Observation of $X(3872)$ muoproduction at COMPASS

The COMPASS Collaboration

Abstract

We have observed exclusive production of the exotic $X(3872)$ hadron in the reaction $\mu^+ N \rightarrow \mu^+ (J/\psi \pi^+ \pi^-) \pi^\pm N'$ using COMPASS data collected with incoming muons of 160 GeV/c and 200 GeV/c momentum. The statistical significance of the $X(3872)$ signal is $6\sigma$. The shape of the two-pion mass distribution shows disagreement with previous observations. The product of cross section and branching fraction of the $X(3872)$ decay into $J/\psi \pi \pi$ is determined to be $71\pm28\text{(stat)}\pm39\text{(syst)}$ pb.

Keywords: COMPASS, $X(3872)$, photoproduction, tetraquark, exotic charmonia

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The exotic hadron $X(3872)$ was first discovered in 2003 by the Belle collaboration [1] and constitutes the first in a long series of new charmonium-like hadrons at masses above 3.8 GeV/$c^2$. The $X(3872)$ was observed as a narrow peak in the $J/\psi \pi^+ \pi^-$ mass spectrum originating from the decay $B^\pm \to K^\pm J/\psi \pi^+ \pi^-$. Subsequently, this state has also been observed in numerous reaction channels and final states: in $e^+e^-$ collisions by Belle [2–5], Babar [6–12] and BES-III [13] and in hadronic interactions by CDF [14–17], D0 [18], LHCb [19–21], ATLAS [22] and CMS [23]. The current world average for the mass of the $X(3872)$ is $3871.69\pm0.17$ MeV/$c^2$ [24], which is very close to the $D^0\bar{D}^0$ threshold at $3871.81\pm0.09$ MeV/$c^2$. However, the decay width of this state was not determined yet as in all experiments the measured widths were compatible with the experimental resolution. Thus only an upper limit for the natural width $\Gamma_{X(3872)}$ of about 1.2 MeV/$c^2$ (CL = 90%) exists [5]. The spin, parity and charge-conjugation quantum numbers $J^{PC}$ of the $X(3872)$ were determined by LHCb to be $1^{++}$ [20, 25]. The $X(3872)$ hadron is peculiar in several aspects and its nature is still not well understood. In particular, approximately equal probabilities to decay into $J/\psi 3\pi$ and $J/\psi 2\pi$ final states $B(X(3872) \to J/\psi \omega)/B(X(3872) \to J/\psi \pi^+ \pi^-) = 0.8\pm0.3$ [26] indicate large isospin symmetry breaking. There are several interpretations of this hadron: pure $c\bar{c}$-state, tetraquark, meson-meson molecule, $c\bar{c}g$ meson, glueball, or others (see reviews [27–29]). In addition to knowing mass and quantum numbers of this state, the measurement of its width would provide a crucial input to narrow down speculations on its nature. Currently such a measurement can only be done by performing energy scans in $p\bar{p}$ annihilations, as it is foreseen at FAIR [30, 31].

In this Letter we report the first observation of $X(3872)$ produced by virtual photons in the charge-exchange reaction

$$\gamma' N \to X^0\pi^+N'$$

at COMPASS. Here, $N$ denotes the target nucleon and $N'$ the unobserved recoil system. The possibility to observe the production of $X(3872)$ in this reaction was first mentioned in Ref. [32].

The COMPASS experiment [33] is situated at the M2 beam line of the CERN Super Proton Synchrotron. The data used in the present analysis were obtained by scattering positive muons of 160 GeV/$c$ or 200 GeV/$c$ momentum off solid $^6$LiD or NH$_3$ targets, which represents the total data set accumulated between 2003 and 2011. The target material was arranged in two or three cylindrical cells placed along the beam direction. It was longitudinally or transversely polarized with respect to this direction. The polarization is opposite in consecutive target cells, and it is reversed periodically during data taking. After combining data with opposite polarization, possible effects from residual target polarization have negligible influence on this analysis. Particle tracking and identification were performed using a two-stage spectrometer, covering a wide momentum range from about 1 GeV/$c$ up to the beam momentum. The event trigger was based on scintillator hodoscopes and hadron calorimeters. Different trigger schemes were used for the different data sets. Possible differences in trigger efficiencies are expected to cancel in the determination of absolute production rates, which are obtained as ratio using a normalization process that was recorded in parallel, see below. Beam halo muons were rejected by veto counters located upstream of the target.

The main subject of this Letter is the study of muoproduction of an intermediate state $X^0$ decaying into $J/\psi \pi^+ \pi^-$ in the process

$$\mu^+ N \to \mu^+ X^0\pi^+ N' \to \mu^+ (J/\psi \pi^+ \pi^-)\pi^\pm N' \to \mu^+ (\mu^+ \mu^- \pi^+ \pi^-)\pi^\pm N',$$

the diagram of which is schematically shown in Fig. 1. In order to select such events, we first require a reconstructed vertex in the target region with an incoming beam muon track, three outgoing muon tracks (two $\mu^+$, one $\mu^-$) and three outgoing pion tracks with appropriate charges. Reconstructed particles are identified as muons if they have crossed more than 15 radiation lengths of material. Other charged particles are assumed to be pions. Candidates for $J/\psi$ decaying into a pair of oppositely charged muons are accepted if their reconstructed mass lies in the range from 3.02 GeV/$c^2$ to 3.18 GeV/$c^2$. With two
\( \mu^+ \) in a given event, we may reconstruct two \( J/\psi \) candidates in the \( \mu^+\mu^- \) final state, in which case the event is rejected. In order to select exclusive production in process (2), we require \( \sum E \) to match the energy \( E_{\text{beam}} \) of the beam particle, except for a small recoil energy to the target. Here, \( \sum E \) is the sum of energies of the scattered muon, of the \( J/\psi \), and of the three pions in the final state. Since at COMPASS the experimental resolution for \( \Delta E = \sum E - E_{\text{beam}} \) is about 2 GeV, we require \( |\Delta E| < 4 \) GeV in order to select exclusive production of the \( J/\psi 3\pi \) final state. The total number of selected exclusive \( \mu^+J/\psi 2\pi^+\pi^- \) and \( \mu^+J/\psi \pi^+2\pi^- \) events is 72 and 49, respectively. The ratio 72/49 corresponds approximately to the ratio of the average numbers of protons and neutrons in the target material.

Figure 2(a) shows the mass spectrum for the \( J/\psi \pi^+\pi^- \) subsystem in reaction (2) from threshold to 5 GeV/c\(^2\) after the aforementioned selection criteria were applied. As there are two equally charged pions per event, this mass spectrum contains contributions from the two possible \( \pi^\pm\pi^- \) combinations. The mass spectrum exhibits two structures below 4 GeV/c\(^2\), which can be assigned to the production and decay of \( \psi(2S) \) and \( X(3872) \). We determine the resonance parameters by a maximum likelihood fit to the mass spectrum from threshold to 5 GeV/c\(^2\), using a sum of two Gaussian functions for the signals and the background term

\[
B(M) = c_1 (M - m_0)^2 e^{-c_3 M}, \tag{3}
\]

where \( m_0 = M_{J/\psi} + 2m_\pi \). We ignore possible contributions from other states like \( \psi(3770) \), \( \psi(4040) \), \( \psi(4160) \), \( X(4260) \), \( X(4360) \) and \( X(4660) \) since their branching fractions into \( J/\psi \pi\pi \) are too small to significantly impact the shape of the observed mass distribution. The fit function has eight free parameters: the resonance mass and the number of events in each mass peak, the same width \( \sigma_M \) for both peaks and the parameters \( c_1, c_2, c_3 \) describing the background shape. The yields for \( \psi(2S) \) and \( X(3872) \) are determined to be \( N_{\psi(2S)} = 24.2 \pm 6.5 \) and \( N_{X(3872)} = 13.2 \pm 5.2 \) events and their masses \( M_{\psi(2S)} = 3683.7 \pm 6.5 \) MeV/c\(^2\) and \( M_{X(3872)} = 3860.4 \pm 10.0 \) MeV/c\(^2\), respectively. The estimated mass values are consistent with the world average values [24]. The fit yields \( \sigma_M = 22.8 \pm 6.9 \) MeV/c\(^2\) for the width. As this value is dominated by the experimental resolution, it appears sufficient to use the same width parameter for both Gaussian functions. In order to estimate the statistical significance of the observed signals, the function \( B(M) \) in Eq. 3 was fitted to the mass spectrum shown in Fig. 2(a) in the region below 5 GeV/c\(^2\), excluding the signal range from 3.62 GeV/c\(^2\) to 3.90 GeV/c\(^2\). The probability \( p(M) \) to find a number of events equal or larger than observed due to a statistical fluctuation in the mass window \( M \pm \Delta M \), where \( \Delta M = 30 \) MeV/c\(^2\), is shown in Fig. 2(b). In order to calculate \( p(M) \) we assume a Poissonian background with the mean value

\[
\tilde{N}(M) = \int_{M-\Delta M}^{M+\Delta M} B(M') dM'. \tag{4}
\]
The statistical significance for $\psi(2S)$ and $X(3872)$, expressed in terms of the Gaussian standard deviation, is $6.9\sigma$ and $4.5\sigma$, respectively. We have repeated the fit keeping the mass separation of the two Gaussians fixed to the value from Ref. [24], which did not significantly alter neither the mass value for the $\psi(2S)$ nor the number of observed events for either state: $M_{\psi(2S)} = 3680.9 \pm 5.7$ MeV/c$^2$, $N_{\psi(2S)} = 24.9 \pm 5.7$ and $N_{X(3872)} = 13.6 \pm 4.8$ events. We investigated several systematic uncertainties of the production yield for both states by varying the selection cuts and found that they are much smaller than the statistical uncertainty of $N_{X(3872)}$.

In order to select a non-exclusive data sample for process (2), we require a larger missing energy, i.e. $-12$ GeV $< \Delta E < -4$ GeV. The resulting invariant mass distribution is shown in Fig. 2(c). Except for $\psi(2S)$, we observe no statistically significant signal of charmonium(-like) production.

In parallel to reaction (2), we investigate the reaction with neutral exchange,

$$\mu^+ N \to \mu^+ X^0 N' \to \mu^+ (J/\psi \pi^+ \pi^-) N' \to \mu^+ (\mu^+ \mu^- \pi^+ \pi^-) N',$$

(5)
by requiring in the final state only two charged pions with opposite charge. Hence the schematic representation of reaction (5) is similar to the one shown in Fig. 1, but without the bachelor pion. The invariant mass distribution for the exclusive $J/\psi \pi^+ \pi^-$ final state is shown in Fig. 3. The parameters of the $\psi(2S)$ peak determined from a fit using the model described above, where the mass of the $X(3872)$ was fixed to its nominal value, are $N_{\psi(2S)} = 314 \pm 18$, $M_{\psi(2S)} = 3687.1 \pm 0.8$ MeV/$c^2$ and $\sigma_M = 13.3 \pm 0.7$ MeV/$c^2$. The $X(3872)$ yield obtained from the fit is $-2.9 \pm 2.5$ events, i.e. no statistically significant evidence for a $X(3872)$ signal was found in reaction (5). A statistical simulation was used to determine the upper limit for $N_{X(3872)}$. Samples were generated according to the fit results for the $\psi(2S)$ peak and the background continuum, while the strength of the $X(3872)$ Gaussian signal was varied. The upper limit $N_{UL}^{UL}(3872)$ for the number of events $N_{X(3872)}$, which is required to obtain the result of $-2.9$ events or lower, is 0.9 events at a confidence level of 90%.

In order to investigate the origins of $X(3872)$ and $\psi(2S)$ in reaction (2) we add the bachelor pion to both states to determine the invariant masses of the $X(3872)\pi^\pm$ and $\psi(2S)\pi^\pm$ systems. For this study, we consider only the two narrow mass regions of $\pm 30$ MeV/$c^2$ around the nominal mass values of $X(3872)$ and $\psi(2S)$. Although no significant structure can be seen in the mass distribution shown in Fig. 4(a), some enhancement of $\psi(2S)\pi^\pm$ events may be spotted at masses of about 4 GeV/$c^2$, where the $Z^\pm$ (4020) charmonium-like state was observed by BES-III [34–38]. Figure 4(b) shows distributions for the missing mass, defined as $M^2_{\text{miss}} = (P_\mu + P_N - P_N^\prime - P_N^\prime)^2$, for reactions (5) and (2). Note that according to this definition, the bachelor pion contributes to the missing mass of reaction (2). The mean value of the missing mass for $\psi(2S)$ produced in reaction (5) is about 1.4 GeV/$c^2$. When $\psi(2S)$ and $X(3872)$ are produced together with a bachelor pion in reaction (2), the mean value for the missing mass is 2.7 GeV/$c^2$ and 4.3 GeV/$c^2$, respectively. The apparent difference that can be seen between the missing mass distributions for $\psi(2S)$ and $X(3872)$ produced in reaction (2) indicates different production mechanisms. The $J/\psi \pi^+ \pi^-$ invariant mass distribution for exclusive $J/\psi \pi^+ \pi^- N'$ events from reaction (2) using the additional requirement $M_{\text{miss}} > 3$ GeV/$c^2$ is shown in Fig. 2 (d). By this requirement the $\psi(2S)$ peak and the background continuum are reduced, while the statistical significance of the $X(3872)$ peak increases up to 6$\sigma$.

Reactions (2) and (5) are characterized by two kinematic variables: the negative squared four-momentum transfer $Q^2 = -(P_\mu - P_N)^2$ and the centre-of-mass (CM) energy of the virtual-photon – nucleon system, $\sqrt{s_{\gamma N}}$. The distributions of these two variables are shown in Figs. 5(a) and 5(b). Most events occur at small values of $Q^2$. The CM energy is distributed between 8 GeV and 18 GeV, while the kinematic limit for beam momenta of 160 GeV/$c$ and 200 GeV/$c$ is 17.3 GeV and 19.4 GeV, respectively. We tested the hypothesis that the observed $X(3872)$ peak is an artificial structure appearing in the reaction $\gamma^* N \rightarrow \psi(2S) N^\prime \rightarrow (J/\psi \pi^+ \pi^-)(N' \pi^\pm)$, where one mixed up the pion from $\psi(2S)$ decay with the pion

![Fig. 3: The $J/\psi \pi^+ \pi^-$ invariant mass distribution for the exclusive $J/\psi \pi^+ \pi^-$ final state from reaction (5).](image-url)
for high $\pi g$. by the Belle \cite{Bell}, CDF \cite{CDF}, CMS \cite{CMS} and ATLAS \cite{ATLAS} collaborations. They found a preference from $\gamma N$ to show the events in the range $-\pm$ 30 MeV/c^2 in the mass spectrum of the two pions resulting from the decay of the $X(3872)$ mass window around the $\psi(2S)$ peak of reaction (5). Blue circles and red squares show the events in the range $\pm$ 30 MeV/c^2 around the $\psi(2S)$ and $X(3872)$ peaks of reaction (2).

The mass spectrum of the two pions resulting from the decay of the $X(3872)$ was precisely studied, e.g. by the Belle \cite{Bell}, CDF \cite{CDF}, CMS \cite{CMS} and ATLAS \cite{ATLAS} collaborations. They found a preference for high $\pi^\pm\pi^\mp$ masses and a dominance of the $X(3872) \rightarrow J/\psi \rho^0$ decay mode. The measured two-pion mass spectrum for events produced in reaction (2) within a $\pm$ 30 MeV/c^2 mass window around the $\psi(2S)$ (blue) and the $X(3872)$ (red) is shown in Fig. 6(a). The result for $\psi(2S)$ is in a good agreement with former observations, while the shape of the $\pi\pi$ mass distribution for $X(3872)$ looks very different from the previous results. The comparison of the shape for the two-pion mass distributions from $X(3872)$ decay, obtained by COMPASS and ATLAS \cite{ATLAS}, is presented in Fig. 6(b). Our studies indicate that the observed difference cannot be explained by acceptance effects. Within statistical uncertainties, the shape of the COMPASS $\pi\pi$ mass distribution is in agreement with a three-body phase-space decay, and it is expected for a state with quantum numbers $J^{PC} = 1^{-+}$ \cite{JPC}. A possible distortion of the two-pion mass spectrum by non-resonant background under the peak was estimated using the sPlot procedure \cite{sPlot} and...
was found to be unlikely for reaction (2). We also investigated the possibility to obtain the observed two-pion spectrum from the decay $X(3872) \rightarrow J/\psi \omega \rightarrow J/\psi \pi^+ \pi^- \pi^0$ where the $\pi^0$ has been lost, and excluded it.

![Graph](image)

**Fig. 6:** (a) Invariant mass spectra for the $\pi^+ \pi^-$ subsystem from the decay of $X(3872)$ (red squares) and $\psi(2S)$ (blue circles) produced in reaction (2). The corresponding distributions for three body phase-space decays are shown by the curves. (b) Invariant mass spectra for the $\pi^+ \pi^-$ subsystem from the decay of $X(3872)$ measured by COMPASS (red squares) and by ATLAS [22] (blue points).

In order to determine the cross section of exclusive $X(3872)$ production in reaction (2), we use the exclusive production of $J/\psi$ off the target nucleon,

$$\mu^+ N \rightarrow \mu^+ J/\psi N,$$

as normalization. The same data are used and the same selection criteria are applied as for reactions (2) and (5). The method used to determine the cross section for reaction (2) relies on the assumption of the same fluxes of virtual photons for reactions (2) and (6). This assumption is supported by similar shapes of the $Q^2$ and $\sqrt{s_{NN}}$ distributions in both cases. In this case, we can relate the photo- and leptoproduction cross sections as follows:

$$\frac{\sigma_{J/\psi N \rightarrow J/\psi N} - \sigma_{J/\psi N \rightarrow J/\psi N}}{\sigma_{J/\psi N \rightarrow J/\psi N}} = \frac{\sigma_{J/\psi N \rightarrow J/\psi N}}{\sigma_{J/\psi N \rightarrow J/\psi N}}.$$

The cross section of the reaction $\gamma N \rightarrow J/\psi N$ is known for our range of $\sqrt{s_{NN}}$; it is $14.0 \pm 1.6$(stat) $\pm 2.5$(syst) nb at $\sqrt{s_{NN}}=13.7$ GeV [41]. Since this value was obtained for the production by a real-photon beam, we reduce it by a factor of 0.8 in order to take into account the $Q^2$ dependence of the cross section [42] and the average photon virtuality in our samples of about 1 GeV/$c^2$. Since the three charged pions appear only in the final state of reaction (2), the ratio of acceptances of the two reactions is in first approximation equal to the pion acceptance $a_\pi$ cubed. Based on previous COMPASS measurements and Monte Carlo simulations, we estimate $a_\pi = 0.6 \pm 0.1$(syst) as average over the geometrical detector acceptance and both target configurations. Thus we set

$$\frac{\sigma_{J/\psi N \rightarrow J/\psi N} - \sigma_{J/\psi N \rightarrow J/\psi N}}{\sigma_{J/\psi N \rightarrow J/\psi N}} = \frac{N_{X(3872)} - N_{J/\psi}}{a_\pi^3},$$

where $N_{X(3872)}$ and $N_{J/\psi}$ are the respective numbers of observed $X(3872)$ and $J/\psi$ events from exclusive production on quasi-free nucleons. The number $N_{J/\psi}$ is determined as $9.6 \times 10^3$, with a systematic uncertainty of about 10% due to non-exclusive background in our data sample. The amount of COMPASS data used in this analysis is equivalent to about 14 pb$^{-1}$ of the integrated luminosity, when considering
a real-photon beam of about 100 GeV incident energy scattering off free nucleons. Using the normalization procedure described in Ref. [43], we determine the cross section for reaction $\gamma N \rightarrow X(3872)\pi N'$ multiplied by the branching fraction for the decay $X(3872) \rightarrow J/\psi \pi^+ \pi^-$ to be

$$\sigma_{\gamma N \rightarrow X(3872)\pi N'} \times B_{X(3872) \rightarrow J/\psi \pi\pi} = 71 \pm 28\,(\text{stat}) \pm 39\,(\text{syst}) \text{ pb}. \quad (9)$$

The statistical uncertainty is given by the uncertainty in the number of $X(3872)$ signal events, while the main contributions to the systematic uncertainty are: (i) 36 pb from the estimation of $a_\pi^3$, (ii) 14 pb from the cross section for reaction (6), (iii) 7 pb from the estimation of $N_{J/\psi}$.

Also, an upper limit is determined for the production rate of $X(3872)$ in the reaction $\gamma N \rightarrow X(3872)N$, mentioned in Ref. [32], using the same procedure for normalization as described above. The result is

$$\sigma_{\gamma N \rightarrow X(3872)N'} \times B_{X(3872) \rightarrow J/\psi \pi\pi} < 2.9 \text{ pb (CL = 90\%).} \quad (10)$$

In summary, we observed muoproduction the exotic hadron $X(3872)$ with a statistical significance of $6\sigma$ in the process depicted in Fig. 1 and determined its absolute production rate. Our observation for the two-pion mass spectrum shows disagreement with previous experimental results. It could be an indication that the $X(3872)$ object could contain a component with quantum numbers different from $1^{++}$. This result may help to clarify the nature of the $X(3872)$ state. The presented results demonstrate the capability to study exotic charmonia-like states in (virtual) photo-production. High precision studies of such states are foreseen at facilities with high intensity photon beams like CLAS [44] or GlueX [45].

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