Measurement of $\Upsilon$ Production for $p+p$ and $p+d$ Interactions at 800 GeV/c

L.Y. Zhu, P.E. Reimer, B.A. Mueller, T.C. Awes, M.L. Brooks, C.N. Brown, J.D. Bush, T.A. Carey, T.H. Chang, W.E. Cooper, C.A. Gagliardi, G.T. Garvey, D.F. Geesaman, E.A. Hawker, X.C. He, D.E. Howell, L.D. I senhower, D.M. Kaplan, S.B. Kaufman, S.A. Klinksiek, D.D. Koetke, D.M. Lee, W.M. Lee, M.J. Leitch, N. Makins, P.L. McGaughey, J.M. Moss, P.M. Nord, V. Papavassiliou, B.K. Park, G. Petitt, J.C. Peng, M.E. Sadler, W.E. Sondheim, P.W. Stankus, T.N. Thompson, R.S. Towell, R.E. Tribble, M.A. Vasiliev, J.C. Webb, J.L. Willis, P. Winter, D.K. Wise, Y. Yin, and G.R. Young

(FNAL E866/NuSea Collaboration)

We report a high statistics measurement of $\Upsilon$ production with an 800 GeV/c proton beam on hydrogen and deuterium targets. The dominance of the gluon-gluon fusion process for $\Upsilon$ production at this energy implies that the cross section ratio, $\sigma(p + d \rightarrow \Upsilon)/2\sigma(p + p \rightarrow \Upsilon)$, is sensitive to the gluon content in the neutron relative to that in the proton. Over the kinematic region $0 < x_F < 0.6$, this ratio is found to be consistent with unity, in striking contrast to the behavior of the Drell-Yan cross section ratio $\sigma(p + d)/2\sigma(p + p)$. This result shows that the gluon distributions in the proton and neutron are very similar. The $\Upsilon$ production cross sections are also compared with the $p + d$ and $p + Cu$ cross sections from earlier measurements.

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In the CERN NA51 and Fermilab E866/NuSea experiments on proton-induced dimuon production, a striking difference was observed for the Drell-Yan cross sections between $p+p$ and $p+d$. As the underlying mechanism for the Drell-Yan process involves quark-antiquark annihilation, this difference has been attributed to the asymmetry between the up and down sea quark distributions in the proton. From the $\sigma(p + d)/2\sigma(p + p)$ ratio the Bjorken-$x$ dependence of the sea-quark $\bar{d}/u$ flavor asymmetry has been extracted.

The Fermilab E866 dimuon experiment also recorded a large number of $\Upsilon \rightarrow \mu^+\mu^-$ events. In this paper, we present results on the $\Upsilon$ differential cross sections for $p+p$ and $p+d$ over the kinematic range $0 < p_T < 3.5$ GeV/c and $0 < x_F < 0.6$. Unlike the electromagnetic Drell-Yan process, quarkonium production is a strong interaction dominated by the subprocess of gluon-gluon fusion at this beam energy. Therefore, the quarkonium production cross sections are primarily sensitive to the gluon distributions in the colliding hadrons. The $\Upsilon$ production ratio, $\sigma(p + d \rightarrow \Upsilon)/2\sigma(p + p \rightarrow \Upsilon)$, is expected to probe the gluon content in the neutron relative to that in the proton. As pointed out by Piller and Thomas, charge symmetry violation at the parton level could lead to a different gluon distribution in the proton versus that in the neutron. A precise measurement of the $\sigma(p + d)/2\sigma(p + p)$ ratio would provide a constraint on the effect of charge symmetry violation on the gluon distributions.

High statistics $\Upsilon$ production cross sections at 800 GeV/c have been reported for $p+d$ and $p+Cu$. The per-nucleon cross sections for $p+d$ were roughly a factor of two greater than those of $p+Cu$. Such a difference could not be explained by the nuclear effect of $\Upsilon$ production, which was found to be small. The $p+p$ and $p+d$ data would shed new light on this apparent discrepancy.

The experiment was performed at Fermilab using the upgraded Meson-East magnetic pair spectrometer.
Upon one of three identical 50.8-cm long cylindrical stainless steel target flasks containing either liquid hydrogen, liquid deuterium, or vacuum. A copper beam dump located inside the second dipole magnet absorbed the protons that passed through the target. Downstream of the beam dump was a 13.4 interaction-length absorber wall of copper, carbon and polyethylene that completely filled the aperture of the magnet. This absorber wall removed hadrons produced in the target and the beam dump.

The targets alternated between hydrogen and deuterium every five beam spills with a single spill collected on the empty flask at each target change. Beam intensity was monitored by secondary-emission detectors, an ion chamber, and quarter-wave RF cavities. Two scintillator telescopes viewing the targets at 90° monitored the luminosity, beam duty factor and data acquisition live-time. The detector system consisted of four tracking stations and a momentum analyzing magnet. The trigger required a pair of triple hodoscope coincidences having a pattern consistent with a muon pair from the target.

Tracks reconstructed in the drift chambers were extrapolated to the target using the momentum determined by the analyzing magnet. The target position was used to refine the parameters of each muon track. The resulting rms mass resolution for the \( \Upsilon \) resonances is \( \approx 250 \) MeV. Monte Carlo studies show that this resolution is dominated by the finite target length and the multiple scattering of muons in the absorber. Figure 1 shows the dimuon mass spectra for the high-mass data collected with the deuterium target. The high-mass data set contains approximately 20,000 \( \Upsilon \) events.

To extract the yields of the \( \Upsilon \) resonances, the contributions of the Drell-Yan continuum under the \( \Upsilon \) resonances need to be determined and subtracted. Monte Carlo simulations for Drell-Yan events using next-to-leading order calculations and the MRS98 reference parton distributions, which reproduce the \( d\bar{u} \) asymmetry observed in the E866 Drell-Yan data \( \cite{13} \) were carried out. The line shapes of the three \( \Upsilon \) resonances were also calculated using Monte Carlo. For each \( x_F \) and \( p_T \) bin, the normalization factors for the Drell-Yan and the \( \Upsilon \) resonances were adjusted to fit the data.
dimuon events from the stainless steel target flask were subtracted using data obtained with the empty-target measurements. The Drell-Yan normalization factors were found to be consistent with unity, showing good agreements between the data and the Monte Carlo simulation. The dimuon mass spectra are well described by the sum of the various contributions considered in the analysis, as illustrated in Fig. 1 for the $p + d$ data. The mass spectra for various $x_F$ and $p_T$ bins are also well described using this fitting procedure.

The values of $Bd\sigma/dx_F$ per target nucleon for the three $\Upsilon$ resonances in $p + p$ and $p + d$ collisions are shown in Fig. 2 and listed in Table I ($B$ is the branching ratio for $\Upsilon \rightarrow \mu^+\mu^-$ decay). The $d\sigma/dx_F$ differential cross sections are obtained by integrating over $p_T$ using a $p_T$ distribution which best fits the data. A $\pm 6.5\%$ overall normalization uncertainty, common to both the $p + p$ and $p + d$ cross sections, is associated with the determination of the beam intensity [8]. Other systematic errors due to the uncertainty of the magnetic fields of the spectrometer and the hadroscop efficiency are estimated to be $\pm 3\%$. Existing E605 data [4] for $p + Cu$ collision covering the kinematic range $-0.15 < x_F < 0.25$ are also shown for comparison. The good agreement between the E866 $p + d$ and the E605 $p + Cu$ data is consistent with the $A$-dependence measurement performed by E772 [10], which showed that the cross section is proportional to $A^n$ with $n \approx 0.962$. Figure 2 also shows that the relative yields for producing the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ resonances are very similar for $p + d$ and $p + Cu$, consistent with no significant nuclear dependences for these relative yields. From this experiment, the ratios $B\sigma(\Upsilon(2S))/B\sigma(\Upsilon(1S))$ and $B\sigma(\Upsilon(3S))/B\sigma(\Upsilon(1S))$ over $0 \leq x_F \leq 0.6$ are determined as $0.321 \pm 0.012$ and $0.127 \pm 0.009$ for $p + d$.

The $p_T$ dependences of the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ cross sections are listed in Table I and shown in Fig. 3 for $p + d$ and $p + p$. The $d\sigma/dp_T^2$ differential cross sections are obtained by integrating over the $-1 < x_F < 1$ range using a parametrization which best describes the data. These $p_T$ distributions are fitted with the parametrization $d\sigma/dp_T^2 = c(1 + p_T^2/p_0^2)^{-6}$ [17] and the results of the fits are shown in Fig. 3. The values of $p_0$, listed in Table I, are somewhat lower than the E605 result [4] where $p_0 = 3.7$ GeV/c was obtained.

Figure 4 compares the $\Upsilon(1S)$ production cross section at 800 GeV/c measured for $p + d$ in E666 and E772 [8], and for $p + Cu$ in E605 [4]. The E772 cross sections are roughly a factor of two greater than those of E606 and E605. Moreover, the shape of the E772 differential cross sections has a steeper fall-off as $x_F$ increases. To shed some light on this apparent discrepancy, calculations for $d\sigma/dx_F$ using the color-evaporation model (CEM) [20] have been performed. The CEM was known to be capable of describing the $x_F$ and energy dependences of quarkonium production successfully [12, 21]. The probability for forming a given quarkonium state is treated as a parameter in this model. As shown in Fig. 4, the $x_F$ dependences of both the E866 and the E605 data are well described by calculations using two different param
While the origin of the discrepancy between the E866 and E772 results is uncertain, the good agreement between the data and the CEM calculation tends to favor the E866 results.

The \( \sigma(p + d)/2\sigma(p + p) \) ratios for \( \Upsilon(1S + 2S + 3S) \) production are shown in Fig. 5 as a function of \( x_2 \). Most of the systematic errors cancel for these ratios, with a remaining \( \approx 1\% \) error from the rate dependence and target compositions \([3]\). Figure 5 shows that these ratios are consistent with unity, in striking contrast to the corresponding ratios for the E866 Drell-Yan cross sections \([4]\) and also shown in Fig. 5 shows that the gluon distributions in the proton \( (g_p) \) and neutron \( (g_n) \) are very similar over the \( x_2 \) range \( 0.09 < x_2 < 0.25 \). The overall \( \sigma(p + d \rightarrow \Upsilon)/2\sigma(p + p \rightarrow \Upsilon) \) ratio, integrated over the measured kinematic range, is \( 0.984 \pm 0.026 \) (stat.) \( \pm 0.01 \) (syst.). These results are consistent with no charge symmetry breaking effect in the gluon distributions.

In summary, we report the measurement of \( \Upsilon \) production for \( p + p \) and \( p + d \) interactions at 800 GeV/c. This measurement allows a first determination of the \( \sigma(p + d \rightarrow \Upsilon)/2\sigma(p + p \rightarrow \Upsilon) \) ratio, which complements the previous measurement of the corresponding Drell-Yan ratio. The \( \Upsilon \) data indicate that the gluon distributions in the proton and neutron are very similar. A comparison of the \( p + d \) data with the previous E605 \( p + Cu \) data shows no significant nuclear effects for \( \Upsilon \) production in the kinematic region near \( x_2 \sim 0 \), consistent with the previous E772 nuclear-dependence measurement.

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