論文の内容の要旨

Study of J/ψ production in 12 GeV proton-nucleus collisions (12 GeV陽子原子核衝突によるJ/ψ粒子生成の研究)

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Production of the J/ψ has the attractive feature that it can provide information on both perturbative and nonperturbative aspects of QCD. So far, the production cross section of the J/ψ by the hadron interactions has been measured in the wide center of mass energy range, $\sqrt{s} = 6.7$ GeV to 13 TeV. However, no measurements for the J/ψ production by hadron interactions at low energy near the production threshold have been carried out yet. Nonperturbative contributions to the J/ψ production are expected to become prominent at lower energy than the former experiments. The data of the low energy J/ψ production has been definitely required to investigate the nonperturbative aspect of QCD.

Intrinsic charm in a nucleon is one of the examples, whose existence has not been established. Intrinsic charm is a five particle Fock state component of a nucleon which includes a $c\bar{c}$ pair. The wavefunction of a proton is expressed as a superposition of Fock components

$$|p\rangle = \psi_{uud}\,|uud\rangle + \psi_{uudg}\,|uudg\rangle + \psi_{uudq\bar{q}}\,|uudq\bar{q}\rangle + \psi_{uudQ\bar{Q}}\,|uudQ\bar{Q}\rangle + \cdots ,$$

where q represents a light quark, Q represents a heavy quark, and ψ represents the wave function amplitude of each Fock component. The intrinsic charm $c\bar{c}$ Fock state in a proton is generated by virtual interaction such as $gg \to c\bar{c}$ where the gluons couple to two or more valence quark in a proton, while "extrinsic charm" is perturbatively generated by the gluon splitting $g \to c\bar{c}$. In pA collisions, for example, this intrinsic charm $c\bar{c}$ pair in a proton can be liberated by a collision of the proton and a target nucleus and can be evolved into a physical state of the J/ψ. The production cross section of the J/ψ from intrinsic charm is proportional to the amount of intrinsic charm, $P_{\rm IC}$, which is defined as

$$P_{\rm IC} = \int_0^1 dxc(x),$$

where $c(x)$ is a parton distribution function of intrinsic charm quark. Recent global QCD analyses predict the $P_{\rm IC}$ ranges from zero to 3%.

This thesis is dedicated to the analysis of the production cross section of the J/ψ in 12 GeV pA reactions, corresponding to the center of mass energy $\sqrt{s} = 5.1$ GeV. This is the lowest energy experiment for the J/ψ production by hadron interactions in all the experiments ever conducted. Actually, $\sqrt{s} = 5.1$ GeV is just above the threshold of the simplest final state ppJ/ψ, which is 4.97 GeV. Therefore one expects that the results of this study can provide crucial information on contributions of nonperturbative processes to the J/ψ production by hadron interactions. The measured production cross section of the J/ψ is compared to intrinsic charm contribution.

The data for this analysis has been obtained in 2001 and 2002 at High Energy Accelerator Research Organization (KEK) 12 GeV Proton-Synchrotron (PS) by the KEK-PS E325 experiment, which has measured the dielectron mass spectra. The spectrometer has been constructed at the primary beamline EP1-B in PS to detect vector mesons, ρ, ω, ϕ, and J/ψ mesons, decaying into the e^+e^- channel. This high intensity primary beam up to 1×10^9 per spill of two seconds enables the analysis on low-yield dielectron decays from vector mesons. The spectrometer consists of nuclear targets, a dipole magnet, tracking devices, and two arms for electron identification.

Nuclear targets were placed at the center of the dipole magnet. Primary protons with a typical intensity of 8.7×10^8 and 6.4×10^8 protons per spill were delivered to the targets in 2001 and 2002, respectively. To cope with this high intensity beam, the thin targets were used as the rate of γ conversions inside the targets is lower than the rate of the π^0 Dalitz decay of 1.2%. In 2001, one carbon and two copper targets were installed, while in 2002 one carbon and four copper targets were installed. The interaction length of the carbon target in 2001 and that in 2002 were 0.11% and 0.21%, respectively, and that of each copper target was 0.054% in both the years. The typical interaction rate was approximately 1.2 MHz in 2002.

The tracking devices consisted of a cylindrical drift chamber and a barrel-shaped drift chamber. These tracking devices were arranged inside a magnetic field provided by the dipole magnet. The strength of the field was 0.71 T at the center of the magnet. The integrated field over the interval between the center of the magnet to the outer most tracking device was 0.81 T·m.

Electron identification is performed with a combination of electron identification counters. They were divided into three stages. The first stage counter was front gas Cherenkov counters (FGC) covering from $\pm12^\circ$ to $\pm90^\circ$ horizontally and $\pm23^\circ$ vertically. The second stage counters consisted of three types of counters: rear gas Cherenkov counters (RGC), rear lead-glass calorimeters (RLG), and side lead-glass calorimeters (SLG). The RGC covered from $\pm12^\circ$ to $\pm54^\circ$ horizontally and $\pm6^\circ$ vertically. The RLG covered from $\pm12^\circ$ to $\pm54^\circ$ horizontally and from $\pm9^\circ$ to $\pm23^\circ$ vertically. The SLG covered from $\pm57^\circ$ to $\pm90^\circ$ horizontally and $\pm23^\circ$ vertically. These three counters of the second stage together covered nearly the same acceptance of the first stage. The third stage counter was forward lead-glass calorimeters (FLG) covering from 12° to 54° in the left arm and -12° to -40° in the right arm, horizontally and $\pm7^\circ$ vertically. The angular coverage of the third stage was limited to forward region and smaller compared to those of the first and second stages. Depending on the particle trajectories, two or three stages were used to identify electrons and positrons.

To evaluate the yields of the J/ψ, obtained invariant mass distributions of e^+e^- pairs is fitted with a sum of an exponential function, representing the background shape, and a J/ψ mass shape obtained with a simulation. The yields of the J/ψ are corrected according to DAQ live time, trigger efficiency, track reconstruction efficiency, vertex reconstruction efficiency, electron identification efficiency, detector acceptance, and the branching ratio to the e^+e^- channel. The total production cross sections of the J/ψ mesons are $7.0\ ^{+3.4}_{-3.1}(\text{stat.})\ ^{+2.9}_{-2.6}$ (syst.) nb and $3.8\ ^{+9.5}_{-3.8}(\text{stat.})\ ^{+2.8}_{-3.8}$ (syst.) nb for the carbon target and for the copper target, respectively. The 95% confidence level upper limits are 21 nb and 33 nb for the carbon target and for the copper target, respectively.

The results are compared to the theoretical calculation based on the non-relativistic QCD (NRQCD) which well reproduces the total production cross section of the J/ψ measured in former experiments. The total production cross section of the J/ψ for the copper target is consistent with the theoretical calculation based on the NRQCD on the assumption of $A^{0.9}$ dependence. However, the total production cross section of the J/ψ for the carbon target shows a slight excess from the theoretical calculation, even taking account of the possible uncertainty from the nuclear effect and the choice of parton distribution functions for the NRQCD calculation. This excess for the carbon target is examined in terms of intrinsic charm. The probability of intrinsic charm $P_{\rm IC}$ is found to be $0.09 \pm 0.06\%$, which is consistent with the result of recent global QCD analyses. This contribution of intrinsic charm to the J/ψ production is also not inconsistent with the J/ψ production cross sections obtained in former experiments in *pp* collisions. It should be noted that the excess due to intrinsic charm was not confirmed in the copper target and the measured cross section was consistent with the contribution of the conventional hard processes calculated with the NRQCD.

In conclusion, the total production cross section of the J/ψ was measured using the invariant mass spectrum of e^+e^- pairs at the KEK-PS E325 experiment. Due to a large experimental uncertainty, the production cross section of the J/ψ in the present study is consistent with the intrinsic charm scenario and the conventional scenario that the J/ψ production is only originated from hard processes.