Indication of anomalous exchange in exclusive charmonium photoproduction.

A. Sibirtsev\textsuperscript{a,b}, S. Krewald\textsuperscript{a} and A.W. Thomas\textsuperscript{b}

\textsuperscript{a}Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich

\textsuperscript{b}Special Research Centre for the Subatomic Structure of Matter (CSSM) and Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia

We find that available data on $J/\Psi$ photoproduction at $|t|\geq 1$ GeV are energy independent over the range $22\leq \sqrt{s} \leq 170$ GeV and show a very soft $t$ dependence. Through a systematic analysis of the data we detect a new trajectory, which manifests itself at threshold and is energy independent. The trajectory couples to the axial form factor of the nucleon and can reproduce the $J/\Psi$ exclusive photoproduction data at large -$t$.

Since the first measurements by the Cornell \cite{1} and SLAC \cite{2} Collaborations charmonium photoproduction has become an effective tool for investigating QCD dynamics. Available data \cite{1,2,3,4,5,6,7,8,9} are generally analysed in terms of the dependence on the invariant collision energy squared, $s$, and four momentum transfer squared, $t$.

Exclusive $J/\Psi$ photoproduction can be described in terms of a $c\bar{c}$ fluctuation of the photon that interacts with the nucleon by gluon ladder exchange. This interaction probes the gluon density, $g(x)$, and therefore experimental results can be used to constrain the gluon parton distribution function (PDF). The more recent DL \cite{10}, MRST2001 \cite{11} and CTEQ6 \cite{12} PDFs come from an analysis of recent data on $J/\Psi$ electroproduction at large $Q^2$. Our systematic analysis \cite{13} shows that the DL and MRST2001 PDFs reproduce available data on forward $J/\Psi$ photoproduction at $\sqrt{s} > 10$ GeV.

Within the two-gluon exchange model the $s$ dependence of the forward $J/\Psi$ photoproduction cross section is given as

$$\frac{d\sigma}{dt} \propto [xg(x)]^2,$$

where $x=m_J^2/s$ and $m_J$ is the $J/\Psi$ mass. The $t$ dependence results from two-gluon correlation in the proton and is not defined by the model but can be taken \cite{14} to be proportional to the proton isoscalar EM form factor

$$F(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \left( \frac{1}{1 - t/t_0} \right)^2,$$ \hspace{1cm} (2)

with $m_p$ the proton mass and $t_0=0.71$ GeV$^2$.

In the Regge model \cite{15,16} the $c\bar{c}$ fluctuation interacts with the proton by exchange of a pomeron trajectory and

$$\frac{d\sigma}{dt} \propto s^{2\alpha(t)-2} F(t)^2 \frac{\mu^4}{(m_J^2 - t)^2 \left( 2\mu^2 + m_J^2 - t \right)^2},$$ \hspace{1cm} (3)

where the last term is the form factor squared, which accounts for the possibility that the coupling between an off-shell charm quark and the pomeron is not pointlike - we take $\mu=\sqrt{1.2}$ GeV. The soft pomeron trajectory is $\alpha(t)=1.08+0.25t$. The $s$ dependence of $J/\Psi$ photoproduction at high energies requires \cite{13} the introduction of an additional hard pomeron \cite{17} with $\alpha(t)=1.44+0.1t$.

The circles in Fig.1 show the results for the forward $J/\Psi$ photoproduction cross section and slope of $t$ dependence evaluated by fitting the data as $d\sigma/dt = A \exp(bt)$. The solid line indicates a calculation based on the Regge model with soft and hard pomeron. The dashed line shows the result \cite{14} from the two-gluon model with the MRST2001 PDF. Both models reproduce the
data at $\sqrt{s}>10$ GeV reasonably well and clearly indicate room for some other contribution at low energy.

Figure 1. The forward $J/\Psi$ photoproduction cross section (upper) and slope $b$ of the $t$ dependence (lower) as a function of the invariant collision energy $\sqrt{s}$. The circles show the original data [1,2,3,4,7,9], while the squares indicate the results of our analysis for a new, soft contribution. The solid lines are the calculations with QCD pomeron exchange, the dashed line shows the pQCD result from two gluon exchange with the MRST2001 PDF [11]. The local slope was calculated at $t=-0.5$ GeV$^2$.

Figure 2. The $\gamma + p \rightarrow J/\Psi + p$ differential cross section as a function of $-t$ measured at different $\sqrt{s}$. The data are from Cornell [1], SLAC [2], EMC [3] and E687 [4]. The solid lines show the calculations including both soft and hard pomeron exchanges. The dashed lines indicate the fit to the soft part of the spectra.

It is important that the slope corresponding to the proton isoscalar EM form factor is

$$ b = -\frac{5.6}{4m_p^2 - 2.8t} + \frac{2}{4m_p^2 - t} + \frac{4}{t_0 - t}. \quad (4) $$

This depends on $t$ and can therefore be considered as a local slope. Furthermore $b \approx 4.6$ at $t=0$ and $b \approx 3.7$ at $t=1$ GeV$^2$. Additional contributions from the pomeron trajectory and quark-pomeron form factor add to the total slope shown in Fig. It is clear that the minimal slope is dictated by the proton EM form factor and the data at $\sqrt{s}<20$ GeV clearly indicate the need for some other mechanism that does not involve the EM form factor of the proton.

Low energy data on $J/\Psi$ photoproduction are shown in Fig.2. The solid lines show the calculations [13,18] within the Regge model, while the dashed lines illustrate the fit using an exponential function with parameters shown by squares in Fig.1. The Cornell and SLAC measurements at $\sqrt{s}<10$ GeV are not reproduced by the pomeron exchange calculations. The data collected at $\sqrt{s} \approx 20$ GeV by the EMC and E687 Collaborations are well described by pomeron exchange at low $t$ and clearly indicate an additional soft contribution at $|t| \geq 1$ GeV.

Furthermore, we reanalyse the data on
Figure 3. The solid circles are the $\gamma+p\to J/\Psi+p$ differential cross section, as a function of $-t$, measured at different invariant collision energies, $\sqrt{s}$, by the ZEUS Collaboration [9]. The solid lines show the calculations including both soft and hard pomeron exchanges. The open circles show the difference between the data and these calculations. This difference has been fit by an exponential function shown by the dashed lines.

$J/\Psi$ photoproduction at $30 \leq \sqrt{s} \leq 170$ GeV reported [9] recently by ZEUS Collaboration and shown in Fig.4 by solid circles in order to extract the soft contribution. Rather than readjusting the parameters of soft and hard pomeron exchanges we attribute the discrepancy between the calculations shown in Fig.4 by the solid lines and the data to an additional contribution. The open circles in Fig.4 show the difference between the experimental results and the calculations and the dashed lines show a fit to this difference using an exponential function with parameters shown in Fig.1 with the squares.

Although the above reanalysis of ZEUS data [9] cannot be considered definitive, because there are only two points at $|t| \geq 1$ GeV, it is compelling if we compare the data at $30 \leq \sqrt{s} \leq 50$ GeV and $150 \leq \sqrt{s} \leq 170$ GeV. In particular, the data differ substantially at these extreme energies and the calculations reproduce the data well at higher energy while definitely failing to describe the experimental results at $30 \leq \sqrt{s} \leq 50$ GeV. But it is important that the difference between the data and the calculations including both soft and hard pomeron exchanges is almost the same and practically energy independent.

Summarizing the results of our analysis shown by squares in Fig.1, we conclude that there is an indication for a new contribution to $J/\Psi$ photoproduction in addition to the to soft and hard pomeron exchanges. This contribution does not depend on $\sqrt{s}$. It dominates at small energies and can be detected at high energies at $|t| \geq 1$ GeV$^2$ since it has a $t$ dependence different from that of pomeron exchange. Moreover, this new contribution has a slope $b<3$ GeV$^{-2}$, which means that it does not involve the proton EM form factor.

Within a Regge model this contribution might come from the exchange of a trajectory, $\alpha(t) \approx 1.0+0t$, resulting in the differential $J/\Psi$ photoproduction cross section given as

$$\frac{d\sigma}{dt} \propto s^{2\alpha(t)-2} \frac{\Lambda^8}{(\Lambda^2 - t)^4},$$

with cut off parameter $\Lambda \approx 1.2$ GeV. The choice of the form factor is dictated by the data, which requires a sufficiently small local slope parameter at $|t| \geq 1$ GeV$^2$.

It is clear that the available data are not good enough to draw a more confident conclusion and explicitly fix the parameters of the trajectory. A somewhat more illustrative presentation of the data is given in Fig.3, where the $\gamma+p\to J/\Psi+p$ differential cross section is shown as a function of $-t$ for different energies, $\sqrt{s}$. Above $|t| \approx 1$ GeV$^2$, which is indicated by an arrow, the data are almost energy independent. The dashed lines in Fig.4 show the contribution from soft and hard pomeron exchanges at $\sqrt{s}=20$ GeV and 170 GeV. The solid line indicates the contribution from the exchange of the new trajectory with an absolute normalization $d\sigma/dt=20$ nb GeV$^{-2}$ at $t=0$.

Our prediction is that starting from threshold the forward $J/\Psi$ photoproduction cross section
Figure 4. The $\gamma + p \rightarrow J/\Psi + p$ differential cross section as a function of $-t$ measured at different energies $\sqrt{s}$. The arrow indicates the value of $t$ above which the data show energy independence. The dashed lines show the calculations with both soft and hard pomeron exchanges for $\sqrt{s} = 20$ GeV and 170 GeV. The solid line shows the contribution from the new trajectory exchange.

should be of order 20 nb GeV$^{-2}$ and should not be strongly energy dependent.

Fig. 4 shows that in contrast to our expectation few experimental results close to threshold show energy dependence. The measurement at lowest energy was done by the Cornell Collaboration [1] with photons of energy between 9.0 and 11.8 GeV that interacted with a beryllium target. It was pointed out [1] that the results were not corrected for fermi motion, which might be important since the $J/\Psi$ threshold corresponds to a photon energy of $\approx 8.15$ GeV. Moreover, the sample of $J/\Psi$ mesons was taken for the squared dielectron masses within the range $7.5 \pm 11.0$ GeV$^2$, that was divided into 10 equal intervals. Since $\Gamma_{J/\Psi \rightarrow ee} = +5.26 \pm 0.37$ keV the correction from the dielectron mass resolution might be large.

Furthermore, the SLAC measurements at a photon energies of 13 and 15 GeV was done inclusively with a deuteron target only at one value of $t$ and were extrapolated to $t=0$ under certain assumption. Only the SLAC measurement at a photon energy of 19 GeV shown in Fig. 1 was done at three different values of $t$. Obviously the $J/\Psi$ photoproduction should be measured at low energies in order to clarify the situation.

The additional trajectory that we propose may correspond to $f_1$ exchange with an odd signature, which distinguishes it from pomeron exchange with even signature. We note that unnatural parity $f_1$ exchange was proposed in Refs. 19,20 as an alternative to a hard pomeron contribution 17 in order to describe $\rho$ photoproduction at large $|t|$. It was suggested 19,20 that $f_1$ couples to an axial form factor of Eq. 5 with $\Lambda = m_{f_1} = 1.28$ GeV, which is slightly different 21 from that extracted from muon neutrino quasi-elastic scattering with average $\Lambda = 1.03 \pm 0.04$ GeV.

However the $J/\Psi$ photoproduction data discarded such an alternative. As is shown in Fig. 4 the data on forward photoproduction require strong energy dependence which is driven by hard pomeron exchange. As well the results for the slope at $|t| < 1$ GeV$^2$ at $\sqrt{s} > 10$ GeV indicate a coupling to the isoscalar EM form factor of the proton. The new trajectory has different features and should not substitute for hard pomeron exchange.

It is important that the energy independence of the data at large $-t$ found in our analysis also leads us to reject various hard processes that are expected to manifest at large $-t$ but are energy dependent. The new exchange can be entirely responsible for $J/\Psi$ photoproduction at $s \leq 10$ GeV where the pomeron exchange is not applicable.

It would be of great interest to study $J/\Psi$ photoproduction at low energies, which should be possible with the operation of HALL D at Jefferson Lab and to clarify whether the forward cross section approaches a value of order 20 nb GeV$^{-2}$ starting from threshold. It will be possible and important to determine quantum numbers of the new trajectory with polarization measurements.

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