Threshold Photo-production of J/ψ Mesons

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Introduction

With the advent of higher energies at Jefferson Lab, the study of charmonium becomes possible. The threshold production of J/ψ meson photo-production on hydrogen is ~ 8.2 GeV, thus with a 8+ GeV beam, the elementary γ-J/ψ cross section can be measured. Threshold charm production on a nucleus can give information on the J/ψ-N interaction. The standard method to extract this cross section has been to measure the nuclear dependence of J/ψ production. The majority of these A-dependent J/ψ production experiments have been measured at high energy, while the only near-threshold experiment was performed using 20 GeV photons. This 20 GeV SLAC experiment measured $\sigma_{J/\psi N}$ = 3.6 ± 0.8 ± 0.5 mb[1]; whereas theory predicts this cross section to be higher, about 7 mb [2]. It is unclear whether the SLAC determination of $\sigma_{J/\psi N}$ corresponds to the physical $\sigma_{J/\psi N}$, due to the fact that at these energies the J/ψ may still be formed outside the nucleus [3] [4]. A measurement of the nuclear dependence of threshold J/ψ photo-production may resolve this issue.

Motivation

The production mechanism of J/ψ mesons from nuclei can be split up into three processes, coherent elastic, quasi-elastic, and inelastic scattering. In coherent production, the photon fluctuates to an off-shell $c\bar{c}$ pair which scatters elastically from the nucleus. In the quasi-elastic reaction, the $c\bar{c}$ pair scatters elastically off a nucleon in the nucleus. At threshold, $t_{\min}$ is large, hence coherent production can be neglected and the dominating process is quasi-elastic production. The leading-order elastic contribution is two qluon exchange [2]. Inelastic scattering is believed to be described by the photon-gluon fusion mechanism [5], where the photon interacts with the gluon content of the nucleon through the sub-process, $\gamma g \rightarrow c\bar{c}$.

Following the convention of Brodsky and Mueller [3], the interaction is split into two time scales, production time (τ_P) and formation time (τ_F). In the target rest frame, the production time is the time of the hard interaction while the formation time is the time that the produced partonic system takes to reach the physical configuration of the hadron. The production time or, as it is sometimes called, the coherence time, has the following form in the target rest frame:

$$\tau_P \cong \frac{2\nu}{4m_c^2 + Q^2} \xrightarrow[Q^2=0]{} 0.04\,\nu \text{ fm GeV}^{-1} \qquad \textbf{(1)}$$

This is the lifetime of the hadronic fluctuation and for energies below 50 GeV the interaction involves a single nucleon in the nucleus. The formation time according to Kopeliovich and Zakharov has the following form:

$$\tau_F \cong \frac{2}{m_{\psi'} - m_{J/\psi}} \left[\frac{E_{J/\psi}}{2m_c} \right] \cong 0.2\ \nu\ \mathrm{fm\,GeV^{-1}} \tag{2}$$

where ν is the photon energy and is approximately equal to the J/ψ energy since for elastic scattering $z = E_{J/\psi} / \nu$ is close to one. There seems to be some disagreement between various authors about the size of the formation time [3] [6] [7], but all draw the same conclusion if the formation time is less than the size of the nucleus. This view is that the Vector Meson Dominance/Glauber prediction shown below is valid for $\tau_F \ll R_A$ where R_A is the radius of the nucleus.

$$T_N(A) \cong 1 - \frac{1}{2A} \sigma_{J/\psi N} \int d^2b\ T(b)^2 \tag{3}$$

where $T_N(A) = \sigma_A / A\sigma_N$ is the transparency factor and $T(b)$ and b are the optical thickness of the nuclei and the impact parameter. Thus one can measure the cross section per nucleon on two nuclear targets and form a ratio to extract the J/ψ-N cross section.

$$\frac{\sigma_{A_1}/A_1}{\sigma_{A_2}/A_2} = \frac{T_N(A_1)}{T_N(A_2)} \tag{4}$$

Forming this ratio enables the extraction of $\sigma_{J/\psi N}$ without measuring absolute cross sections. Since there is a large uncertainty in the formation time, it is advantageous to measure J/ψ production with a low energy probe, hence maximizing the chance that the $c\bar{c}$ forms into a J/ψ within the nucleus. As an example, using the formation time from Equation 2, the J/ψ's produced in the SLAC near-threshold experiment would have a formation time of 4 fm. While this is consistent with the typical nuclear size, it is unclear whether the application of the Glauber model is valid.

A $c\bar{c}$ state is thought to interact with a nucleon or nucleus through multiple gluon exchange, since valence quark exchange is not possible in QCD. This multiple gluon exchange behaves similar to a (color) van der Waals interaction [8]. Luke, Manohar, and Savage have shown that in the limit where the inverse radius, $r_Q^{-1} \sim \alpha_s(r_Q^{-1})m_Q$, of the $Q\bar{Q}$ bound state is larger than the QCD scale Λ_{QCD}, the process can be determined directly from the operator product expansion [9]. Furthermore, it has been established that hadron corrections to the J/ψ-N interaction are negligible[2]. Consequently, a measurement of the J/ψ-N interaction may provide information on the actual strength of this (color) van der Waals potential.

There is some thought that the large spin-spin correlation A_{NN} observed in *pp* elastic scattering [10] near the charm threshold may be a signal of strong $c\bar{c}$ interactions with nucleons [11]. Using the arguments from Ref. [11], de Téramond, Espinoza, and Ortega-Rodríguez have determined that a value of the J/ψ-N cross section equal to about 5 mb could explain the anomalous spin-spin correlation [12]. Since a van der Waals force is attractive, there is a possibility of nuclear bound quarkonium [8][9][13]. Although the J/ψ's produced in this experiment will have rather large momentum and will not likely form a bound state with the nucleus, this experiment seeks to verify whether the physical J/ψ-N cross section is indeed larger than previous experiments found, thus allowing for such an effect.

Another interesting application of the J/ψ-N cross section is in the interpretation of relativistic heavy ion collisions. It is thought that a signature for the formation of a quark-gluon plasma is J/ψ suppression [14][15]. The belief is that at sufficiently high parton densities there will be deconfinement which leads to an average gluon momentum that is five times higher than in a confined medium [16]. Since the dominant break up process for a J/ψ is through the exchange of hard gluons, one would expect J/ψ suppression in deconfined matter. To be able to distinguish J/ψ production between confined and deconfined matter requires understanding the propagation of fully formed J/ψ's in nuclear matter.

Experiment

The experiment could be run in either Hall A or Hall C using the existing spectrometer pairs. A 6 % cu radiator would be used to create the bremmstralung photons and the targets would also be 6 % of a radiation length (with the exception of the liquid H_2 and D_2 targets whose length is dictated by the spectrometer y_{tgt} acceptance). The lepton pair from the decay of the J/ψ would be detected in coincidence in the two spectrometers. Čerenkov detectors would discriminate between the leptons and pions and the lead glass shower counter would discriminate between the electrons and muons. The invariant mass and p_T resolutions would be better than 0.5 % resulting in easy separation of J/ψ signal from the background. Table 1 shows the rates per day for various targets assuming 40 μAmp beam current at an energy of 9 GeV and tagging the J/ψ via lepton pair decay.

Table 1 J/ψ rate per day (using $\sigma_{\gamma J/\psi}$ ~ 0.5 nb and $d\sigma/dt \sim \exp(2\cdot t)$).

Target	H_2	D_2	Be	C	Cu	Au
J/ψ Rate (per Day)	380	700	5000	3200	960	480

Summary

Based on the calculated rates, the elementary and A dependent photo-production cross sections could be measured using the standard setup in Halls A or C. From these data, the J/ψ-N cross section could be extracted.

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