Nuclear Dependence of the Production of Υ Resonances at 800 GeV

D. M. Alde, H. W. Baer, T. A. Carey, G. T. Garvey, A. Klein, C. Lee, M. J. Leitch, J. W. Lillberg, P. L. McGaughey, C. S. Mishra, J. M. Moss, and J. C. Peng
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

C. N. Brown, W. E. Cooper, and Y. B. Hsiung
Fermilab, Batavia, Illinois 60510

M. R. Adams
University of Illinois at Chicago, Chicago, Illinois 60680

R. Guo and D. M. Kaplan
Northern Illinois University, DeKalb, Illinois 60115

R. L. McCarthy
State University of New York at Stony Brook, Stony Brook, New York 11794-3800

G. Danner and M. J. Wang
Case Western Reserve University, Cleveland, Ohio 44106
and Los Alamos National Laboratory, Los Alamos, New Mexico 87545

M. L. Barlett and G. W. Hoffmann
University of Texas, Austin, Texas 78712
(Received 7 February 1991)

The yields of the $1S$ and the sum of the $2S$ and $3S$ Υ resonances have been measured for 800-GeV protons incident on targets of ^{2}H, C, Ca, Fe, and W. A significant nuclear dependence is seen in the yield per nucleon which, within errors, is the same for the $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ states. A large decrease in the relative yield from heavy nuclei is found for the range $x_F<0$. Significant nuclear dependence is also observed in the p_t distribution. Differential cross sections for the $\Upsilon(1S)$ for ^{2}H are presented over the ranges $0.24 \leq p_t \leq 3.4$ GeV/c and $-0.15 \leq x_F \leq 0.5$.

PACS numbers: 13.85.Ni, 12.38.Qk, 25.40.Ve

The nuclear dependence of quarkonium production in hadronic reactions has received much attention recently, particularly in connection with J/ψ production in high-energy heavy-ion collisions.[1-6] The nuclear dependence of the Υ resonances offers a different view of many of the same physics issues. A potential advantage of the Υ region is that the higher Q^2 of the production vertex allows a more reliable application of QCD.

We report here, from Fermilab E772, new results for the A dependence of the Υ family of resonances. This follows a study of the J/ψ and ψ' resonances from the same experiment.[7] Previous studies[8,9] of the Υ lacked the statistical precision to observe significant nuclear effects. The experiment, carried out with an 800-GeV primary proton beam, had sufficient mass resolution to resolve the $\Upsilon(1S)$ and partially resolve the $2S$ and $3S$ states (Fig. 1). Solid nuclear targets of C, Ca, Fe, and W and a liquid-deuterium target were interchanged frequently during the experiment. The experimental apparatus and general data analysis procedures have been described in detail previously.[7,10] The present data set consists of approximately 17×10^3 $1S$, 5×10^3 $2S$, and 2.6×10^3 $3S$ decays, corresponding to $\sim 5\times10^{16}$ protons on target. The data were collected by employing two spectrometer configurations for which the mean dimuon masses [dominated by the continuum Drell-Yan[11] (DY) process] were, respectively, 7.0 and 9.5 GeV. The main additional difference between the two configurations is the Feynman-x (x_F) acceptance. The acceptance range is roughly $0\leq x_F \leq 0.7$ for the lower mass range, and $-0.2 \leq x_F \leq 0.6$ for the higher.

In order to extract peak areas for the three Υ resonances, it was necessary to have an accurate simulation of the background DY process. This was accomplished by analyzing a large number of Monte Carlo–generated DY events with the same analysis software that was employed for the real data. The DY event generator, which used the structure functions of Eichten *et al.*,[12] gives an excellent description of the continuum data.[10] The resulting Monte Carlo mass spectra, for individual transverse momentum (p_t) and x_F bins, were fitted to determine the shape of a polynomial function. This polynomial plus three asymmetric Gaussians, constrained to be of identical shape for the three resonances, were fitted to

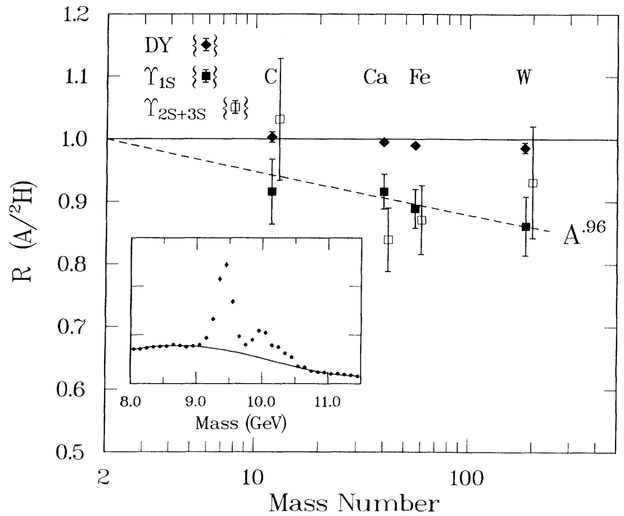

FIG. 1. The ratio of yields per nucleon vs A for the $\Upsilon(1S)$ and the sum of the $\Upsilon(1S+2S)$ resonances. The data have been integrated over the ranges $0 \leq x_F \leq 0.6$ and $0 \leq p_t \leq 4$ GeV/c. Inset: The mass spectrum in the Υ region. The solid line is a fit with the Drell-Yan continuum which is described in the text.

the experimental data in each p_t and x_F bin. For each individual target the fitting parameters were thus the three peak areas and the polynomial continuum normalization. Detailed Monte Carlo calculations were performed to correct for small acceptance variations among the different targets. As in previous publications of E772 results,[7,10] the total systematic error in the ratios is less than 2%. Errors quoted in the figures and text are statistical only unless otherwise indicated.

Figure 1 shows, for each target, the yield per nucleon relative to deuterium, R, for the Υ $1S$ and for the sum of the $2S$ and $3S$ resonances. These data have been integrated over the ranges $0 \leq x_F \leq 0.6$ and $0 \leq p_t \leq 4$ GeV/c. Describing the A dependence by the usual parametrization,

$$\sigma_A = \sigma_N A^\alpha ,$$

one finds $\alpha_{1S} = 0.962 \pm 0.006$ and $\alpha_{2S+3S} = 0.948 \pm 0.012$. The 2% overall normalization uncertainty contributes an additional error of ± 0.008. These values are significantly below the $\alpha = 1$ expected for hard scattering processes in nuclei, and found for the DY process.[10] They are significantly larger than those of the J/ψ and ψ' resonances ($\alpha = 0.92 \pm 0.008$) which were taken at a somewhat larger x_F range ($0.15 \leq x_F \leq 0.65$).[7] As in the case of the charmonium states the values of α for the $1S$ and $2S+3S$ resonances are the same within experimental errors, indicating no apparent dependence on the final hadronic size.

Figure 2 shows the dependence of α on x_F, x_2, and p_t for the $\Upsilon(1S)$ and sum of the Υ $2S$ and $3S$ resonances.

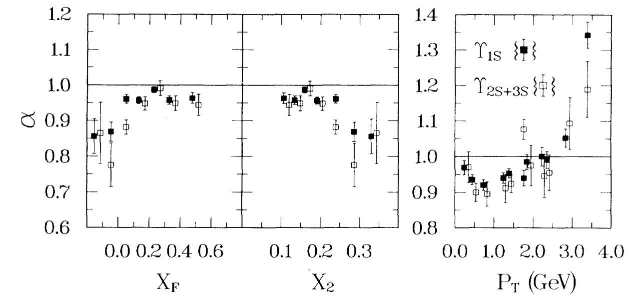

FIG. 2. The parameter α vs x_F, x_2, and p_t for the $\Upsilon(1S)$ and the $\Upsilon(2S+3S)$ states based on fits to all targets.

The x_F and x_2 dependence is particularly interesting as it shows a significant change in α over the kinematic range. Data at negative x_F are rare in fixed-target experiments, and, to our knowledge, a large decrease in α at small x_F has not been observed before. In the spirit of the parton fusion model, one can calculate x_2, the momentum fraction of the target parton, via the relations

$$m^2 = x_1 x_2 s, \quad x_F = x_1 - x_2 .$$

We assume that $m = 10.25$ GeV (mass of the χ_b states), but the resulting x_2 distribution is not very sensitive to this value within a reasonable (~ 1 GeV) range.

The large Q^2 of beauty-quark production suggests the applicability of perturbative QCD. In spite of the com-

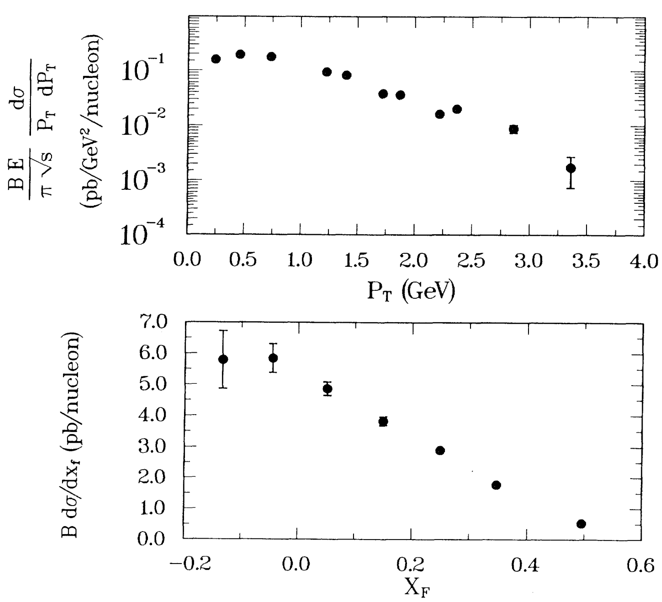

FIG. 3. Invariant cross section (per nucleon) times the branching ratio for the $\Upsilon(1S)$ resonance for the ^{2}H data vs p_t and x_F. The cross sections were integrated over x_F and p_t, respectively. The error bars are statistical; the overall normalization error is an additional $\pm 15\%$.

TABLE I. Change in mean-squared transverse momentum, $\Delta\langle p_t^2\rangle = \langle p_t^2(A)\rangle - \langle p_t^2(^2\mathrm{H})\rangle$, in GeV^2/c^2 vs A for the $\Upsilon(1S)$ state and the DY continuum ($4 \leq M \leq 9$ and $M \geq 11$ GeV). These are based on fits to the ^{2}H data with the function, $[1+(p_t/p_0)^2]^{-6}$, which determines p_0. For the ^{2}H data one finds $p_0(\Upsilon(1S))=3.22$ GeV/c and p_0(Drell-Yan)=2.71 GeV/c. For the above function one has $\langle p_t^2\rangle = p_0^2/4$.

	C	Ca	Fe	W
Υ	0.171 ± 0.129	0.388 ± 0.089	0.423 ± 0.097	0.667 ± 0.133
Drell-Yan	0.0 ± 0.015	0.046 ± 0.011	0.048 ± 0.012	0.113 ± 0.016

plication of a hadronic final state, QCD-based semiphenomenological models of Υ production[13,14] have aimed at interpreting the process in terms of various parton-parton fusion reactions. For 800-GeV protons gluon fusion processes are predicted to dominate the central production cross section. Thus the A dependence of Υ production could be sensitive to an A dependence of the gluon structure function of a bound nucleon (Fig. 2).

Given the poor understanding of the large A dependence in hadronic J/ψ production,[7] however, it would be unwise to interpret $\alpha(x_2)$ for the Υ directly in terms of a nuclear dependence of the gluon structure function. It has been shown recently,[7] for example, that $\alpha(x_2)$ for proton-induced J/ψ production does not scale between 200 and 800 GeV. Moreover, only a very small A dependence has been observed in the nuclear antiquark distribution[10] in this region of x_2. Thus the large decrease in α for $x_2 > 0.2$ (or $x_F < 0$) and the integrated value of $\alpha \sim 0.95$ probably reflect physics beyond that intrinsic to the gluon structure. Other possibilities include comover interactions[3,5,6,15] and heavy-quark components of hadronic wave functions.[4]

Figure 3 shows the cross section times the branching ratio to dimuons for the $\Upsilon(1S)$ for ^{2}H vs p_t and x_F (at mean values, respectively, of $\langle x_F\rangle = 0.23$ and $\langle p_t\rangle = 1.16$ GeV/c). The error bars are statistical; the overall normalization error is an additional $\pm 15\%$. The present x_F data are in good agreement with previous measurements[16] at 800 GeV (taken on a Cu target), but extend the x_F range considerably. The distribution is similar to that observed with 400-GeV protons.[17]

The cross section shows a rapid decrease with increasing p_t (Fig. 3). The parameter α increases with p_t (Fig. 2) as has been observed for the DY process[10,18] and J/ψ production.[7,19] Earlier work[20] showed a similar effect in high-p_t single-hadron production. Table I presents the data for both the $\Upsilon(1S)$ and the DY continuum in terms of

$$\Delta\langle p_t^2\rangle = \langle p_t^2(A)\rangle - \langle p_t^2(^2\mathrm{H})\rangle .$$

These values were derived by fitting the p_t cross sections for ^{2}H by the function[8] $[1+(p_t/p_0)^2]^{-6}$ to determine the parameter p_0. The ratio of yields per nucleon relative to ^{2}H was then fitted to determine $\Delta\langle p_t^2\rangle$. The increase in $\langle p_t^2\rangle$ is consistent with a dependence on $A^{1/3}$ expected in multiple-scattering models.[15,21] Both the mean values for ^{2}H and the increases with A are larger for the Υ than for the DY continuum.

In summary, we have made the first precision measurements of the nuclear dependence of Υ production. In the positive x_F range α is less than unity and approximately the same for the $\Upsilon(1S)$ and the $\Upsilon(2S+3S)$ states. A large decrease in α is found in the range $x_F < 0$. The A dependence of the p_t distribution for the $\Upsilon(1S)$ state is larger than that of the DY continuum, and both are in qualitative accord with parton multiple-scattering models. Differential cross sections for the $\Upsilon(1S)$ from ^{2}H decrease rapidly with increasing p_t and x_F.

We would like to acknowledge the efforts of the Fermilab Research and Accelerator Divisions and funding from the U.S. Department of Energy and the National Science Foundation. We also thank the Japanese Ministry of Education for providing parts of the spectrometer.

[1]C. Baglin *et al.*, Phys. Lett. B **220**, 471 (1989).

[2]T. Matsui and H. Satz, Phys. Lett. B **178**, 416 (1986).

[3]S. J. Brodsky and A. H. Mueller, Phys. Lett. B **206**, 685 (1988).

[4]S. J. Brodsky and P. Hoyer, Phys. Rev. Lett. **63**, 1566 (1989).

[5]J. P. Blaizot and J. Y. Ollitrault, Phys. Lett. B **217**, 386 (1989).

[6]S. Gavin and M. Gyulassy, Phys. Lett. B **207**, 257 (1988); S. Gavin and R. Vogt (to be published).

[7]D. M. Alde *et al.*, Phys. Rev. Lett. **66**, 133 (1991).

[8]A. Ito *et al.*, Phys. Rev. D **23**, 604 (1981).

[9]H. Sutter, in *Proceedings of the International Europhysics Conference on High Energy Physics, Uppsala, Sweden, 1987*, edited by O. Botner (European Physical Society, Geneva, Switzerland, 1987), p. 186.

[10]D. M. Alde *et al.*, Phys. Rev. Lett. **64**, 2479 (1990).

[11]S. Drell and T. M. Yan, Phys. Rev. Lett. **25**, 316 (1970).

[12]E. Eichten *et al.*, Rev. Mod. Phys. **56**, 579 (1984); **58**, 1065 (1986).

[13]V. Barger and A. D. Martin, Phys. Rev. D **31**, 1051 (1985), and references therein.

[14]W.-Y. P. Hwang, J. M. Moss, and J. C. Peng, Phys. Rev. D

38, 2785 (1988).
[15]S. Gavin and M. Gyulassy, Phys. Lett. B **214**, 241 (1988).
[16]G. Moreno, Ph.D. thesis, Centro de Investigacion y de Estudios Avanzados, Mexico, 1989 (unpublished); G. Moreno *et al.*, Phys. Rev. D **43**, 2815 (1991).
[17]S. Childress *et al.*, Phys. Rev. Lett. **55**, 1962 (1985).
[18]P. Bordalo *et al.*, Phys. Lett. B **193**, 373 (1987).
[19]J. Badier *et al.*, Z. Phys. C **20**, 101 (1983).
[20]J. W. Cronin *et al.*, Phys. Rev. D **11**, 3105 (1975); L. Kulberg *et al.*, Phys. Rev. Lett. **38**, 670 (1977).
[21]J. Hufner, Y. Kurihara, and H. J. Pirner, Phys. Lett. B **215**, 218 (1988).