with opposite charge and total energy greater than 70 GeV.

of charged particles emerging from the absorber. Since muons typically lose more than 3 GeV and suffer multiple scattering with about 170-MeV/c rms transverse momentum in the absorber, the dimuon mass resolution is worse. The neutron analysis is checked by restoring the photon beam and observing a comparable number of photoproduced dimuons with the absorber still in place. Thus, by comparing to the photoproduced-dimuon data described in the preceding Letter, we directly measure the effect of the absorber on our resolution in the kinematical variables.

To calculate the dimuon mass $M_{\mu\mu}$, we use the high-energy, small-angle formula

$$M_{\mu\mu}^2 = m^2\left(2 + \frac{E_1}{E_2} + \frac{E_2}{E_1}\right) + E_1E_2\theta_{12}^2, \tag{2}$$

where m is the muon mass, E_1 and E_2 are the muon energies corrected for loss in the absorber, and θ_{12} is the opening angle between the two muons. If the production point is known, the measurement of θ_{12} least affected by multiple scattering is obtained by dividing the apparent separation of the two muons when they are extrapolated back to the plane 50 cm downstream from the middle of the Fe absorber by the distance from the production point to that plane. Mistakenly assuming that the dimuon originating in the absorber had been produced in the target would seriously underestimate the dimuon mass.

The invariant-mass distribution calculated for oppositely charged dimuons of total energy greater than 70 GeV is shown in Fig. 2. We see clear peaks at 0.76 and 3.1 GeV/c^2 with widths consistent with the expected experimental resolution. There are 43 events in the 3.1-GeV/c^2 region. To be included in the mass plot, the reconstructed vectors must pass within 2.5 cm of one another when extrapolated to their point of closest approach and their mean transverse separation from the beam axis weighted by energy must be less than 7.5 cm at that point.

For dimuons of mass above 1 GeV our resolution in the distance of closest approach is sufficient to separate pairs produced in the dump from those produced in the target. The large enhancement seen at the ρ mass in Fig. 2 clearly indicates ρ production in the target, but any ρ produced by interactions in the absorber would be lost in the continuous distribution at lower masses. Similarly, low-mass dimuons produced in the target are indistinguishable from those produced in the dump by photons from π^0 decay.

Figures 3(a) and 3(b) show the $P_\perp^2$ distribution of the dimuons in the two mass regions: $0.7 < M_{\mu\mu} < 0.85$ GeV/c^2 and the high-mass region $2.6 < M_{\mu\mu}$. Note that the 3.1-GeV/c^2 object is produced with a considerably larger average value of $P_\perp^2$ than the ρ meson. We show the total momentum distribution of the dimuon in Fig. 3(c).

We have compared our data with Monte Carlo simulations of events generated according to

$$d^2\sigma/dx\,dP_\perp^2 \propto \exp(-\alpha x)\exp(-\beta P_\perp^2), \tag{3}$$

where x is the ratio of the dimuon momentum to that of the incoming neutron. The simulated

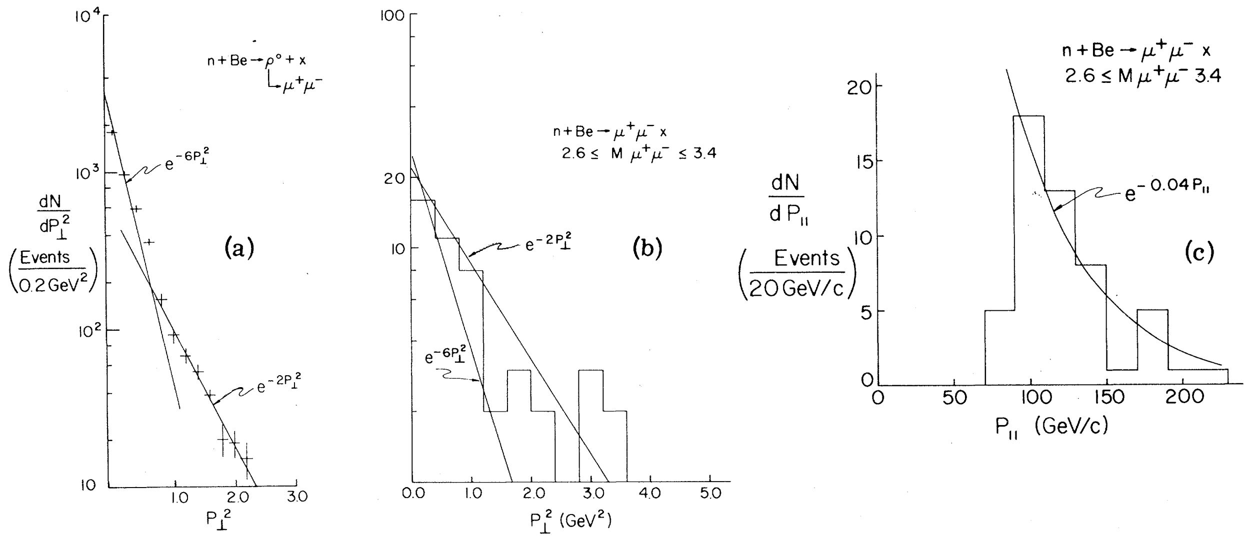

FIG. 3. Distributions for events in Fig. 2: (a) $P_\perp^2$ for $0.7 < M_{\mu\mu} < 0.85$ GeV/c^2; (b) $P_\perp^2$ and (c) $P_\parallel$ for $2.6 < M_{\mu\mu} < 3.4$ GeV/c^2.

events were then multiply scattered through the absorber and accepted by the apparatus. The resulting distributions for $P_\perp^2$ and $P_\parallel$ are shown as the solid curves in Figs. 3(a)–3(c), for different values of β as indicated and for $\alpha = 10$.

The total cross section is calculated as follows: The total number of interactions was recorded. Each interaction was assumed to be 40 mb per nucleon. After correcting for electronic deadtime and geometric acceptance, we obtain

$$\sigma(n + \text{Be} \to 3.1 + X) = 3.6\times 10^{-33}\ \text{cm}^2/\text{nucleon for } |x| > 0.24$$
$$\quad\ \llcorner\!\to \mu^+\mu^-$$
$$= 1.7\times 10^{-33}\ \text{cm}^2/\text{nucleon for } |x| > 0.32\,.$$

In calculating geometric acceptance, we used $\alpha = 10$ and $\beta = 2$. We also calculated the acceptance for $\alpha = 7.5$, $\alpha = 12.5$, and $\beta = 1$, $\beta = 4$. On the basis of these calculations, we believe that we measured the total cross section to within a factor of 2.

Since the geometric acceptance of the experiment by Aubert *et al.* is very different from ours, a direct comparison of the total cross section is difficult. However, it is clear that the cross section measured in our experiment is substantially larger than that observed at Brookhaven National Laboratory.

Our ratio of signal to continuum at $M = 3.1$ GeV/c^2 is $\gtrsim 2$. If our mass resolution were 2 MeV instead of 200 MeV, this ratio would become 200, which is very much larger than the value 6 measured at SPEAR.[4] Therefore the production of 3.1-GeV/c^2 resonance in Be is not an electromagnetic process.

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Observations of Narrow Antiproton-Neutron Resonances near Threshold*†

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The behavior of the $\bar{p}n$ annihilation cross section has been observed above and below threshold by studying annihilations in deuterium at low energies with a ± 2.5-MeV resolution. It varies inversely to the $\bar{p}n$ relative momentum except for a pronounced resonance with $(M, \Gamma) = (1897 \pm 1, 25 \pm 6)$ associated with large proton momenta (200 to ~ 300 MeV/c) and a narrower one (consistent with resolution) at ~ 1932 MeV associated with lower (100–200 MeV/c) proton momenta. Since the production of these $I=1$ states varies with the $\bar{p}n$ relative momentum their spins are not zero.

During the last decade several experiments were performed in search of high-mass, nonstrange boson resonances. In spite of the plethora of the reported effects no well-established[1,2] resonances beyond the g exist. The $\bar{N}N$ formation experiments yielded a number of energy-dependent phenomena[1] but none of them has as yet been confirmed.[2] On the other hand, many resonances and bound $\bar{N}N$ states are expected on the basis of nonrelativistic[3,4] and relativistic[5] $\bar{N}N$ potentials as well as from general considerations.[6]

In particular, the 1929-MeV peak observed in the CERN missing-mass spectrometer[7] has found support[8] from $\bar{p}p \to \bar{p}p$ at 180° although an alternative interpretation has been presented.[9] Carroll *et al.*,[10] extending their high-statistics $\bar{p}p$ and $\bar{p}d$ total cross-section measurements to low energies, observed a narrow peak in both $\bar{p}p$ and $\bar{p}d$ above a smooth background with $(M, \Gamma) = (1932 \pm 2, 9^{+4}_{-3})$ MeV. Because of uncertainties in Glauber corrections no firm conclusion on isospin was reached although $I=1$ has been favored.

In view of the interestingly puzzling observations[11] made with stopping and low-energy antiprotons (e.g., breakdown of S-capture dominance,[12,13] evidence of bound states,[13,14] cross sections rising faster[15] than $1/P$) we have sought an experiment for the exploration of the region around threshold with good resolution. This became possible by exploiting the kinematical consequences of the Fermi motion in deuterium and by studying events of the type

$$\bar{p} + d \to (\bar{p}n \to \text{annihilation}) + p_{\text{vis}}. \qquad (1)$$

The square of the mass of the annihilation products is given by

$$(2M_p + Q)^2 = M_d^2 + 2M_p^2 + 2M_d(\omega_p - \omega_q) - 2(\omega_p\omega_q - \vec{p}\cdot\vec{q}), \qquad (2)$$

where $\vec{p}$, $\vec{q}$ are the $\bar{p}$ and p_{vis} momenta. Q being a function of p and q, $\cos(\vec{p}, \vec{q})$ *can be positive and negative and be reached with different sets of these variables in constrast to annihilations on free-nucleon targets. An interesting aspect of this freedom is the possibility of searching for* $\bar{N}N$ *states as a function of their relative momentum* $|\vec{p} + \vec{q}|$ *and thus the ability to maximize their production which will occur at* $|\vec{q} + \vec{p}|R \simeq J$, where R is the interaction radius and J the spin of the resonance. *We further note that the sensitivity of Q on these variables is not independent of the variables themselves. Particularly it is relevant to emphasize here that for spectator momenta greater than* ~ 200 MeV/c, *Q is most sensitive to the beam spectator angle.*[11b,11c]

To this end, the Brookhaven National Laboratory 30-in. bubble chamber was exposed to a separated antiproton beam at the alternating-gradient synchrotron which stops at the end of the fiducial region.[16] About 10% of the 300 000 pictures have been scanned twice for events with visible protons. Antiprotons and protons have been measured only; a uniform scanning-measuring efficiency of 96% has been reached for events with proton momenta > 100 MeV/c. Criteria based on curvature and residual range have been found separating unambiguously in-flight (> 260 MeV/c) an-