Nuclear Modification of ψ', χ_c, and J/ψ Production in d + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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(Received 24 May 2013; revised manuscript received 29 August 2013; published 12 November 2013)

We present results for three charmonia states (ψ', χ_c, and J/ψ) in d + Au collisions at $|y| < 0.35$ and $\sqrt{s_{NN}} = 200$ GeV. We find that the modification of the ψ' yield relative to that of the J/ψ scales approximately with charged particle multiplicity at midrapidity across $p + A$, d + Au, and $A + A$ results from the Super Proton Synchrotron and the Relativistic Heavy Ion Collider. In large-impact-parameter collisions we observe a similar suppression for the ψ' and J/ψ, while in small-impact-parameter collisions the more weakly bound ψ' is more strongly suppressed. Owing to the short time spent traversing the Au nucleus, the larger ψ' suppression in central events is not explained by an increase of the nuclear absorption owing to meson formation time effects.

DOI: 10.1103/PhysRevLett.111.202301 PACS numbers: 25.75.Dw

Understanding the evolution of heavy quark-antiquark pairs into bound color singlet quarkonium states represents a challenge within quantum chromodynamics. An excellent tool for probing the time scale for this evolution is the measurement of production rates for multiple quarkonium states, with different physical sizes and binding energies, in proton- or deuteron-nucleus collisions. The evolving quark-antiquark pair must traverse the target nucleus, and by varying the path length in the nucleus one can probe this time scale.

Measurements of J/ψ and ψ' production rates at $\sqrt{s_{NN}} = 38.7$ GeV, as a function of Feynman-x (x_F), in proton-nucleus collisions by E866/NuSea [1] show a greater suppression of ψ' compared to J/ψ production near $x_F \approx 0$, and a comparable suppression for $x_F > 0$. Similar measurements by NA50 [2] at $\sqrt{s_{NN}} = 27.4$ GeV and $x_F \approx 0$ show a stronger suppression of ψ', compared to J/ψ production for larger nuclei. This has been interpreted as an effect of the charmonia formation time [3]. When the time spent traversing the nucleus by the $c\bar{c}$ pair becomes longer than the charmonia formation time, the larger ψ' meson will be further suppressed by a larger nuclear breakup effect. It is critical to test these assumptions at the collision energies provided by the Relativistic Heavy Ion Collider (RHIC), where the time spent traversing the nucleus is expected to be much shorter than this formation time.

Also, the binding energy of the ψ' (≈ 0.05 GeV) is significantly smaller than that of the χ_c (≈ 0.20 GeV) or J/ψ (≈ 0.64 GeV) [4], and may play an important role in understanding the effects of producing quarkonia in a nuclear target.

The PHENIX experiment has previously reported measurements of J/ψ production rates in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV using data collected in 2008 [5,6]. Here, we present measurements of ψ' production rates, as well as the fraction of J/ψ yield which comes from χ_c decays, in d + Au collisions at midrapidity from the same data set. Using the corresponding measurements in $p + p$ collisions by PHENIX [7], we construct the nuclear modification factor, $R_{d\mathrm{Au}}$, for ψ' and χ_c production and compare it with the measurements of the J/ψ $R_{d\mathrm{Au}}$ at the same energy.

The PHENIX detector is described in detail in Ref. [8]. The data presented here were collected using the two PHENIX central arms, each of which detect electrons, photons, and hadrons over $|\eta| < 0.35$ and $\Delta\phi = \pi/2$. The d + Au data used in this analysis were recorded using a minimum bias (MB) trigger in coincidence with an additional electron level-1 trigger. The MB trigger requires at least one hit in each of the two beam-beam counters (BBCs) covering $3 < |\eta| < 3.9$. This MB selection covers $(88 \pm 4)\%$ of the total d + Au inelastic cross section of 2.26 barns [9]. The electron trigger requires a minimum energy deposited in any group of 2×2 towers in the electromagnetic calorimeter and an associated hit in the ring imaging Čerenkov counter. Thresholds of 600 and 800 MeV were used, each for roughly half of the data sample. The data set represents analyzed integrated luminosities of 62.7 and 66.2 nb^{-1} for the ψ' and χ_c analyses, respectively.

The ψ' invariant yield is calculated as

$$B_{ee}\frac{dN_{\psi'}}{dy} = \frac{cN_{\psi'}}{N_{\mathrm{MB}}\epsilon A \Delta y}, \tag{1}$$

where B_{ee} is the $\psi' \to e^+e^-$ branching ratio, $N_{\psi'}$ is the measured $\psi' \to e^+e^-$ yield, N_{MB} is the number of sampled MB events, and Δy is the width of the rapidity bin. A GEANT-3 based model of the PHENIX detector combined with measurements of the momentum dependence of the single electron trigger efficiency, as described in Ref. [6], is used to calculate the product of the acceptance and efficiency ϵA, which includes the level-1 trigger efficiency. This model is also used to estimate the detector effects on the simulated signal and background line shapes when fitting the measured dielectron signal. Following the procedures described in Ref. [6], ϵA is found to have an average value of 0.91% with a relative systematic uncertainty of 6.4%. The correction factor c accounts for the trigger and centrality bias present in events which contain a hard scattering [6]. The track multiplicity dependence of the reconstruction efficiency is negligible in d + Au collisions, and a 1% systematic uncertainty was assigned based on the J/ψ studies performed in Ref. [6].

The $\psi' \to e^+e^-$ yield is extracted from fits to the unlike-sign (e^+e^-) invariant mass distribution, after the subtraction of the like-sign ($e^+e^+ + e^-e^-$) background, where at least one of the electrons fired the level-1 trigger. The fit is performed over the mass range $2.0 < M_{ee}[\mathrm{GeV}/c^2] < 5.5$, and includes line shapes for $J/\psi \to e^+e^-$ and $\psi' \to e^+e^-$ decays, as well as the remaining correlated background from open heavy flavor and Drell-Yan decays.

The J/ψ and ψ' line shapes include the natural line shape, smeared based on the PHENIX mass resolution, and radiative decays ($J/\psi \to e^+e^-\gamma$ for $E_\gamma > 100$ MeV), using calculations of the mass distribution from quantum electrodynamics [10]. The line shape for Drell-Yan decays was generated using PYTHIA-6 [11]. Line shapes for open heavy flavor decays were generated using three different Monte Carlo (MC) generators, including PYTHIA-6 in both hard scattering and forced charm (or bottom) production modes as well as the MC at next-to-leading-order (MC@NLO) generator [12]. Input parton distribution functions CTEQ6L and CTEQ6M [13] were used for PYTHIA-6 and MC@NLO, respectively.

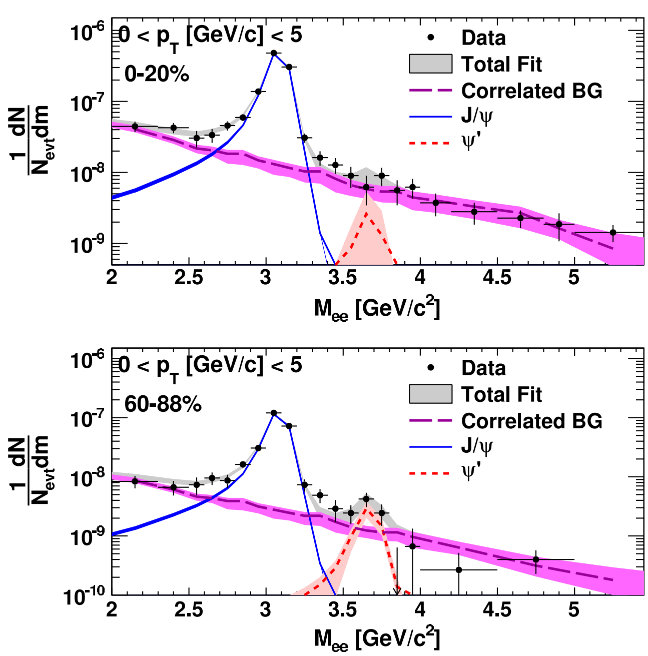

FIG. 1 (color online). The e^+e^- mass distribution, after like-sign subtraction, for (0–20)% (top) and (60–88)% (bottom) d + Au collisions. The line shapes are those fit to the data to extract the ψ' yield. The simulated line shapes are drawn as lines connecting yields integrated over the width of the bin and plotted at the center of each bin, as is done with the data.

After applying the detector acceptance and efficiency effects, the line shapes are fit to the invariant mass distributions.

It was found that the heavy flavor line shapes generated using PYTHIA-6 set to hard scattering mode gave the lowest χ^2 per degree of freedom (68.5/68), while those generated using PYTHIA-6 set to charm (bottom) production as well as those generated using MC@NLO provided slightly poorer agreements with a χ^2 per degree of freedom of 79.1/68 and 83.4/68, respectively. The different line shapes resulted in changes in the extracted ψ' yield of less than 20% in peripheral events. In central events a ψ' peak is barely discernible. Fits using the different assumed shapes gave ψ' yields which varied by up to 83%; however, all required a nonzero ψ' yield within the fit uncertainty. In all cases, the continuum line shapes were generated for $p + p$ collisions, and may be modified in d + Au collisions. The effect of nuclear shadowing on the Drell-Yan and open heavy flavor line shapes using the EPS09S parametrization [14] was found to change the extracted ψ' yield by less than 5%.

Figure 1 shows the results of the fit for central and peripheral d + Au collisions. The shaded bands represent the combined uncertainty in the fit normalizations, as well as changes in the shape of the correlated background obtained using the three different sets of open heavy flavor line shapes.

The resulting invariant yields are used, in conjunction with the measured values in $p + p$ collisions [7], to calculate the nuclear modification factor $R_{d\mathrm{Au}}$. The ψ' $R_{d\mathrm{Au}}$ is calculated as

$$R^{\psi'}_{d\mathrm{Au}} = \frac{dN^{d\mathrm{Au}}_{\psi'}/dy}{N_{\mathrm{coll}} dN^{pp}_{\psi'}/dy}, \qquad (2)$$

where N_{coll} is the mean number of nucleon-nucleon collisions, and $dN^{d\mathrm{Au}}_{\psi'}/dy$ and $dN^{pp}_{\psi'}/dy$ are the measured invariant yields in d + Au and $p + p$ collisions, respectively. The value of N_{coll} is calculated using a Glauber MC model coupled with a simulation of the PHENIX BBC response (see [6] for details). The (0–100)% centrality integrated $R^{\psi'}_{R_{d\mathrm{Au}}}$ is given in Table I.

The feed-down fraction of the inclusive J/ψ yield from χ_c decays in d + Au collisions ($F^{d\mathrm{Au}}_{\chi_c \to J/\psi}$) is measured via the $\chi_c \to J/\psi + \gamma \to e^+e^- + \gamma$ decay channel, where the $e^+e^-\gamma$ is fully reconstructed in the PHENIX central arms. The procedure for extracting $F^{d\mathrm{Au}}_{\chi_c \to J/\psi}$ is the same as that presented for $p + p$ collisions in [7] for a data sample

TABLE I. A comparison of the (0–100)% centrality integrated $R_{d\mathrm{Au}}$ values for the different charmonium states. The quoted uncertainties are statistical followed by systematic uncertainties. The binding energies are taken from Ref. [4].

Charmonia state	Binding energy [GeV/c]	$R_{d\mathrm{Au}}$
$\psi' \to e^+e^-$	0.05	$0.54 \pm 0.11^{+0.19}_{-0.16}$
$\chi_c \to e^+e^-$	0.20	$0.77 \pm 0.41 \pm 0.18$
Feed-down corrected $J/\psi \to e^+e^-$	0.64	$0.81 \pm 0.12 \pm 0.23$

of comparable statistical precision. The final feed-down fraction is found to be $F^{d\mathrm{Au}}_{\chi_c \to J/\psi} = 0.32 \pm 0.09(\mathrm{stat}) \pm 0.03(\mathrm{syst})$.

Using the measured feed-down fraction in $p+p$ collisions and the J/ψ $R_{d\mathrm{Au}}$, the χ_c $R_{d\mathrm{Au}}$ is calculated as

$$R^{\chi_c}_{d\mathrm{Au}} = R^{J/\psi}_{d\mathrm{Au}} \frac{F^{d\mathrm{Au}}_{\chi_c \to J/\psi}}{F^{pp}_{\chi_c \to J/\psi}}. \quad (3)$$

The nuclear modification of χ_c production in $d+\mathrm{Au}$ collisions is given in Table I.

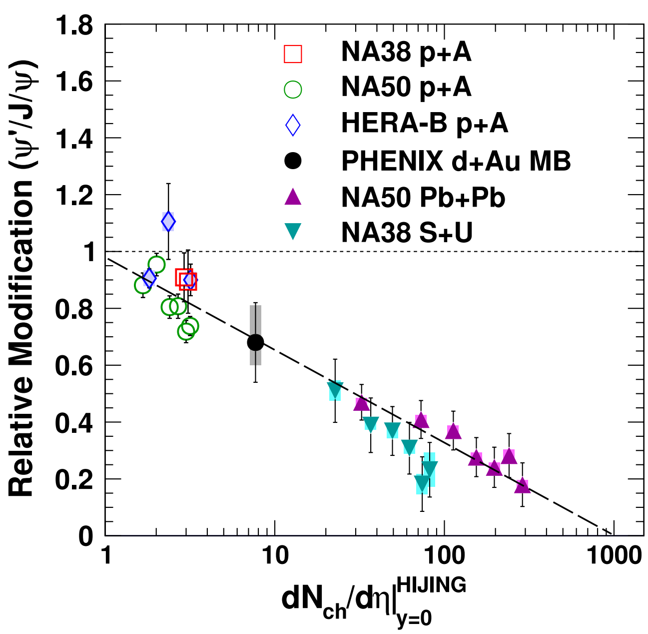

FIG. 2 (color online). The relative modification of the ψ' to the J/ψ as a function of $dN_{ch}/d\eta|_{y=0}$. The plotted data include NA38 [2] $p+A$ at $\sqrt{s_{NN}} = 19.4$ GeV, NA50 [19] $p+A$ at $\sqrt{s_{NN}} = 27.4$ GeV, HERA-B [20] $p+A$ at $\sqrt{s_{NN}} = 41.5$ with a global uncertainty of $\pm 4.4\%$, PHENIX $d+\mathrm{Au}$ at $\sqrt{s_{NN}} = 200$ GeV with a global uncertainty of $\pm 24\%$, NA50 [21] Pb + Pb at $\sqrt{s_{NN}} = 17.2$ GeV, and NA38 [21] S + U at $\sqrt{s_{NN}} = 19.4$ GeV. The Super Proton Synchrotron (SPS) and Hadron-Electron-Ring Accelerator (HERA-B) results are calculated using the extrapolated $p+p$ ψ' to J/ψ ratios quoted in the respective references. There is a common global uncertainty in the SPS points of 5% owing to the uncertainty in the $p+p\,\psi'/J/\psi$ ratio. The dashed line is included only to guide the eye.

With the ψ' and χ_c nuclear modification in hand, it is possible to correct the measured modification of inclusive J/ψ production for their feed-down effects, thus giving a closer representation of the modification of direct J/ψ production. Here we use the ψ' and χ_c feed-down fractions in $p+p$ collisions measured by PHENIX in Ref. [7]. The corrected J/ψ modification is calculated as

$$R^{\mathrm{direct}J/\psi}_{d\mathrm{Au}} = \frac{(R^{\mathrm{incl}J/\psi}_{d\mathrm{Au}} - F^{pp}_{\psi' \to J/\psi} R^{\psi'}_{d\mathrm{Au}} - F^{pp}_{\chi_c \to J/\psi} R^{\chi_c}_{d\mathrm{Au}})}{(1 - F^{pp}_{\psi' \to J/\psi} - F^{pp}_{\chi_c \to J/\psi})}, \quad (4)$$

where $R^{\mathrm{incl}J/\psi}_{d\mathrm{Au}} = 0.77 \pm 0.02(\mathrm{stat}) \pm 0.16(\mathrm{syst})$ is the modification of inclusive J/ψ production, reported in Ref. [5]. The feed-down corrected J/ψ modification is given in Table I. While there still remains a contribution from $B \to J/\psi + X$ decays, its value is expected to be small ($\approx 2.7\%$ [15]). When comparing the nuclear modification of the three charmonium states, we find that they are consistent within the current uncertainties, though they are also consistent with a decrease in suppression with increasing binding energy. To reduce the systematic uncertainties we proceed to take the ratio of nuclear modification factors.

Figure 2 compares the PHENIX results to data taken at different collision energies and species by plotting the relative modification of ψ' to J/ψ production ($R^{\psi'}_{d\mathrm{Au}}/R^{\mathrm{incl}J/\psi}_{d\mathrm{Au}}$) as a function of charged particle multiplicity calculated from HIJING [16]. In the ratio, $R^{\mathrm{incl}J/\psi}_{d\mathrm{Au}}$ is integrated only over $0 < p_T[\mathrm{GeV}/c] < 5$ to match the p_T range of the ψ' results. When taking the ψ' to J/ψ ratio, a number of uncertainties cancel or are reduced, such as the uncertainty in ϵA. Nuclear effects that are common between the J/ψ and ψ' (such as nuclear shadowing) will also cancel. The trend observed in Fig. 2 may arise from a mixture of cold ($p+A$) and hot ($A+A$) nuclear matter effects. However, it may indicate that interactions with final-state hadrons play a role even in smaller colliding systems and in particular for the larger ψ', as in the framework of comover models [17]. The ψ' $R_{d\mathrm{Au}}$ is further calculated for different centrality bins matched to those used in the previous J/ψ analyses [5,6].

Figure 3 shows ψ' $R_{d\mathrm{Au}}$ as a function of N_{coll}, with the same centrality binning used in [5]. Also shown in Fig. 3 is the previously published J/ψ $R_{d\mathrm{Au}}$ [5], here integrated

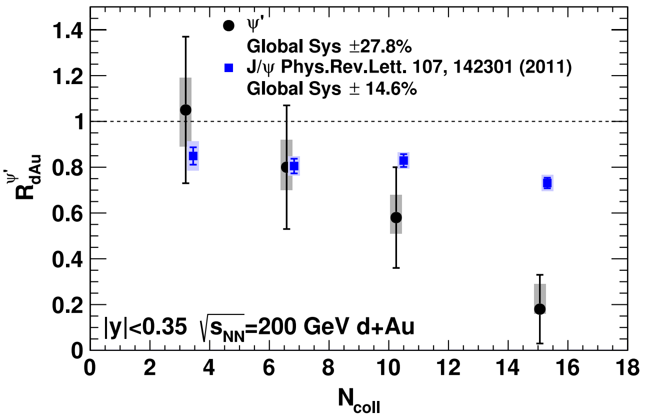

FIG. 3 (color online). The ψ' and J/ψ [5] $R_{d\mathrm{Au}}$ as a function of N_{coll}. Note that the $J/\psi R_{d\mathrm{Au}}$ plotted here is not corrected for ψ' and χ_c feed-down, and the N_{coll} values are shifted slightly to aid in clarity.

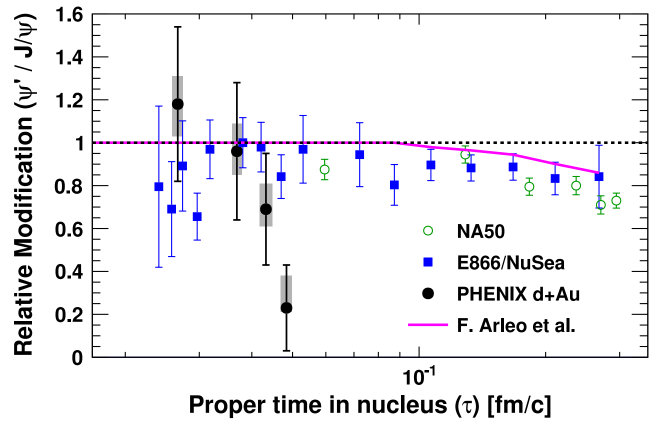

FIG. 4 (color online). The relative modification of the ψ' to the J/ψ as a function of the proper time spent by the quarkonia (or $c\bar{c}$ precursor) in the nucleus. The data include NA50 [19] $p+A$ at 400 GeV/nn, E866/NuSea [1] $p+A$ at 800 GeV/nn and PHENIX d + Au at $\sqrt{s_{NN}} = 200$ GeV which include a global systematic uncertainty of $\pm 24\%$. The E866/NuSea points are calculated for ψ' and J/ψ modifications in similar rapidity intervals. The curve is a calculation by Arleo *et al.* [3] discussed in the text.

over the full rapidity coverage of the central arm. We observe a strong suppression of ψ' production with increasing N_{coll}. The observed suppression in the (0–20)% most central d + Au collisions (large N_{coll}) is a factor of ≈ 3 times larger than the observed suppression for inclusive J/ψ production.

Reference [3] presents a model that explains the lower energy E866/NuSea and NA50 results using an expanding color neutral $c\bar{c}$ pair. As the $c\bar{c}$ expands, it has an increased nuclear absorption owing to its larger physical size. Once the time spent by the $c\bar{c}$ pair traversing the nucleus becomes larger than the J/ψ formation time, the ψ' will see a larger nuclear absorption owing to its larger size ($r_0 \approx 0.9$ fm for the ψ' and $r_0 \approx 0.5$ fm for the J/ψ [4]). This explains the transition from a similar level of suppression between the J/ψ and ψ' at high x_F to a larger suppression of the ψ' relative to the J/ψ at $x_F \approx 0$ observed by E866/NuSea.

This idea is tested at RHIC energies by calculating the average proper time τ spent in the nucleus by the quarkonia (or $c\bar{c}$ precursor). The τ is calculated as $\tau = \langle L \rangle / (\beta_z \gamma)$, where $\langle L \rangle$ is the longitudinal path of the $c\bar{c}$ through the nucleus and β_z is the velocity of the quarkonia along the beam direction in the nuclear rest frame. Here, β_z is calculated using the $\langle p_T \rangle$ of the J/ψ. The $\langle L \rangle$ values for each PHENIX centrality bin are calculated using the same Glauber MC model used to determine N_{coll} and have a systematic uncertainty owing to the Glauber input values of less than 5%.

Figure 4 shows the relative modification of the ψ' to the J/ψ as a function of τ, where the E866/NuSea and NA50 results have also been included. The solid curve is the calculation by Arleo *et al.* [3], which is consistent with the trends observed by E866/NuSea and NA50.

The values of τ for the PHENIX data are similar to the $c\bar{c}$ formation and color neutralization time of ≈ 0.05 fm/c, and well below the J/ψ formation time of ≈ 0.15 fm/c [3]. Therefore the model cannot explain the strong differential suppression of the ψ' in the PHENIX data. We note that Ref. [18] shows that the extracted breakup cross section for the inclusive J/ψ displays a strong departure of the E866/NuSea result from τ scaling below ≈ 0.05 fm/c, indicating the presence of different effects that modify charmonium production at short time scales. The PHENIX data further indicate that there are effects at short crossing time scales that can differentially suppress the ψ' relative to the J/ψ.

In summary, we have presented measurements of ψ' production, as well as the J/ψ feed-down fraction from χ_c decays, in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Using the corresponding measurements in $p+p$ collisions, we have obtained the nuclear modification factor $R_{d\mathrm{Au}}$ for ψ' and χ_c production. We find that the relative modification of ψ' to inclusive J/ψ measured by PHENIX follows the same approximate scaling with the charged particle multiplicity measured at midrapidity as lower energy data. We further find that ψ' production is heavily suppressed in central d + Au collisions relative to J/ψ production. Because the nuclear crossing time is very short, this cannot be explained by the difference in size of the fully formed ψ' and J/ψ. It instead suggests that there is a process occurring on the time scale of $c\bar{c}$ formation that differentially suppresses the ψ'.

We thank the staff of the collider-accelerator and physics departments at Brookhaven National Laboratory and the staff of the other PHENIX participating institutions for their vital contributions. We acknowledge support from the Office of Nuclear Physics in the Office of Science of the Department of Energy, the National Science Foundation, Abilene Christian University Research Council, Research Foundation of SUNY, and Dean of the College of Arts and Sciences, Vanderbilt University (U.S.), Ministry of Education, Culture, Sports, Science, and Technology and the Japan Society for the Promotion of Science (Japan), Conselho Nacional de Desenvolvimento Científico e Tecnológico and Fundação de Amparo à Pesquisa do Estado de São Paulo (Brazil), Natural Science Foundation of China (People's Republic of China), Ministry of Education, Youth and Sports (Czech Republic), Centre National de la Recherche Scientifique, Commissariat à l'Énergie Atomique, and Institut National de Physique Nucléaire et de Physique des Particules (France), Bundesministerium für Bildung und Forschung, Deutscher Akademischer Austausch Dienst, and Alexander von Humboldt Stiftung (Germany), Hungarian National Science Fund, OTKA (Hungary), Department of Atomic Energy and Department of Science and Technology (India), Israel Science Foundation (Israel), National Research Foundation and WCU program of the Ministry Education Science and Technology (Korea), Ministry of Education and Science, Russian Academy of Sciences, Federal Agency of Atomic Energy (Russia), VR and Wallenberg Foundation (Sweden), the U.S. Civilian Research and Development Foundation for the Independent States of the former Soviet Union, the U.S.-Hungarian Fulbright Foundation for Educational Exchange, and the U.S.-Israel Binational Science Foundation.

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