# Nuclear Dependence of the Production of $\Upsilon$ Resonances at 800 GeV


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## Abstract

The yields of the $1S$, and the sum of $2S + 3S$ $\Upsilon$ resonances have been measured for 800 $GeV$ protons incident on targets of $^2H$, $C$, $Ca$, $Fe$, 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 $^2H$ are presented over the ranges $0.24 \leq p_t \leq 3.4$ $GeV/c$ and $-0.15 \leq x_F \leq 0.5$.



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The nuclear dependence of quarkonium production in hadronic reactions has received much attention recently, particularly in connection with $J/\psi$ production in high-energy heavy ion collisions.[1−6] Nuclear dependence of the $\Upsilon$ resonances offers a different view of many of the same physics issues. A potential advantage of the $\Upsilon$ 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 $\Upsilon$ family of resonances. This follows a study of the $J/\psi$ and $\psi'$ resonances from the same experiment.[7] Previous studies[8,9] of the $\Upsilon$ 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 $\sim 5 * 10^{16}$ 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 $x$-Feynman ($x_F$) 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 $\Upsilon$ 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[12] et al., 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 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 $\Upsilon$ $1S$ 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 parameterization,

$$\sigma_A = \sigma_N * A^{\alpha},$$

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 $\pm 0.008$. 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 $J/\psi$ and $\psi'$ 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 $\alpha$ 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 $\alpha$ on $x_F$, $x_2$, and $p_t$ for the $\Upsilon(1S)$ and sum of the $\Upsilon$ $2S$ and $3S$ resonances. The $x_F/x_2$ dependence is particularly interesting as it shows a significant change in $\alpha$ over the kinematic range. Data at negative $x_F$ are rare in fixed-target experiments, and to our knowledge, a large decrease in $\alpha$ 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

$$m^2 = x_1 x_2 s; \qquad x_F = x_1 - x_2.$$

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

The large $Q^2$ of beauty-quark production suggests the applicability of perturbative $QCD$. In spite of the complication of a hadronic final state, $QCD$-based semi-phenomenological models of $\Upsilon$ 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 $\Upsilon$ production could be sensitive to an A-dependence of the gluon stucture function of a bound nucleon (Fig. 2).

Given the poor understanding of the large A-dependence in hadronic $J/\psi$ production,[7] however, it would be unwise to interpret $\alpha(x_2)$ for the $\Upsilon$ 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 $J/\psi$ 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 $\alpha$ 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 gluon structure. Other possibilities include co-mover 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 $^2H$ versus $p_t$ 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 $\alpha$ increases with $p_t$ (Fig. 2) as has been observed for the DY process[10,18] and $J/\psi$ production.[7,19] Earlier work[20] showed a similar effect in high $p_t$ single hadron production. Table 1 presents the data for both the $\Upsilon(1S)$ and the DY continuum in terms of

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

These values were derived by fitting the $p_t$ cross sections for $^2H$ to the function,[8] $(1 + (p_t/p_0)^2))^{-6}$, to determine the parameter $p_0$. The ratio of yields per nucleon relative to $^2H$ were 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 $^2H$ and the increases with $A$ are larger for the $\Upsilon$ than for the DY continuum.

In summary we have made the first precision measurements of the nuclear dependence of $\Upsilon$ production. In the positive $x_F$ range $\alpha$ is less than unity and approximately the same for the $\Upsilon(1S)$ and the $\Upsilon(2S+3S)$ states. A large decrease in $\alpha$ 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 $^2H$ decrease rapidly with increasing $p_t$ and $x_F$.

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**References**


1. C. Baglin et al., Phys. Lett. **B220**, 471 (1989).

2. T. Matsui and H. Satz, Phys. Lett. **B178**, 416 (1986).

3. S.J. Brodsky and A.H. Mueller, Phys. Lett. **206B**, 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. **B217**, 386 (1989).

6. S. Gavin and M. Gyulassy, Phys. Lett. **B207**, 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, Proc. of the International Europhysics Conference on High Energy Physics, Uppsala, Sweden (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. **B214**, 241 (1988).

16. G. Moreno, Ph. D. Thesis, Centro de Investigacion y de Estudios Avanzados, Mexico, 1989 (unpublished); G. Moreno et al., submitted to Phys. Rev. D.

17. S. Childress et al., Phys. Rev. Lett. **55**, 1962(1985).

18. P. Bordalo et al., Phys. Lett. **B193**, 373(1987).

19. J. Badier et al., Z. Phys. **C20**, 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. **B215**. 218(1988).

**Figure Captions**

Fig. 1 The ratio of yields per nucleon versus $A$ 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 $0 \leq p_t \leq 4\ GeV/c$. The inset shows the mass spectrum in the $\Upsilon$ region. The solid line is a fit to the Drell-Yan continuum which is described in the text.

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

Fig. 3 Invariant cross section (per nucleon) times branching ratio for the $\Upsilon(1S)$ resonance for the $^2H$ data versus $p_t$ 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 1. Change in mean squared tranverse momentum, $\Delta\langle p_t^2\rangle = \langle p_t^2(A)\rangle - \langle p_t^2(^2H)\rangle$, in $[GeV^2/c^2]$ versus $A$ 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 $^2H$ data with the function, $(1+(p_t/p_0)^2))^{-6}$, which determine $p_0$. For the $^2H$ 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 |
|---|---|---|---|---|
| Upsilon | $0.171 \pm 0.129$ | $0.388 \pm 0.089$ | $0.423 \pm 0.097$ | $0.667 \pm 0.133$ |
| Drell-Yan | $0.0 \pm 0.015$ | $0.046 \pm 0.011$ | $0.048 \pm 0.012$ | $0.113 \pm 0.016$ |