ed for the 5.5% inefficiency of the $T$ counter. This efficiency was determined from the ratio of the number of $J$ events from the target which had the $T$ counter on to all $J$ which came from the target. In the $J$ mass region the separation of target and dump is unambiguous.

We have fitted the intensity-normalized dilepton yields per nucleus for $p > 75$ GeV/$c$ with the power law $A^{\gamma}$. We find values of $\gamma$ of $0.62 \pm 0.03$ for the $\rho+\omega$ mass region, $0.85 \pm 0.05$ for $C_1$, $0.85 \pm 0.04$ for $C_2$, and $0.93 \pm 0.04$ for the $J$ region. The yields for the $\rho+\omega$ and $J$ as functions of $A$ are shown in Fig. 3(a). Most of the increase in $\gamma$ occurs in the mass interval between the $\rho$ and 1.2 GeV/$c^2$ as can be seen from Fig. 3(b). The variation in $\gamma$ for larger masses is consistent with either a constant value of $\gamma$ near 0.9 or a slow increase from 0.8 toward 1.0. In the $\rho+\omega$ region $\gamma$ depends on $p_\perp$ as can be seen from Fig. 3(c). This behavior has been observed for other hadrons by Cronin *et al.*[6] An examination of the $J$ mass region showed that $\gamma$ did not depend on $p_\perp$. We note that the dependence of $\gamma$ on $p_\perp$ is very similar to its dependence on mass.

The dependence of $\gamma$ on $p_\parallel$ in the $\rho+\omega$ mass region is also shown in Fig. 3(c). $\gamma$ did not depend on $p_\parallel$ in the $J$ region to within statistics. Finally, we note that the $A$ dependence in the continuum region is three standard deviations away from an $A^1$ behavior, which might be expected if the only source of dileptons in this mass range were the Drell-Yan process.[7]

It is a pleasure to acknowledge the assistance of the staff of the Fermi National Accelerator Laboratory, especially the Proton Department and the Computing Department.

*Supported by the U. S. Energy Research and Development Administration.

†Supported by the National Science Foundation.

[1]B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975); T. O'Halloran, in *Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Stanford, California, 1975,* edited by W. T. Kirk (Stanford Linear Accelerator Center, Stanford, Calif., 1975).

[2]G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1975); F. W. Busser *et al.*, Phys. Lett. 56B, 482 (1975); K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1976).

[3]Y. M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976). Earlier observations of dileptons at lower energies were made at Brookhaven National Laboratory by J. H. Christenson *et al.*, Phys. Rev. Lett. 25, 1523 (1970), and Phys. Rev. D 8, 2016 (1973).

[4]The $J$ was first observed in hadron-hadon collisions by J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974), and subsequently by the authors of Refs. 1–3, as well as by H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976). This last experiment has also made observations on the dilepton mass spectrum between 3 and 10 GeV/$c^2$. D. C. Hom *et al.*, Phys. Rev. Lett. 36, 1236 (1976).

[5]S. D. Drell and D. M. Yan, Phys. Rev. Lett. 25, 316 (1970).

[6]J. W. Cronin *et al.*, Phys. Rev. D 11, 3105.

[7]For example, G. R. Farrar, Phys. Lett. 56B, 185 (1975).

# Dimuon Production in the $\rho$, $J$, and Continuum Regions

M. Binkley, I. Gaines, J. Peoples, B. Knapp, W. Lee, P. Leung, S. D. Smith, A. Wijangco, J. Knauer, J. Bronstein, R. Coleman, G. Gladding, M. Goodman, M. Gormley, R. Messner, T. O'Halloran, J. Sarracino, and A. Wattenberg

*Fermi National Accelerator Laboratory, Batavia, Illinois 60510,* and Columbia University, Irvington-on-Hudson, New York 10533,† and University of Hawaii, Honolulu, Hawaii 96822,† and University of Illinois, Urbana, Illinois 61801**

(Received 17 May 1976)

We have measured the $p_\perp$ and $p_\parallel$ dependence of $J$ production by high-energy neutrons in comparison with the production of the conventional vector mesons. We also report values for total inclusive cross sections for resonance and continuum dimuons, and give an upper limit for $\psi'$ production.

Although it has been a year and a half since the discovery of $J$[1,2] and of the $\psi'(3684)$ particles,[3] very little is known about the mechanism for their production by hadrons. The increase of the inclusive cross section for $J$ production by a factor of 100 between ~30 and ~300 GeV does not have an experimentally verified explanation.[4] We have made a measurement of the dynamical dependence of this inclusive cross section. At the same time we have measured the same properties of the in-

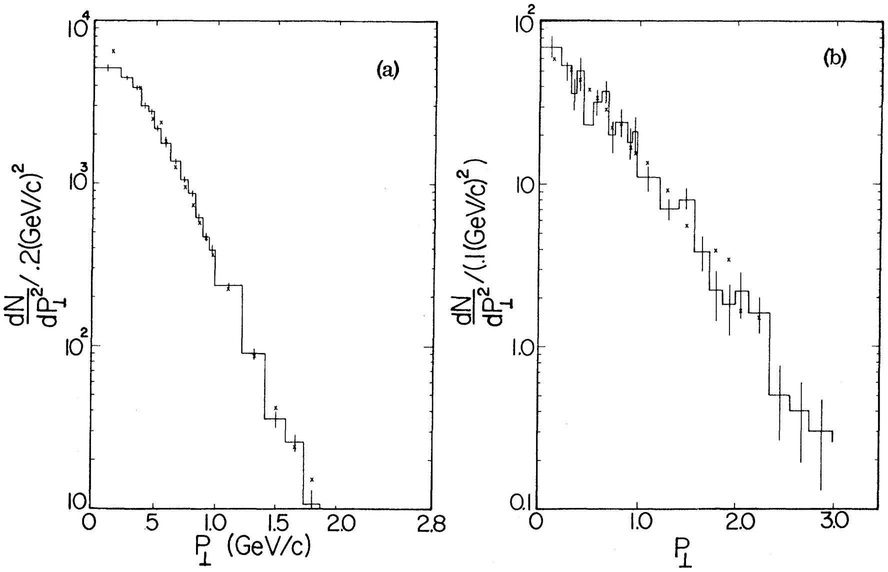


FIG. 1. $dN/dp_\perp^2$ vs $p_\perp$ for (a) $\rho+\omega$, (b) $J$. Solid curve, raw data; crosses, Monte Carlo calculation: $\exp(-4.2p_\perp)$ for $\rho+\omega$ and $\exp(-1.6p_\perp)$ for $J$.

clusive cross sections for $\rho$, $\omega$, and $\varphi$ production in order to compare these data with the $J$ data. In addition, we have measured the production dynamics of dileptons of masses between the $\varphi$ and the $J$ in order to determine whether the dominant source of these dileptons is a Drell-Yan continuum of virtual photons.

Our results were obtained from an analysis of dimuon production by 300-GeV neutrons[5] on nuclear targets in a high-energy neutron beam at Fermilab. The $A$ dependence of the dimuon cross section was reported in Ref. 5, where we also described the apparatus and the methods of analysis.

The data were divided into five mass regions: $\rho+\omega$, 0.6 to 0.9 GeV/$c^2$; $\varphi$, 0.9 to 1.15 GeV/$c^2$; $C_1$ (continuum), 1.15 to 1.4 GeV/$c^2$; $C_2$ (continuum), 1.4 to 2.6 GeV/$c^2$; and $J$, 2.6 to 3.6 GeV/$c^2$. The calculation of yields and background subtractions has been described in Ref. 5. Background corrections were only necessary in the first three mass regions. The yields from all targets were summed to give the $p_\perp$ and $p_\parallel$ distributions shown in Figs. 1 and 2 and fitted as described below.[6]

We parametrized the invariant cross section

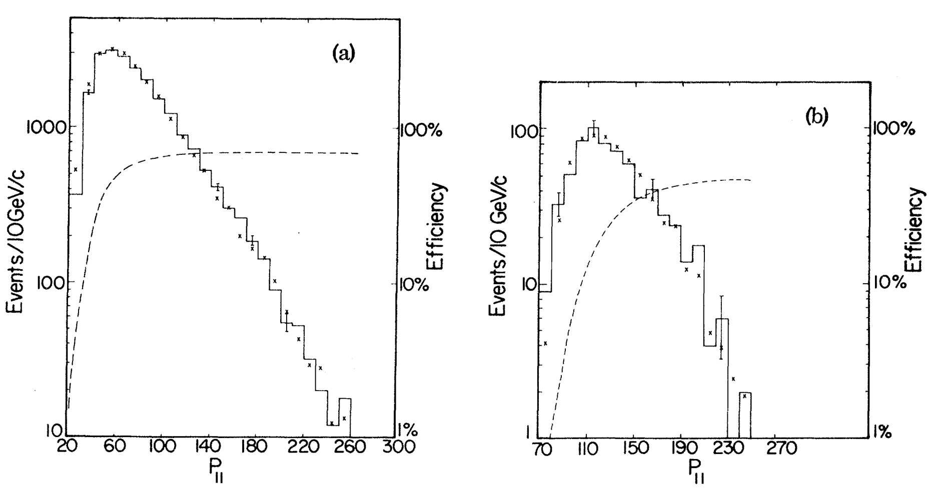


FIG. 2. $dN/dp$ vs $p_\parallel$ for (a) $\rho+\omega$, (b) $J$. Solid curve, raw data; crosses, Monte Carlo calculation (fits described in text). Dashed curve denotes efficiency.

for inclusive dimuon production in each mass interval by[7]

$$Ed^3\sigma/dp^3 = C(M)(1-X_F)^{\alpha(M)}\exp[-b(M)p_\perp],\quad X_0 < X_F < 1,$$
$$Ed^3\sigma/dp^3 = C'(M)\exp[-b(M)p_\perp],\quad 0 < X_F < X_0,\quad C' = C(1-X_0)^\alpha. \tag{1}$$

The actual yield of dimuons as a function of $p_\perp$ and $X_F$ was compared to the yield of events generated by a Monte Carlo calculation in order to determine values for the parameters $\alpha$, $b$, and $X_0$ in each mass interval. Equation (1) was used to determine the probability of producing a dimuon as a function of $p_\perp$ and $X_F$. The laboratory momentum for the Monte Carlo-generated events was computed using an incident-neutron momentum distribution given by[8]

$$dN/dE = E/400,\quad 0 < E < 320$$
$$dN/dE = 4(1-E/400),\quad 320 < E < 400. \tag{2}$$

The calculation included the effects of multiple scattering, ionization loss, and straggling in the absorber, the limiting of the acceptance by the finite apertures of the magnet and multiwire proportional chambers (MWPC's), and the effect of the finite resolution of the MWPC's. Finally, we assumed that the angular distribution of the positive muon was isotropic in the dimuon center-of-mass system.

The parameters $\alpha$, $b$, and $X_0$ were varied until the difference in shape between the Monte Carlo sample of events and the data was a minimum. The $p_\perp$ and $p_\parallel$ distributions for the $\rho+\omega$ and the $J$ mass regions together with the best-fitting Monte Carlo distributions are shown in Figs. 1 and 2. The efficiency for detecting a dimuon with $X_F < 0.2$ was greater than 10% only in the $\rho+\omega$ mass region, as can be seen from the dashed curves in Fig. 2. The value of $X_0 = 0.3$ determined from the $\rho+\omega$ region was used in the fits for all masses.

TABLE I. Parameters describing inclusive dimuon production. $\alpha$ and $b$ are described in the text. Errors are statistical only.

| Mass range | $\alpha$ | $b$ | $\int_{0.24}^{1.0} B_{\mu\mu}(d\sigma/dX_F)dX_F$ (nb/nucleon) |
|---|---|---|---|
| $\rho+\omega$ | $3.0 \pm 0.3$ | $4.2 \pm 0.2$ | 100 |
| $\varphi$ | $3.4 \pm 0.6$ | $3.5 \pm 0.3$ | 16.1 |
| $C_1$ | $2.7 \pm 0.8$ | $3.5 \pm 0.4$ | 1.4 |
| $C_2$ | $3.3 \pm 0.5$ | $2.4 \pm 0.2$ | 1.1 |
| $J$ | $5.2 \pm 0.5$ | $1.6 \pm 0.2$ | 3.5 |

The results of these calculations are given in Table I. The use of more refined models for the cross section and the neutron spectrum did not significantly improve the quality of the fits of the Monte Carlo distribution to the data. However, the value of $\alpha$ was sensitive to the value of the energy at which the neutron spectrum peaks. Changing this peak energy from 320 GeV by $\pm 10\%$ changes the value of $\alpha$ by $\frac{1}{2}$ unit.

While we assumed an isotropic angular distribution for the decay, there were sufficient data in the $\rho+\omega$ mass region to test this assumption. Figure 3 shows the observed distributions in dimuon energy asymmetry $(|E_+ - E_-|/|E_+ + E_-|)$, compared to Monte Carlo-generated distributions for the three hypotheses of $1+\cos^2\theta$, isotropic, and $\sin^2\theta$. The results clearly favor an isotropic distribution.

These values of $\alpha(m)$ are within the range of values which have been observed for hadrons. For example, Taylor *et al.*[9] have found that $\pi$'s and $K$'s have a value of $\alpha$ between 2 and 4 while $\bar{p}$'s have $\alpha \approx 8$. It is worth noting that our data show that the $\rho$ inclusive cross section is independent of $X_F$ for $X_F < 0.3$.

The parameter $b$ which characterizes the $p_\perp$ distribution decreases monotonically as the mass of the dimuon increases. We point out that the value of $b$ at the $J$ mass is not due to an unreliable extrapolation since we have observed $J$'s produced with $p_\perp > 3$ GeV/$c$. Furthermore, a parametrization which is proportional to $\exp(-b^* p_\perp^2)$ is

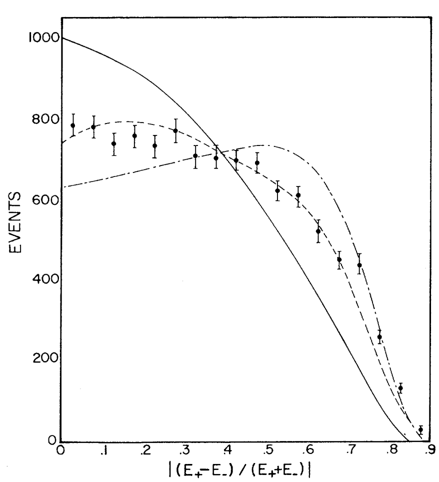


FIG. 3. Decay angular distribution for $\rho+\omega$. Solid line, $\sin^2\theta$ distribution; dashed line, isotropic distribution; dot-dashed line, $1+\cos^2\theta$ distribution.

inconsistent with our data.

The total integrated inclusive cross section for dimuon production for $X_F > 0.24$ in each mass interval was determined from the yield of events normalized to the incident neutron flux, as described in Ref. 5, and the geometric efficiency as determined from the Monte Carlo calculation. The cross sections were extrapolated to $A = 1$ using the $A$ dependences measured in Ref. 5. These results are given in Table I.

In the $\varphi$ mass region, we assumed the same $A$ dependence as in the $\rho + \omega$ region. No subtraction was made for the $\rho + \omega$ tail, so the values of $\alpha$, $b$, and the cross section are for all dimuons in the $\varphi$ mass region. We estimate that between $\frac{1}{2}$ and $\frac{2}{3}$ of the cross section is due to the $\varphi$.

Since there was reasonable acceptance for $X_F < 0.24$ in the $\rho + \omega$ mass interval, a total inclusive cross section could be determined. We find that $B_{\mu\mu}{}^{\rho}\sigma^{\rho} + B_{\mu\mu}{}^{\omega}\sigma^{\omega} = 700$ nb/nucleon. We can then determine $\sigma^{\rho}$ for two extreme assumptions about the amount of $\omega$ production[10]: $\sigma^{\rho} = 16$ mb if $\sigma^{\omega} = 0$, and $\sigma^{\rho} = 6$ mb if $\sigma^{\rho} = \sigma^{\omega}$. The best fit to the mass spectrum requires some $\omega$ production. The second result is consistent with the value of 6 mb for inclusive $\rho^0$ production in 205-GeV $pp$ collisions.[11] That experiment detected the $\rho$ through its $2\pi$ decay mode.

The integrated inclusive cross section for $J$ for $X_F > 0.24$ is in agreement with previous experiments.[12] Assuming that $d\sigma/dy$ is constant for $0 < X_F < 0.3$ ($y$ is the c.m. rapidity), we obtain $B_{\mu\mu}{}^{J} \times d\sigma/dy|_{y=0} = 8.9$ nb/nucleon, which agrees well with the recent measurement of Snyder *et al.*[13] Such a flattening at low $X_F$ has been observed in other measurements of $J$ production[14] as well as in the measurements of the $\rho$ presented here. If one uses this extrapolation for the unobserved region of $X_F$ the total inclusive cross section is $B_{\mu\mu}{}^{J}\sigma_{\text{tot}}{}^{J} = 22$ nb/nucleon.

We have studied the events with mass above 3.5 GeV/$c^2$ for evidence of $\psi'(3684)$ production. The twelve events from the data in the mass range 3.5–3.9 GeV/$c^2$ are equal to a predicted twleve events in this range due to the tail of the $J$. Since we have no evidence for $\psi'$ production, we place a 90%-confidence-level upper limit for $\psi'$ production in our kinematic range of $X_F > 0.25$ of

$$R = B_{\mu\mu}{}^{\psi'}\sigma^{\psi'}/B_{\mu\mu}{}^{J}\sigma^{J} < 0.015.$$

Snyder *et al.*[13] have recently measured this ratio to be $0.014 \pm 0.004$ at $X_F = 0$.

The value of $d\sigma/dM^2$ per nucleon is shown plotted in Fig. 4. We have calculated the expected yield of Drell-Yan pairs for $p_{\parallel} > 75$ GeV under two assumptions[15] for $\nu W_2$ and these are shown as solid and dashed curves in Fig. 4. We have assumed three colors in each case. The observed yield is greater than the predictions.

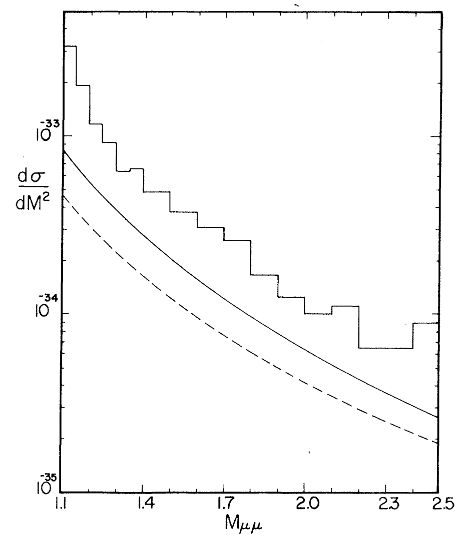


FIG. 4. $d\sigma/dM^2$ vs $M$ in continuum region, for $p_{\parallel} > 75$ GeV. Solid and dashed lines are Drell-Yan calculations with color included (Ref. 13).

In conclusion, we find that the dynamical dependence of inclusive dimuon production does vary with dimuon mass, but that further studies are needed to determine whether the differences between $\rho$ and $J$ production can be attributed solely to the heavier mass of the $J$.

*Supported by the U. S. Energy Research and Development Administration.

†Supported by the National Science Foundation.

[1] J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974).

[2] J. E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974).

[3] G. S. Abrams *et al.*, Phys. Rev. Lett. 33, 1453 (1974).

[4] B. Knapp *et al.*, Phys. Rev. Lett. 34, 1044 (1975); F. W. Busser *et al.*, Phys. Lett. 56B, 482 (1975); G. J. Blanar *et al.*, Phys. Rev. Lett. 35, 346 (1975); K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1975).

[5] M. Binkley *et al.*, preceeding Letter [Phys. Rev. Lett 37, 571 (1976)].

[6] Combing targets by doing a separate extrapolation to $A = 1$ in each bin of $p_{\parallel}$ and $p_{\perp}$ results in only minor changes to $\alpha$ and $b$, since the variations in $A$ dependence come only at high $p_{\perp}$ and high $p_{\parallel}$, where there are small numbers of events. For example, $\alpha$ for the $\rho + \omega$ region changes from $3.0 \pm 0.3$ to $2.4 \pm 0.3$.

[7] $X_F$ is the ratio of $p$ to $p_{max}$ in the neutron-nucleon c.m. system. If we had chosen the alternate parametrization $d\sigma/dx = C(1-x)^{\alpha^*}$, then $\alpha^* \approx \alpha + 1.5$.

[8] T. Ferbel, in "Proceedings of the International School of Subnuclear Physics Ettore Majorana, Erice, 1975," edited by A. Zichichi (Academic, New York, to be published); M. Longo *et al.*, University of Michigan Report No. UM-HE-74-18 (unpublished).

[9] F. E. Taylor *et al.*, Phys. Rev. D (to be published).

[10] We have used branching ratios for the $\rho$ and $\omega$ dilepton decays of $B_{\mu\mu}{}^{\rho} = 4.3\times 10^{-5}$ and $B_{\mu\mu}{}^{\omega} = 7.6\times 10^{-5}$, as determined from storage ring measurements: T. G. Trippe *et al.*, Rev. Mod. Phys. 48, S1 (1976).

[11] R. Singer *et al.*, Phys. Lett. 60B, 385 (1976).

[12] We note several important systematic effects on the absolute cross section. If the $J$ angular decay distribution is $1+\cos^2\theta$ rather than isotropic, the cross section is raised by 30%. In addition, uncertainties in the incident neutron spectrum introduce an uncertainty in all absolute cross sections of $\pm 25\%$.

[13] H. D. Snyder *et al.*, Phys. Rev. Lett. 36, 1415 (1976).

[14] Y. M. Antipov *et al.*, Phys. Lett. 60B, 309 (1976); K. J. Anderson *et al.*, Phys. Rev. Lett. 36, 237 (1975).

[15] The calculation was made using alternate sets of parton distribution functions: R. Blankenbecler *et al.*, Stanford Linear Accelerator Center Report No. SLAC-PUB-1531, 1975 (unpublished); J. Okada *et al.*, University of Hawaii Report No. UH-511-209-76, 1976 (to be published). In our kinematic range, the most important difference in these models is in the value of $\nu W_2(0)$.

# Limit on Production of Charmed Particles in Association with the $J$

M. Binkley, I. Gaines, and J. Peoples
*Fermi National Accelerator Laboratory, Batavia, Illinois 60510**

and

B. Knapp,† W. Lee, P. Leung, S. D. Smith, and A. Wijangco
*Columbia University, Irvington-on-Hudson, New York 10533‡*

and

J. Knauer and D. Yount
*University of Hawaii, Honolulu, Hawaii 96822‡*

and

J. Bronstein, R. Coleman, G. Gladding, M. Goodman, M. Gormley, R. Messner, T. O'Halloran, J. Sarracino, and A. Wattenberg
*University of Illinois, Urbana, Illinois 61801**
(Received 21 June 1976)

We have searched for charmed particles produced hadronically in coincidence with the $J$ particle by looking for muons from the leptonic or semileptonic decays of the charmed particles. In a sample of 2500 $J$'s, we see no muons above the level expected from $\pi$ and $K$ decays.

Shortly after the original discovery of the $J$ particle,[1] it was shown that the cross section for hadronic production of the $J$ increased by more than two orders of magnitude between alternating-gradient synchrotron (AGS) energies (~30 GeV) and Fermilab energies (~300 GeV).[2] One possible explanation of this increase is that the major mechanism for $J$ production by hadrons is the Okubo-Zweig-Iizuka (OZI)-rule-allowed[3] reaction:

$$N + N \to JC\overline{C} + \cdots, \tag{1}$$

where $C$ and $\overline{C}$ are hadrons containing charmed quarks. Since the threshold for this process is above the energy of the AGS, only OZI-forbidden production is possible there, and so the cross section is suppressed. Possible support for this mechanism comes from recent observations of an excess of $K$'s in hadronic production of the $\varphi$ meson.[4]

We have tested this hypothesis by searching for the leptonic or semileptonic decays of charmed particles produced in association with a $J$ particle as in Reaction (2). The $J$ was produced in neutron-nuclear collisions at Fermilab (average neutron energy about 300 GeV), and detected