Measurement of the A Dependence of J/ψ Photoproduction*

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J/ψ photoproduction has been measured from beryllium and tantalum targets by observing the yield of single muons at a transverse momentum of 1.65 GeV/c with a bremsstrahlung beam of $E_0 = 20$ GeV. The results have been interpreted in terms of a nuclear-optics model to yield the ψ-nucleon total cross section. The result is $\sigma_{\psi N} = 3.5 \pm 0.8$ mb.

The measurement of the differential cross section for the reaction $\gamma N \rightarrow \psi N$, elastic ψ photoproduction from a nucleon or nucleus, in principle allows a determination of the ψ-nucleon total cross section by means of the optical theorem and vector-dominance arguments. Such measurements have indicated that $\sigma_{\psi N}$, the J/ψ-nucleon total cross section, is of the order of 1 mb.[1,2] This argument assumes that the forward ψ-nucleon scattering amplitude is purely imaginary and that the value of $\gamma_\psi^2/4\pi$, the photon-ψ coupling constant as determined from storage-ring experiments, also applies to the case of real photons. It is therefore important to determine the value of $\sigma_{\psi N}$ by an independent method which does not involve the use of these assumptions. Measurements of the A dependence of J/ψ photoproduction provide just such an independent determination of $\sigma_{\psi N}$. The basic principle is the use of nuclear targets to measure the absorption by nuclear matter of the outgoing particle. If the outgoing particle lives long enough to traverse the nucleus, then by varying the path length in nuclear matter (i.e., by the use of differently sized nuclei) and measuring the relative yield per nucleon, the total cross section can be deduced from a relatively simple nuclear-optics theory. This technique has been used to determine the total cross section for the ρ, ω, and φ vector mesons.[3]

In a previous experiment at the Stanford Linear Accelerator Center (SLAC), J/ψ and ψ' photoproduction measurements were made by detecting muon or electron pairs from ψ decay.[1] This technique yields ψ cross-section measurements with very small background rates but has the limitation that the event rate is relatively low. Measurements of the A dependence are best done using targets with the same number of radiation lengths, and consequently the yield from the large A targets becomes prohibitively small if the double-arm technique is used. During the course of the previous measurement made at this laboratory, it was determined that J/ψ photoproduction could be studied with single-arm measurements by observing prompt electrons from ψ decay.[4] Single-arm measurements have the advantage that the yield is larger by approximately a factor of 25.

The present experiment was designed for single-arm measurements with muon detection. Muon detection has several advantages over electron detection. The Bethe-Heitler muon-pair-production yields are typically smaller by a factor of 3 compared to electron detection; and the extrapolations required to determine the prompt muon yield are, in principle, less involved than the extrapolation to zero radiator thickness required for the measurement of prompt electrons.

The SLAC 20-GeV spectrometer was used for these measurements. The spectrometer was unchanged from its arrangement in the earlier double-arm measurement[1] except for the addition of a second gas Cherenkov counter. The targets were enclosed in a narrow helium-filled scattering chamber with thin aluminum beam windows. A hadron absorber, consisting of a set of iron slabs, was arranged in such a way as to provide variable absorber thickness and a decay space of variable length between the target and the entrance to the spectrometer. The slab closest to the target was lined with tungsten in order to minimize the physical length of the first hadron interaction length. Figure 1 shows a detailed view of the target assembly and hadron absorbers.

The optimum amount of hadron absorber (~ 7 absorption lengths) was established by measuring

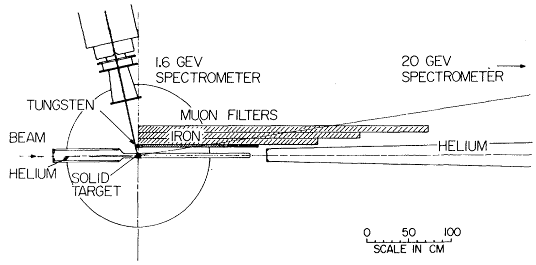

FIG. 1. Plan view of the target area showing details of the target and the hadron absorbers.

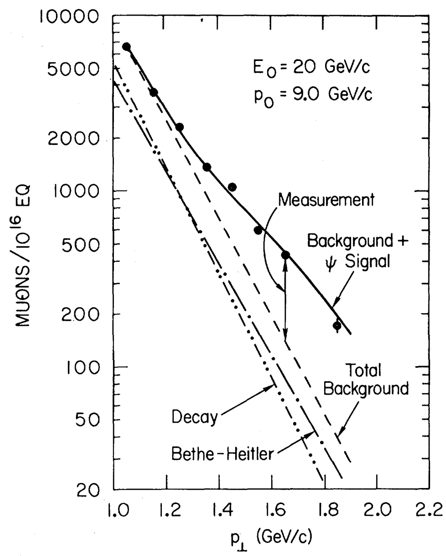

FIG. 2. Muon yield as a function of transverse momentum obtained with a beryllium target. The dashed lines indicate the calculated background contributions and the solid line shows the fitted total muon yield including the J/ψ-production contribution. The transverse momentum is varied by changing the spectrometer angle.

the muon yield as a function of absorber thickness and selecting the minimum amount consistent with negligible hadron punch-through. Data for the A-dependence measurements were taken with μ^- rather than μ^+ in order to minimize kaon punch-through and decay muons from K decay. The quality of the signal was established by measuring the muon yield as a function of transverse momentum from 1.0 to 1.85 GeV/c and observing the increase in muon yield at $p_\perp \simeq 1.5$ GeV/c resulting from the onset of the J/ψ-production contribution. The kinematic conditions chosen for the measurements were a muon momentum $p_0 = 9.0$ GeV/c corresponding to a spectrometer momentum of $p = 6.54$ GeV/c due to energy loss in the hadron absorber, and a bremsstrahlung end-point energy $E_0 = 20$ GeV. The yield as a function of transverse momentum was obtained by varying the spectrometer angle, but keeping the hadron absorber thickness fixed.

A yield curve taken with a beryllium target is shown in Fig. 2. The contribution from J/ψ decay is clearly evident. The background was assumed to consist of muons from hadron decays and Bethe-Heitler pair production with the requirements (1) that for $p_\perp$ values below 1.0 GeV/c these contributions should fully account for the muon yield, and (2) that for $p_\perp$ values in the ψ region, muon yield with this background subtracted should agree with ψ cross sections which were determined by the double-arm measurements. The same background assumptions were made for the tantalum target. The prompt-muon yield from Bethe-Heitler production was determined from the cross-section calculations and computer program of Tsai.[5] The muon contribution from π and K decays was determined for both targets from direct measurements of the pion yield taken with no absorber. Most of the A-dependence data were taken at a transverse-momentum setting of $p_\perp = 1.65$ GeV/c, as a reasonable compromise between counting rate and background, with ~0.3-radiation-length beryllium and tantalum targets. The empty-target rates were less than 5% of the tantalum rate and an order of magnitude smaller for the beryllium target. Approximately 4000 beryllium and 1200 tantalum muon events were accumulated over a one-week period at beam intensities of about 10^{10} equivalent quanta per pulse.

The J/ψ-nucleon total cross section was determined from the measured ratio of the ψ production yields from beryllium and tantalum. Several corrections must be made to this ratio before it is directly applicable for a determination of $\sigma_{\psi N}$.

(1) The cross-section ratio per nucleon at $p_\perp \simeq 1.65$ GeV/c was measured to be $\sigma(\text{Be})/\sigma(\text{Ta}) = 1.19 \pm 0.04$. Muons from hadron decays were determined to be 0.11 of the total muon yield with a measured A dependence for π^- at the same kinematic conditions of $[\sigma(\text{Be})/\sigma(\text{Ta})]_{\pi\to\mu} = 1.18 \pm 0.01$. The muons from K^- decay are a factor of 5 less than those from π^- decay and are therefore not large enough to produce a significant muon background. Bethe-Heitler production was calculated to be 0.20 of the total muon yield with an A dependence of $[\sigma(\text{Be})/\sigma(\text{Ta})]_{\text{B-H}} = 1.03$. These background sources of muons fully account for the muon yield at $p_\perp$ values below the step due to J/ψ production and give a cross section in good

agreement with the double-arm data as indicated in Fig. 2.[1] The cross-section ratio corrected for these backgrounds is $[\sigma(\mathrm{Be})/\sigma(\mathrm{Ta})]_\psi = 1.25 \pm 0.07$ with muons from ψ decay comprising ~0.69 of the total. The results are relatively insensitive to the precise background admixture.[6]

(2) The cross-section ratio for muons from ψ decay must also be corrected for several A-dependent nuclear-physics effects. The single-nucleon–ψ cross section was assumed to be related to the cross section from a nucleus A by the relation

$$\sigma_{\gamma A} = A_{\mathrm{eff}}\sigma_{\gamma N}\{1 - |F(t)|^2\}C + A_{\mathrm{eff}}^2\sigma_{\gamma N}|F(t)|^2,$$

where $F(t)$ is the nuclear form factor[7] at momentum transfer t and C is a correction factor which takes into account the Pauli exclusion principle and the effect of the motion of the nucleons. The use of A_{eff} rather than A reflects the effect of ψ absorption in nuclear matter. The $A_{\mathrm{eff}}^2\sigma_{\gamma N}|F(t)|^2$ term represents the coherent-production contribution. The correction factor C was calculated using a Fermi-gas model for the nucleus. The values of the Fermi momentum P_{F} used for these corrections were $P_{\mathrm{F}}(\mathrm{Be}) = 0.195$ GeV/c and $P_{\mathrm{F}}(\mathrm{Ta}) = 0.265$ GeV/c as determined from quasielastic electron scattering measurements.[8] The Pauli-principle correction slightly suppresses incoherent production from Ta relative to Be while the Fermi-motion correction enhances Ta relative to Be. The latter correction arises from the energy dependence of the J/ψ cross section. These corrections were analytically calculated and integrated over the full range of photon energies and momentum transfers which contribute to the ψ production. The J/ψ production cross section was parametrized from the results of the earlier double-arm measurements and a series of measurements made in conjunction with the present experiment.[1,9] The mean photon energy contributing to the J/ψ yield is approximately 17 GeV with an rms spread of 2 GeV, while the momentum-transfer contribution is dominated by the region near t_{min}. The corrections are tabulated in Table I and multiply the $[\sigma(\mathrm{Be}/\sigma(\mathrm{Ta})]_\psi$ ratio to yield a corrected ratio for incoherent ψ production $[\sigma(\mathrm{Be})/\sigma(\mathrm{Ta})]_{\psi\,\mathrm{corrected}} = 1.21 \pm 0.07$.

The quantity $\sigma_{\psi N}$ is determined from this corrected ratio based on a simple nuclear-optics theory of Gottfried and Yennie.[10] The effective A value for incoherent J/ψ production is determined from an integration over nuclear density and impact parameters and is related to $\sigma_{\psi N}$ in the following approximate way:

TABLE I. Nuclear-physics corrections to the ψ yield. The correction factors multiply the ratio $[\sigma(\mathrm{Be})/\sigma(\mathrm{Ta})]_\psi$.

Coherent production	0.967
Pauli exclusion effect	0.948
Fermi motion	1.060

$$A_{\mathrm{eff}}/A = 1 - 9\sigma_{\psi N}A^{1/3}/16\pi r_0^2,$$

where r_0 is related to the nuclear radius by $R = r_0A^{1/3}$. The nuclear parameters for beryllium and tantalum were determined from the Landolt-Börnstein compilation of electron-scattering data[7] and the measurements of effective nuclear radii as determined from ρ photoproduction data by Alvensleben *et al.*[11] The uniform model radii used for the determination of $\sigma_{\psi N}$ were $r_0^{\mathrm{Be}} = 1.45$ fm and $r_0^{\mathrm{Ta}} = 1.25$ fm, yielding

$$\sigma_{\psi N} = 3.5 \pm 0.8 \text{ mb},$$

where the error is statistical only.[12] The systematic error arising from the various corrections is estimated to be ~±0.5 mb.

This value of $\sigma_{\psi N}$ is to be compared to the approximate value of 1 mb based on the J/ψ photoproduction cross sections and vector-dominance arguments.[1,2] The ψ-nucleon cross section is significantly different from zero; and the present value based on a measurement independent of vector dominance and amplitude phase gives a value for $\sigma_{\psi N}$ in general agreement with, but somewhat higher than, the value based on vector-dominance ideas.

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Search for μe Events in Antineutrino-Nucleon Interactions

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A search for μe events produced in an antineutrino hydrogen-neon experiment using the Fermilab 15-ft bubble chamber is reported. Based on a single candidate, the 90%-confidence upper limit for the relative yield of $\mu^+ e^-$ events is 0.5% of all charged-current events with antineutrino energy greater than 10 GeV.

Recently evidence has been reported for neutrino-induced events with both a positron and a negative muon in the final state. At high energy these events are reported to occur at a level of ~1% of all neutrino interactions. There is evidence that the rate of strange-particle production in these events is anomalously high. The existence of these events cannot be explained in terms of the properties of known particles and interactions.[1,2]

This Letter reports on a search for similar events produced in an antineutrino beam. The data are based on an exposure of 74 400 pictures obtained with use of the Fermilab 15-ft bubble chamber filled with a hydrogen-neon mixture containing 21 at.% of neon. The density of this mixture is 0.3 g cm^{-3} and the average γ conversion length is 140 cm.

The chamber was exposed to a broad-band double-horn-focused antineutrino beam. An absorptive plug downstream of the target was used to suppress the neutrino contamination to less than 4% of the flux. The proton energy was 300 GeV and the mean proton intensity was $(0.8-0.9)\times 10^{13}$ protons/pulse.

The external muon identifier (EMI) was used in