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M. Ablikim *et al.* (BESIII Collaboration)

Phys. Rev. D **96**, 112001 — Published 4 December 2017

DOI: 10.1103/PhysRevD.96.112001

Branching fraction measurement of $J/\psi \to K_S K_L$ and search for $J/\psi \to K_S K_S$

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Using a sample of 1.31×10^9 J/ψ events collected with the BESIII detector at the BEPCII collider, we study the decays of $J/\psi \to K_S K_L$ and $K_S K_S$. The branching fraction of $J/\psi \to K_S K_L$ is determined to be $\mathcal{B}(J/\psi \to K_S K_L) = (1.93 \pm 0.01 \text{ (stat.)} \pm 0.05 \text{ (syst.)}) \times 10^{-4}$, which significantly improves on previous measurements. No clear signal is observed for the $J/\psi \to K_S K_S$ process, and the upper limit at the 95% confidence level for its branching fraction is determined to be $\mathcal{B}(J/\psi \to K_S K_S) < 1.4 \times 10^{-8}$, which improves on the previous searches by two orders in magnitude and reaches the order of the Einstein-Podolsky-Rosen expectation.

PACS numbers: 13.66.Bc, 13.25.Gv, 03.65.Vf

I. INTRODUCTION

The charmonium state J/ψ with a mass below the open charm threshold decays to light hadrons through the annihilation of $c\bar{c}$ into one virtual photon, three gluons or one photon and two gluons. The J/ψ decaying to $K_S K_L$ proceeds via the first two processes, thereby providing valuable information to understand the nature of J/ψ decays. The available measurements of its branching fraction, $\mathcal{B}(J/\psi \to K_S K_L)$, based on 57.7 million J/ψ events collected at BESII [1] and 24.5 million $\psi(3686)$ events at CLEO [2], are given by $(1.82 \pm 0.04 \pm 0.13) \times 10^{-4}$ and $(2.62 \pm 0.15 \pm 0.14) \times 10^{-4}$ respectively. Due to the discrepancy between these two measurements, the world average value in the particle data group (PDG) [3] has quoted a relative precision of 19%, which limits the precise understanding of J/ψ decay mechanisms.

In the CP-violating decay of J/ψ to $K_S K_S$, the two identical bosons from the decay would need to form an antisymmetric state, and the process would be ruled out according to Bose-Einstein statistics. However, according to the Einstein-Podolsky-Rosen (EPR) [4] paradox, the quantum state of a two-particle system can not always be decomposed into the joint state of the two particles. Thus the space-like separated coherent quantum system may also yield a sizable decay branching fraction of $J/\psi \to K_S K_S$ at the 10^{-8} level [5]. In this way, the $K_S K_S$ system can be used to test the EPR paradox versus quantum theory. There also might be a small possibility to have a $K_S K_S$ final state due to CP violation. In the $K^0 \bar{K}^0$ oscillation model [6], the CP violating branching fraction of $J/\psi \to K_S K_S$ is calculated to be $(1.94 \pm 0.20) \times 10^{-9}$. The MARKIII experiment searched for the decay $J/\psi \to K_S K_S$ with 2.7 million events, and the upper limit was determined to be $\mathcal{B}(J/\psi \to K_S K_S) < 5.2 \times 10^{-6}$ at the 90% confidence level (C.L.) [7]. Based on 57.7 million J/ψ events collected at the BESII detector, the upper limit on the branching fraction was improved to be 1.0×10^{-6} at the 95% C.L. [8], which is still far from the expectations from $K^0 - \bar{K}^0$ oscillation and EPR.

The world's largest J/ψ sample with 1.31×10^9 events was accumulated at BESIII during 2009 and 2012 [9]. In this paper, we measure the branching fraction of $J/\psi \to K_S K_L$, and also search for the CP violating decay $J/\psi \to K_S K_S$.

II. APPARATUS AND MONTE CARLO SIMULATION

The Beijing Spectrometer III (BESIII), located at the double-ring e^+e^- Beijing Electron Positron Collider (BEPCII), is a general purpose detector as described in Ref. [10]. It covers 93% of 4π in geometrical acceptance and consists of four main detectors. A 43-layer small-cell, helium gas based main drift chamber, operating in a 1.0 (0.9) T solenoidal magnetic field in 2009 (2012), provides an average single-hit resolution of 135 μm. A time-of-flight system, composed of 5 cm thick plastic scintillators with 176 bars of 2.4 m length, arranged in two layers in the barrel and 96 fan-shaped counters in the end-caps, has a time resolution of 80 ps (100 ps) in the barrel (end-caps) region providing 2σ K/π separation for momenta up to 1.0 GeV/c. An electromagnetic calorimeter, which consists of 5280 CsI(Tl) crystals arranged in a cylindrical structure in the barrel and 480 crystals in each of the two end-caps, provides an energy resolution for a 1.0 GeV/c photon of 2.5% in the barrel region and 5% in the end-caps. The position resolution is 6 mm (9 mm) in the barrel (end-caps). A muon counter system, which consists of resistive plate chambers arranged in nine barrel and eight end-cap layers, provides 2.0 cm position resolution.

The optimization of event selection criteria, the determination of detection efficiencies, and the estimation of background are performed by means of Monte Carlo (MC) simulations. The KKMC [11] generator is used to simulate the $J/\psi \to K^0 \bar{K}^0$ process. The angular distribution of the K^0 or $\bar{K}^0$ is generated to be proportional to $\sin^2\theta$, where θ is the polar angle in the laboratory system. In the MC simulation, the interference between the J/ψ resonance decay and the continuum process is ignored. A GEANT4-based [12, 13] detector simulation software, which includes the geometric and material description of the BESIII spectrometer, and the detector response, is used to generate the MC samples. The background is studied with a MC sample of 1.23×10^9 inclusive J/ψ decays, in which the known decays are generated with the EvtGen [14, 15] generator by setting the branching fraction to the values in the PDG [3] and the remaining unknown decays are generated with the LUNDCHARM [16].

III. BRANCHING FRACTION MEASUREMENT OF $J/\psi \to K_S K_L$

The K_S candidate is reconstructed from its charged $\pi^+\pi^-$ final state, while the K_L is assumed not to decay in the detector leaving only the signature of missing energy. The K_S candidates are reconstructed with vertex-constrained fits to pairs of oppositely charged tracks, assumed to be pions, whose polar angles satisfy the condition $|\cos\theta| < 0.93$. Only one K_S candidate is accepted in each event. The K_S candidates are required to satisfy $L >$1 cm and $L/\sigma_L > 2$, where L is the distance between the common vertex of the $\pi^+\pi^-$ pair and the interaction point and σ_L is its uncertainty. The invariant mass of the $\pi^+\pi^-$ pair, $M_{\pi^+\pi^-}$, shown in Fig. 1, is required to satisfy $|M_{\pi^+\pi^-} - M_{K_S}| < 18$ MeV/c^2, where M_{K_S} is the K_S nominal mass [3]. There should be no extra tracks satisfying $|\cos\theta| < 0.93$, within 1 cm of the interaction point in the transverse direction to the beam line and 10 cm of the interaction point along the beam axis. In order to suppress γ conversion background, the angle between the two charged tracks, $\theta_{\rm ch}$, is required to satisfy $\theta_{\rm ch} > 15^\circ$.

The same event selection criteria are applied to the inclusive MC sample. The major potential backgrounds are $J/\psi \to \pi^0 K_S K_L$ and $J/\psi \to \gamma K_S K_S$ events, but the leakage of their K_S momentum (P_{K_S}) spectra into the signal region is smooth and tiny.

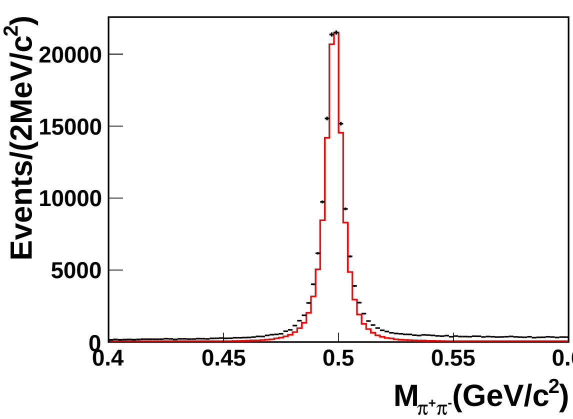

FIG. 1: (color online) The distribution of $M_{\pi^+\pi^-}$. The (black) crosses are from data, and the (red) histogram represents the signal MC sample.

The $J/\psi \to K_S K_L$ signal yield is determined from a maximum likelihood fit to the P_{K_S} distribution, as shown in Fig. 2. In the fit, the signal shape is described by a double Gaussian function with a common mean value and two different widths. The background shape is represented by a second-order Chebychev polynomial function.

The continuum process $e^+e^- \to K_S K_L$ is studied with a data set of 30.0 pb^{-1} taken at 3.080 GeV. The same selection criteria are applied. The result of the maximum likelihood fit to the P_{K_S} distribution is shown in Fig. 3. In the fit, the signal function is the same as that used in the fit of J/ψ data. The background shape is represented by a first-order Chebychev polynomial function.

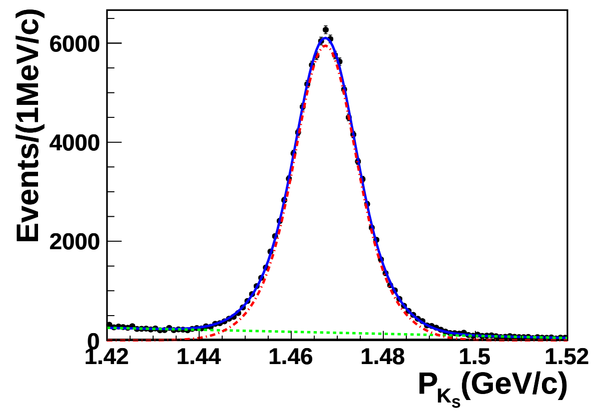

FIG. 2: (color online) The momentum distribution of K_S in the e^+e^- rest frame. The (black) crosses are from data, and the (blue) solid line is the fit result. The (red) long-dashed line is the signal, and the (green) short-dashed line is background.

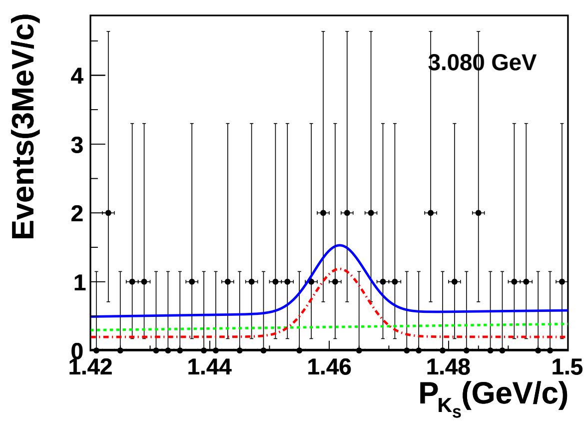

FIG. 3: (color online) The K_S momentum distribution for data taken at $\sqrt{s} = 3.080$ GeV. The (black) crosses are data, and the (blue) solid line is the fitting result. The (red) long-dashed line corresponds to the signal, and the (green) short-dashed line represents the background.

The event selection efficiencies are assumed to be the same at 3.080 GeV and the J/ψ resonance. The continuum contribution to the J/ψ resonance region is estimated from

$$N^{J/\psi}_{\rm cont} = N^{3.080}_{\rm obs} \cdot \frac{\mathcal{L} \cdot s'^3}{\mathcal{L}' \cdot s^3}, \quad (1)$$

where $N^{3.080}_{\rm obs}$ is the signal yield at 3.080 GeV, $\mathcal{L}$ and $\mathcal{L}'$ are the luminosities collected at the J/ψ and at 3.080 GeV, determined with $e^+e^- \to \gamma\gamma$ events [9], while s and s' correspond to the squares of center-of-mass energies of J/ψ and 3.080 GeV. The power law of the center-of-mass energy follows the K^+K^- cross section slope measured by BaBar [17].

Assuming no interference between the J/ψ decay and the continuum process, the branching fraction is determined from

$$\mathcal{B}(J/\psi \to K_S K_L) = \frac{N_{\rm obs}^{J/\psi} - N_{\rm cont}^{J/\psi}}{\epsilon \cdot N^{J/\psi} \cdot \mathcal{B}(K_S \to \pi^+\pi^-)}, \quad (2)$$

where $N_{\rm obs}^{J/\psi}$ is the number of signal events obtained in the J/ψ sample, ϵ is the event selection efficiency, $N^{J/\psi}$ is the number of J/ψ events [9] and $\mathcal{B}(K_S \to \pi^+\pi^-)$ is the branching fraction of $K_S \to \pi^+\pi^-$. Table I summarizes the values used in the calculation, and $\mathcal{B}(J/\psi \to K_S K_L)$ is determined to be $(1.93\pm0.01)\times10^{-4}$, where the quoted uncertainty is purely statistical.

TABLE I: Numbers used in the branching fraction calculation for the $K_S K_L$ channel, where the uncertainties are statistical only.

	3.097 GeV (J/ψ)	3.080 GeV
$N_{\rm obs}$	110203 ± 504	13 ± 5
ϵ (%)	62.9	62.9
$\mathcal{L}$ (pb^{-1})	394.7	30.9
$\mathcal{B}(K_S \to \pi^+\pi^-)$ [3]	0.692	0.692

The systematic uncertainties for the $\mathcal{B}(J/\psi \to K_S K_L)$ measurement include those due to K_S reconstruction, the requirement on $\theta_{\rm ch}$, the fit to the P_{K_S} spectrum, the branching fraction of the K_S decay, and the number of J/ψ events.

The K_S reconstruction involves the charged track reconstruction of the $\pi^+\pi^-$ pair, the vertex fit and the K_S mass window requirement. The corresponding systematic uncertainty is estimated using a control sample of $J/\psi \to K^{*\pm}(892)K^{\mp}$ events, where $K^{*\pm}(892) \to K_S\pi^{\pm}$. The momentum of the K_S, P_{K_S} in $J/\psi \to K_S K_L$ decay is around 1.46 GeV/c, thus only K_S candidates with momentum larger than 1 GeV/c in the control sample are considered. The ratio of the reconstruction efficiency of the data over that in the MC is taken as a correction factor to the $K_S K_L$ selection efficiency, while the uncertainty of the ratio, 1.4%, is taken as the systematic uncertainty.

The uncertainty from the $\theta_{\rm ch}$ requirement is estimated by varying the selection range. The range is expanded and contracted by 5°, and the largest change in the branching fraction with respect to the nominal value is taken as the systematic uncertainty.

The systematic uncertainty related to the fit method is estimated by varying the fit range and the background shape simultaneously. The fit range is expanded and contracted by 8 MeV/c. For the J/ψ data sample, the background shape is varied from a second-order Chebyshev polynomial function to a third-order Chebyshev polynomial function and an exponential function. For the continuum data sample, the background is replaced by a second-order Chebychev polynomial function. The largest change in the branching fraction is treated as the systematic uncertainty.

TABLE II: Systematic uncertainties for the measurement of branching fraction of the $K_S K_L$ channel.

Source	Uncertainty (%)
K_S reconstruction	1.4
$\theta_{\rm ch}$	1.0
Fit to P_{K_S}	1.9
$\mathcal{B}(K_S \to \pi^+\pi^-)$	0.1
$N_{J/\psi}$	0.6
Total	2.6

The branching fraction of $K_S \to \pi^+\pi^-$ is taken from the PDG [3] and its uncertainty is 0.1%. The number of J/ψ events and its uncertainty are determined with J/ψ inclusive decays [9].

The summary of all individual systematic uncertainties is shown in Table II, where the total uncertainty is obtained by adding the individual contributions in quadrature.

IV. SEARCH FOR $J/\psi \to K_S K_S$

For $J/\psi \to K_S K_S$ with $K_S \to \pi^+\pi^-$, the final state is $\pi^+\pi^-\pi^+\pi^-$. The candidate events are required to have at least four charged tracks whose polar angles satisfy $|\cos\theta| < 0.93$. The K_S candidates are reconstructed by secondary vertex fits to all oppositely charged track pairs assuming them to be pions, and the $\pi^+\pi^-$ invariant mass must be within 18 MeV/c^2 from the K_S nominal mass. The K_S candidates must have a momentum within the range of [1.40, 1.60] GeV/c. In order to suppress the non-K_S backgrounds, the decay length over its uncertainty (L/σ_L) has to be larger than 2.0. Each event must have at least two K_S candidates. If there are more than two K_S candidates, the combination with the smallest sum of χ^2 of the secondary vertex fits is selected.

The $K_S K_S$ candidates are then combined in a 4C kinematic fit, where the constraints are provided by energy and momentum conservation. Only events with $\chi^2 < 40$ are retained. The distribution of the K_S momentum in the J/ψ rest frame is shown in Fig. 4. The K_S momentum resolution is determined from the signal MC sample as $\sigma_w = 1.3$ MeV/c, which is the weighted average of the standard deviations of two Gaussians with common mean. The number of signal events is obtained by counting the remaining events within $5 \times \sigma_w$ of the expected momentum. After all requirements have been imposed, two events remain in this region.

The same selection criteria are applied to the inclusive MC sample, which shows that the background mainly comes from the processes $J/\psi \to \pi^+\pi^-\pi^+\pi^-$ and $J/\psi \to K_S K_L$. Their contributions are estimated from

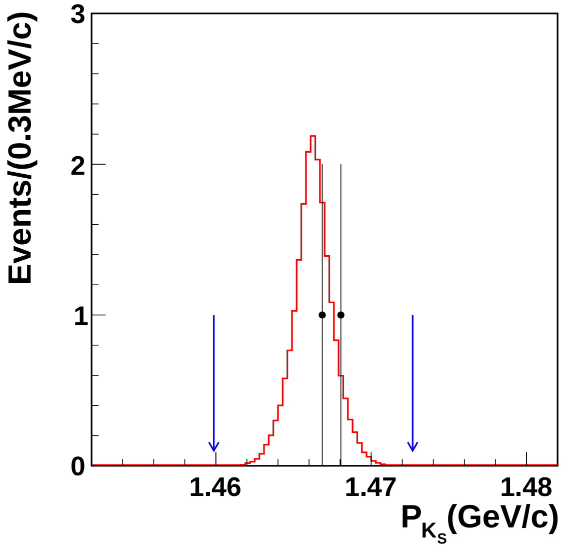

FIG. 4: (color online) The distribution of K_S momentum in the J/ψ rest frame. The (black) crosses are from data, and the (red) solid line is from the signal MC sample. The arrows indicate the $5\times\sigma_w$ selection region.

the corresponding MC samples using

$$N^X_{\rm exp} = N_{J/\psi} \cdot \mathcal{B}(J/\psi \to X) \cdot \epsilon^X_{K_S K_S}, \quad (3)$$

where X represents the corresponding channels $J/\psi \to \pi^+\pi^-\pi^+\pi^-$ or $J/\psi \to K_S K_L (K_S \to \pi^+\pi^-)$, and N^X_{exp} is the expected number of events from channel X. $\mathcal{B}(J/\psi \to X)$ is the product branching fractions of the cascade decay, where $\mathcal{B}(J/\psi \to \pi^+\pi^-\pi^+\pi^-)$ is taken from the PDG [3], $\mathcal{B}(J/\psi \to K_S K_L)$ is set to the value obtained in this paper, and $\epsilon^X_{K_S K_S}$ is the $K_S K_S$ selection efficiency for a sample of X events. The efficiencies of $J/\psi \to \pi^+\pi^-\pi^+\pi^-$ and $K_S K_L$ channels are $(1.9\pm0.6)\times10^{-7}$ and $(8.5\pm3.4)\times10^{-6}$, respectively. The expected background numbers are calculated to be $N^{\pi^+\pi^-\pi^+\pi^-}_{\rm exp} = 0.9 \pm 0.3$ and $N^{K_S K_L}_{\rm exp} = 1.5 \pm 0.6$, where the uncertainties are from propagation of the items in equation 3. Some other exclusive processes, such as $J/\psi \to \gamma K_S K_S$, are also studied with high statistics MC samples, but none of them survive the event selection.

Table III summarizes the systematic uncertainties in the search for $J/\psi \to K_S K_S$. Common uncertainties including those from the number of J/ψ decays and the $K_S \to \pi^+\pi^-$ branching fraction are the same as described in Section III. The uncertainty from K_S reconstruction is evaluated according to the K_S selection criteria used in this channel, with a method similar to that in Section III, and is determined to be 1.5% per K_S. The uncertainty from the 4C kinematic fit is investigated using the control sample of $J/\psi \to \gamma K_S K_S$, and the difference of the efficiency between the data and MC samples is taken as the systematic uncertainty associated with the kinematic fit.

TABLE III: The systematic uncertainties related to the search for $J/\psi \to K_S K_S$.

Source	Uncertainty (%)
K_S reconstruction	3.0
4C kinematic fit	1.1
$\mathcal{B}(K_S \to \pi^+\pi^-)$	0.2
$N_{J/\psi}$	0.6
Total	3.2

Since we have not observed a significant signal, an upper limit for $\mathcal{B}(J/\psi \to K_S K_S)$ is set at the 95% C.L. The upper limit is calculated using the relation

$$\mathcal{B}(J/\psi \to K_S K_S) < \frac{N^{\rm UL}}{\epsilon_{\rm MC} \cdot N_{J/\psi}}. \quad (4)$$

where $N^{\rm UL}$ is upper limit on the number of signal events estimated with $N_{\rm obs}$ and $N_{\rm bkg}$ using a frequentist approach with the profile likelihood method, as implemented in the ROOT framework [18], and $\epsilon_{\rm MC}$ is the detection efficiency. The calculation includes statistical fluctuations and systematic uncertainties. The signal and background fluctuations are assumed to follow Poisson distributions, while the systematic uncertainty is taken to be a Gaussian distribution. The branching fraction of $K_S \to \pi^+\pi^-$ is included in the event selection efficiency $\epsilon_{\rm MC}$. The values of variables used to calculate the upper limit on the branching fraction and the final result are summarized in Table IV, where the $N_{\rm bkg}$ is the sum of $N^{\pi^+\pi^-\pi^+\pi^-}_{\rm exp}$ and $N^{K_S K_L}_{\rm exp}$.

TABLE IV: Numbers used in the $\mathcal{B}(J/\psi \to K_S K_S)$ calculation of the upper limit on the signal yield at the 95% C.L.

$N_{\rm obs}$	2
$N_{\rm bkg}$	2.4
$N^{\rm UL}$	4.7
$\epsilon_{\rm MC}$(%)	25.7
$\mathcal{B}(J/\psi \to K_S K_S)$ (95% C.L.)	$< 1.4 \times 10^{-8}$

V. SUMMARY

Based on a data sample of 1.31×10^9 J/ψ events collected with the BESIII detector, the measurements of $J/\psi \to K_S K_L$ and $K_S K_S$ have been performed. The branching fraction of $J/\psi \to K_S K_L$ is determined to be $\mathcal{B}(J/\psi \to K_S K_L) = (1.93 \pm 0.01\ ({\rm stat.}) \pm 0.05\ ({\rm syst.})) \times 10^{-4}$, which agrees with the BESII measurement [1] while discrepancy with the CLEO data [2] persists. Compared with the world average value listed in the PDG [3], the relative precision is greatly improved, while the central value is consistent. With regard to the search for the CP and Bose-Einstein statistics violating process $J/\psi \to K_S K_S$, an upper limit on its branching fraction is set at the 95% C.L. to be $\mathcal{B}(J/\psi \to K_S K_S) < 1.4 \times 10^{-8}$, which is an improvement by two orders in magnitude compared to the best previous searches [7, 8]. The upper limit reaches the order of the EPR expectations[5].

VI. ACKNOWLEDGEMENT

The BESIII collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. This work is supported in part by National Key Basic Research Program of China under Contract No. 2015CB856700; National Natural Science Foundation of China (NSFC) under Contracts Nos. 11235011, 11335008, 11425524, 11625523, 11635010; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the CAS Center for Excellence in Particle Physics (CCEPP); Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts Nos. U1232105, U1332201, U1532257, U1532258; CAS under Contracts Nos. KJCX2-YW-N29, KJCX2-YW-N45, QYZDJ-SSW-SLH003; 100 Talents Program of CAS; National 1000 Talents Program of China; INPAC and Shanghai Key Laboratory for Particle Physics and Cosmology; German Research Foundation DFG under Contracts Nos. Collaborative Research Center CRC 1044, FOR 2359; Istituto Nazionale di Fisica Nucleare, Italy; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS; Koninklijke Nederlandse Akademie van Wetenschappen (KNAW) under Contract No. 530-4CDP03; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Natural Science Foundation of China (NSFC) under Contract No. 11505010; National Science and Technology fund; The Swedish Resarch Council; U. S. Department of Energy under Contracts Nos. DE-FG02-05ER41374, DE-SC-0010118, DE-SC-0010504, DE-SC-0012069; University of Groningen (RuG) and the Helmholtzzentrum für Schwerionenforschung GmbH (GSI), Darmstadt; WCU Program of National Research Foundation of Korea under Contract No. R32-2008-000-10155-0.

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