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χ -PARTICLE PRODUCTION IN π^-p COLLISIONS AT 38 GeV/c

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ABSTRACT

The production of χ -particles in reaction $\pi^-p \rightarrow \chi + \dots$ has been studied near threshold. The measurements have been performed at the 70 GeV IHEP proton synchrotron using the hodoscope spectrometer GAMS-2000. The χ -particles have been identified through their decay $\chi \rightarrow J/\psi + \gamma$, $J/\psi \rightarrow e^+e^-$. In the region $X_F \geq 0.4$ the fraction of observed J/ψ particles which are obtained via the decay of χ states is 0.44 ± 0.16 . The χ longitudinal and transverse momentum distributions are similar to those obtained for J/ψ . The inclusive production cross-section of χ -particles (3P_1 and 3P_2 states) at 38 GeV/c is $\sigma_{X_F > 0}(\pi^-p \rightarrow \chi + \dots) = (28 \pm 11)$ nb.

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1. INTRODUCTION

The present work is devoted to the study of inclusive production of particles with hidden charm, namely χ particles (P wave, even C states of charmonium) in reaction

$$\pi^- p \rightarrow \chi + \dots \quad (1)$$

and also J/ψ particles in reaction

$$\pi^- p \rightarrow J/\psi + \dots \quad (2)$$

in the near-threshold energy region.

Contrary to type (2) processes, which have been studied in great detail (see, e.g. survey [1]), data on the production of χ states in reaction (1) have a fragmentary character only [2-8] and do not exist at all for energies below 200 GeV.

At energies of 200 GeV and above, the J/ψ production proceeds directly as in process (2), but also partly through the indirect process (1) followed by the decay

$$\chi \rightarrow J/\psi + \gamma \quad (3)$$

The ψ' production cross-section [1,9] as a function of energy also shows the importance of direct J/ψ production.

2. EXPERIMENTAL CONDITIONS

The measurements have been performed with 38 GeV/c negative pions produced by the 70 GeV synchrotron at IHEP. χ -particles have been identified through their decay (3) and the J/ψ -particles by their decay into electron-positron pairs

$$J/\psi \rightarrow e^+ + e^-. \quad (4)$$

The layout of the experiment is shown on fig. 1. Photons and electrons (positrons) are detected in the hodoscope spectrometer GAMS-2000 which gives their coordinates and energy. Coordinates of electrons and positrons are also determined by the scintillation hodoscope TH. More details about the experimental set-up may be found in previous works [10,11].

The data have been taken within the same apparatus simultaneously with those of a search for glueballs and heavy particles with high spin in exclusive charge-exchange processes [10,12]. In order to perform both experiments in parallel, independent multi-level "exclusive" and "inclusive" triggers have been built, each of them making use of fast dedicated processors [11].

The exclusive trigger includes guard counters (fig. 1) in anticoincidence and selects processes with neutral final states

$$\pi^- p \rightarrow M^0 n \quad (5)$$

which eventually decay into photons [10-13]. In the final stage, the exclusive trigger sorts out M^0 systems according to their mass ($\geq 1 \text{ GeV}/c^2$) and energy ($\geq 25 \text{ GeV}$). At such a selection level the number of events of exclusive reaction (5), recorded on magnetic tape by the data taking system, is about 50 per machine cycle (1.6 s). This keeps the possibility to detect approximately the same number of inclusive $\pi^- p$ events during the same cycle (the limitation on the number of recorded events comes mainly from the on line minicomputer).

The initial selection in the inclusive trigger is given by the combination of signals $S_1.S_2.S_3.S_4.S_5.\overline{F_7}$. The energy release in GAMS is taken into account at the next stage. Therefore, the counters of GAMS have been grouped into sets of 64 units (8x8), the signals delivered by the last dynode of all PM's in each group being summed with passive adders mounted on the spectrometer itself. Then, the signal from each group of counters enters a linear fan-in circuit and the overall sum signal of GAMS A_{tot} is analyzed in amplitude. The value of A_{tot} is used as a 2nd level selection criterium by the fast inclusive trigger. It is also measured with a standard 12-bit ADC circuit.

The essential requirement of such a trigger system is the precise equalization of the dynode outputs for all counters in the spectrometer. The gain adjustment [14] of GAMS-2000 counters has been carried out in a wide electron beam [15]. Further calibration has shown that the value of the sum signal A_{tot} does practically not depend on the impact point of the electrons in GAMS; its dispersion does not exceed 10%.

The rate of events selected by the inclusive trigger with $A_{\text{tot}} \geq 20$ GeV is $\approx 1.5 \times 10^3/\text{cycle}$. Further reduction of the event rate is accomplished at the 3rd level of the trigger. The energy deposit $\tilde{E} = \sum \alpha_j A_j$ and the radial moment of the GAMS signals $\tilde{M}_r = \sum \alpha_j A_j r_j / L$ (where A_j is the value of the signal in the j -th counter, r_j is the distance of this counter to the beam axis, α_j is a normalization coefficient determined during the calibration of GAMS and L is the distance between GAMS and the liquid hydrogen target (fig. 1)) are evaluated through fast processors. Signals from the central zone of GAMS (16×16) are excluded from the summations in $\tilde{E}$, $\tilde{M}_r$ and A_{tot} in order to reduce the background due to diffractive processes. Such a geometry of the trigger favours the selection of the symmetrical decays of $J/\psi(4)$ ($\cos \theta \lesssim 0.4$, where θ is the decay angle in the J/ψ rest frame).

Finally events which fulfill the conditions $\tilde{E} > 21$ GeV, $\tilde{M}_r > 2.8$ GeV are selected. With these requirements, an efficient detection is insured for particles produced in reactions (1) and (2) in the interval $0.4 \lesssim X_F < 1$, where $X_F = p_{\parallel} / p_{\parallel}^{\text{max}}$ ($p_{\parallel}$ is the χ or J/ψ longitudinal c.m. momentum). In these conditions, the event rate corresponds to about 50 $\pi^- p$ interactions per accelerator cycle. For each event, the amplitude of the signals delivered by the counters in GAMS and by the guard system as well as the response of all the other detectors in the set-up are written on magnetic tape.

The geometry of the set-up and the selection criteria for the inclusive trigger given above have been chosen on the basis of Monte-Carlo calculations taking into account the development of electromagnetic and hadronic showers in GAMS [11,16]. $\pi^- p$ interactions without formation of charmed particles (i.e. background processes in the present work) have been generated according to the procedure of ref. [17] with 0.3 GeV/c average transverse pion momentum. The form of the charged pion multiplicity distribution has been taken according to KNO scaling with the

parametrization of ref. [18]. Longitudinal and transverse momentum distributions measured for nearby energies [1], have been used for J/ψ produced in reaction (2). Analog distributions have been taken for χ particles.

Preliminary experiments with GAMS have shown that $\tilde{E}$ and $\tilde{M}_T$ distributions of π^-p events detected by the spectrometer agree with the calculated ones within 50%, while the number of events changes by three orders of magnitude.

The measurements on reactions (1) and (2) have been made with a beam intensity of $10^7 \pi^-/\text{cycle}$. During the measurements (one week), $4.5 \times 10^{11} \pi^-$ have reached the liquid hydrogen target. Four million events have been written on magnetic tape, for off line analysis.

3. DATA HANDLING

The recorded events are analysed with a set of programs which search for showers in GAMS and determine the coordinates of incoming particles and the energy release in showers. Depending on their shape in GAMS, the showers are identified as photons (electrons) or hadrons [16].

First, events that are candidate for reaction (2) are selected. At this stage of the analysis it is required that at least two charged particles have been recorded by the hodoscope TH. Further, the effective mass of all pairs of showers found in GAMS, with an energy release larger than 0.8 GeV, is determined by the method of moments. Only those events with at least one combination of showers giving an effective mass greater than $2.3 \text{ GeV}/c^2$ are kept for further analysis. It is also checked that the involved showers correspond to charged particles which are detected in the hodoscope TH. This selection (with very loose criteria) already reduces the number of events to be analysed by two orders of magnitude, down to 30.000.

For these remaining events, the shower profiles have been fitted and the kinematic reconstruction has been done. A further selection is accomplished according to the following criteria:

- 1) the fit of the profile of each electron shower has a $\chi^2 < 7$ (95% probability);
- 2) the energy deposit in each shower E_e is 4 GeV minimum (this corresponds also to the acceptance cut in decay (4));
- 3) the coordinates of a particle, as measured by hodoscope TH, agree with their projections on GAMS within 4 standard deviations;
- 4) the effective mass of each pair $M_{ee} > 2.3 \text{ GeV}/c^2$;
- 5) the total energy deposited in GAMS is less than 43 GeV (2 standard deviations from the beam energy);
- 6) at least five amongst the 8 hodoscope planes H_1-H_4 , must have been fired by one beam particle only.

The last two requirements are introduced to reduce piling up effects due to the high load of GAMS. The number of events satisfying the above conditions is 1100. Individual examination of these events confirmed the correctness of their identification by the system of programs.

A peak, containing about 60 events, shows up in the M_{ee} mass spectrum in the region of the J/ψ particle. Still, the background under the peak is large. In order to reduce it, additional selection criteria have been introduced:

- 7) the electron pair energy $E_{ee} > 21 \text{ GeV}$;
- 8) the number N of charged particles detected in hodoscope TH does not exceed $7^{(*)}$.

Furthermore, stronger cuts have been used instead of criteria 1 to 3, namely:

- 1') $\chi^2 < 5$;
- 2') $E_e > 7 \text{ GeV}$;
- 3') the number of standard deviations admitted in 3) is reduced to 2.

(*) The total multiplicity of charged particles in an event is usually quite higher than N as many of them, which cross the hole in the center of hodoscope TH, are not detected.

4. REACTION $\pi^- p \rightarrow J/\psi + \dots$

The resulting effective mass spectrum M_{ee} contains 120 events (fig. 2). It shows a clean peak (40 events) corresponding to the production of J/ψ -particles in reaction (2). The events on the left of the J/ψ peak are due to a background which is decreasing rapidly when M_{ee} increases and which practically disappears in the peak region. With the stronger cut, $E_{ee} > 23$ GeV, the number of detected J/ψ -particles is as expected one third less while the left-hand background is decreased by more than an order of magnitude. The spectrum observed in this energy region is in agreement with the shape of the expected e^+e^- Drell-Yan continuum.

The width of the observed J/ψ peak is due to the instrumental resolution of the spectrometer. The cross-section for 38 GeV/c π^- is found to be

$$\sigma_{x_F > 0}(\pi^- p \rightarrow J/\psi + \dots \rightarrow e^+ e^-) = (1.10 \pm 0.25) \text{ nb}$$

taking into account a detection efficiency ϵ of about 4% and the J/ψ distribution as given in [1]. The value of ϵ has been obtained by simulation with real showers collected in a data base [11]. The analysis of simulated events has been performed with the same programs and the same selection criteria^(*) which have been used for the analysis of the experimental data. The obtained cross-section agrees with the value quoted in previous works [1]: $(1.0 \pm 0.2)\text{nb}$.

The distribution of the selected J/ψ 's versus x_F , the reduced longitudinal momentum, is shown on fig. 3(a). It is in agreement with the one calculated with the data from ref. [19]. The sharp drop at $x_F \approx 0.4$ is due to the finite acceptance of the spectrometer and to the criteria used for the selection.

(*) Criteria 5), 6) and 8) have not been taken into account in the simulation. Their use hardly modifies the number of events in the J/ψ peak by a few percent (so by putting $N < 8$ instead of $N < 7$ in criterium 8) the number of J/ψ 's increases by one unit) but decreases much the background.

The J/ψ transverse momentum distribution shows the exponential behaviour $\exp(-bp_T^2)$ in agreement with previous works (from data [19], $b = (1.4 \pm 0.2)\text{GeV}^{-2}\text{c}^2$ in the same X_F interval as considered here).

5. REACTION $\pi^- p \rightarrow \chi + \dots$

The next step in the data analysis is devoted to the search for events candidate of reaction (1) which give one J/ψ and one isolated photon in the final state. Therefore, events have been selected with an electron pair in the mass range of the J/ψ peak, $2.8 \text{ GeV}/c^2 < M_{ee} < 3.4 \text{ GeV}/c^2$, and with a photon satisfying the following criteria:

- a) a $\chi^2 < 5$ is obtained for the fit of the shower;
- b) no charged particle is observed in the corresponding counters of the hodoscope TH;
- c) in pairing it with any other observed photon, the effective mass of the pair lies outside the π^0 or η mass range;
- d) the photon energy $E_\gamma > 2 \text{ GeV}$.

The mass of the selected γee events has been evaluated fixing $M_{ee} = M_{J/\psi}$. The resulting mass spectrum (fig. 4(a)) shows a peak containing 10 events in the mass region $M_{\gamma J/\psi} \approx 3.5 \text{ GeV}/c^2$. It corresponds to χ -particles produced in reaction (1) and their subsequent decays (3),(4). By using a narrower mass interval for the accepted electron pairs, namely $3.0 \text{ GeV}/c^2 < M_{ee} < 3.3 \text{ GeV}/c^2$, the $M_{\gamma ee}$ mass spectrum becomes a peak with no visible background, its width being close to the resolution of the spectrometer for reactions (1), (3), (4).

The spectrum of the photons with an energy larger than 2 GeV associated with J/ψ 's is given on fig. 5.

The distributions of χ -particles versus X_F (fig. 6(a)) and p_T (fig. 6(b)) are analogous to those obtained with J/ψ particles, as already noticed at higher energies [3,8].

From the number of measured χ and J/ψ particles it is possible, knowing the efficiency of the apparatus, to estimate the cross-section $\sigma(\chi)$ for χ production in reaction (1) and also the fraction R of

J/ψ particles produced through the radiative decay (3):

$$R = \sum_J \sigma(\chi_J) \cdot BR(\chi_J \rightarrow \gamma J/\psi) / \sigma(J/\psi) \quad (6)$$

$\sigma(J/\psi)$ is the cross-section for J/ψ inclusive production (as well "direct" as through decay channels) in reaction (2).

Fig. 4 shows no evidence for the lowest P-state $\chi_0(3415)$ with spin $J = 0$ (3P_0) in the measured χ mass spectrum. This is in agreement with results from the Goliath group [8] but not with the data of ref. [7]. The absence of measured χ_0 contribution is related to the fact that the branching ratio $BR(\chi_J \rightarrow \gamma J/\psi)$ is 30 times lower for χ_0 than for χ_1 and χ_2 . The states $\chi_1(3510)$ and $\chi_2(3555)$ are not separated in the present experiment (fig. 4). As in previous works, [2-7] their production cross-sections have been taken equal: $\sigma(\chi_1) = \sigma(\chi_2)$. This has been confirmed by direct measurements [8] giving $\sigma(\chi_1)/\sigma(\chi_2) = 0.78 \pm 0.21$.

The detection efficiency for χ -particles produced in reaction (1), which subsequently decay according to (3) and (4), depends on the angular distribution of the decay products. This in turn is determined by the spin and parity of the χ states and by their production mechanism. The observed angular distribution of electrons from J/ψ particles is isotropic [1]. The detection efficiency for χ and J/ψ has been determined assuming isotropic decays for both particles (as in previous works [2-8]). The value of the fraction R (fig. 7) obtained in this way is

$$R = (\chi \rightarrow \gamma J/\psi) / (J/\psi) = 0.44 \pm 0.16 \quad (7)$$

Calculations [20] show that if light quark annihilation is the dominant production process, as expected at low energies, a large anisotropy $1 + \lambda \cos^2 \theta$ should be observed (θ is the angle of the positron relative to the beam direction in the χ rest frame). Such a distribution with $\lambda = 1$ would lead to a ratio $R = 0.41$. Using formulae given in [20], one gets $R = 0.47$ for the process $q\bar{q} \rightarrow c\bar{c}$ and by adding also the mechanism $g\bar{g} \rightarrow c\bar{c}$, R increases up to 0.49. If one takes carefully into account the motion of the quarks and gluons inside the hadrons [20] the difference between these values and the value (7) becomes even smaller. R thus depends only little on the precise form of the decay angular distribution.

The ($E_\gamma > 2$ GeV) photon spectrum from $\chi \rightarrow J/\psi + \gamma$ is only weakly dependent on the exact production mechanism (fig. 5).

Knowing the measured ratio (7) and the probability of the decays $\chi_J \rightarrow J/\psi + \gamma$ [21], one may evaluate the cross-section of reaction (1) induced by 38 GeV/c pions:

$$\sigma_{X_F > 0} (\pi^- p \rightarrow \chi + \dots) = (28 \pm 11) \text{nb}. \quad (8)$$

(x_F and p_T distribution as in [1]).

For the production cross-section of each χ_J state this gives $\sigma(\chi_1) = \sigma(\chi_2) = (14 \pm 5) \text{nb}$, which is twice larger than the "direct" production cross-section of J/ψ particles, $(7.5 \pm 2.5) \text{nb}$. The value (8) has been obtained using as input the cross-section of reaction (2) at the same energy, which is equal to $(14 \pm 3) \text{nb}$ [1].

The energy dependence of the cross-section is shown on fig. 8. As for other particle with hidden charm, the production cross-section may be parametrized as follows:

$$\sigma \sim \exp(-aM/\sqrt{s}) \quad (9)$$

The values of the parameter a for ψ' and χ production in $\pi^- N$ collisions are not very different.

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FIGURE CAPTIONS

Fig. 1 Experimental layout. H_3 , H_4 are 1 mm step two-dimensional hodoscopes; C_4 is a gas threshold Cerenkov counter for beam particle identification; S_4 , S_5 are the last scintillation counters which define the useful beam reaching the liquid hydrogen target (LH_2) (more upstream scintillation counters S_1 - S_3 , H_1 and H_2 hodoscopes, and also gas Cerenkov counters C_1 - C_3 are not shown on the figure); F_1 - F_3 , A, B, O are guard system counters; F_5 - F_6 are lead-scintillator sandwich counters; TH is a two-dimensional scintillation hodoscope with a hole of $9 \times 9 \text{ cm}^2$ in the center; GAMS-2000, a matrix of 48×32 lead-glass counters, is a hodoscope spectrometer.

Fig. 2 Effective mass spectrum of electron pairs. The arrows correspond to the known masses of J/ψ and ψ' particles. The curves fit the J/ψ peak (taking into account the resolution of the spectrometer, $\sigma_M/M = 3\%$) and the background. The thick line histogram corresponds to $E_{ee} > 21 \text{ GeV}$ and the hachured one corresponds to $E_{ee} > 23 \text{ GeV}$.

Fig. 3a) Distribution of events in the J/ψ peak versus X_F (thick line histogram). The dashed line corresponds to data [19] and the dashed-dotted curve is the result of a simulation taking into account the efficiency and the selection criteria. The thin line histogram is the background distribution, $M_{ee} < 2.8 \text{ GeV}/c^2$;

3b) distribution of J/ψ events versus the transverse momentum squared (thick line histogram); distribution of background events (thin line histogram). The first histogram varies like $\exp(-1.4 p_T^2)$.

Fig. 4a) Mass spectrum of selected $\gamma J/\psi$ events (hachured histogram). The arrows point to the known masses of χ_J states with different spin J. The thin line histogram correspond to the events which do not obey the selection criteria 8), 1'), 2') and 3') for e^+e^- pairs and the cut a) for photons accompanying J/ψ particles;

- 4b) the same for $3.0 \text{ GeV}/c^2 < M_{ee} < 3.3 \text{ GeV}/c^2$.

The curve corresponds to the calculated resolution of the spectrometer ($\sigma_M = 27 \text{ MeV}/c^2$, $\sigma_M/M = 0.8\%$).

Fig. 5 Energy spectrum of photons associated ($E_\gamma > 2 \text{ GeV}$) with J/ψ particles (hachured histogram). The curves correspond to Monte-Carlo calculations with various angular distributions for the decay of χ -particles taking into account the acceptance of the spectrometer and the selection criteria. The full curve corresponds to an isotropic distribution; the same result is obtained with a $1 + \cos^2 \theta'$ distribution. (θ' is the angle between the positron and the photon in the X rest frame). A very similar curve is obtained in the quark fusion model for $q\bar{q} \rightarrow \chi_1$ [20]. The dashed curve corresponds to $q\bar{q} \rightarrow \chi_2$ and the dashed-dotted line is for $gg \rightarrow \chi_2$ process (also after [20]).

Fig. 6a) Distribution of χ particles versus X_F (hachured histogram). J/ψ data from fig. 3a are also reported for comparison (thin lines);

- 6b) Integrated distribution over p_T^2 for χ particles and J/ψ particles (see Fig. 3b).

Fig. 7 Fraction (6) of J/ψ particles produced through decay (3): $M_\chi = 3.5 \text{ GeV}/c^2$, s is the center of mass energy squared. $\bullet$ are the data of the present work ($\pi^- p$ interactions); $\circ$, $\square$, $\diamond$, ∇ are the data given in [4-8] ($\pi^- \text{Be}$) and $\times$, Δ are the data [2,3] (pp).

Fig. 8a) Cross section of χ production in reaction (1) (3P_1 and 3P_2 states). $\sigma(\chi_1) \approx \sigma(\chi_2) \approx 1/2\sigma(\chi)$. The used symbols are defined in the previous figure caption. The curve is the cross-section (2) after data [1];

- 8b) cross-section for inclusive production of χ , J/ψ and ψ' particles in πN and pN collisions as a function of the scaling variable $M/\sqrt{s}$. Straight lines correspond to parametrization (9).

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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

FIG. 7

FIG. 8