Production of new charmonium-like states in $e^+e^- \rightarrow J/\psi D^{(*)} \bar{D}^{(*)}$ at $\sqrt{s} \approx 10.6$ GeV

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arXiv:0708.3812v2 [hep-ex] 5 Oct 2007
We present a study of the $X(3940)$ state in the process $e^+e^- \rightarrow J/\psi D^*\overline{D}$. The $X(3940)$ mass and width are measured to be $(3942^{+7}_{-6} \pm 6)$ MeV/$c^2$ and $\Gamma = (37^{+26}_{-15} \pm 8)$ MeV. In the process $e^+e^- \rightarrow J/\psi D^{*+}D^{*-}$ we have observed another charmonium-like state, which we denote as $X(4160)$, in the spectrum of invariant masses of $D^{*+}D^{*-}$ combinations. The $X(4160)$ parameters are $M = (4156^{+25}_{-26} \pm 15)$ MeV/$c^2$ and $\Gamma = (139^{+111}_{-61} \pm 21)$ MeV. The analysis is based on a data sample with an integrated luminosity of 693 fb$^{-1}$ recorded near the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB $e^+e^-$ asymmetric-energy collider.

PACS numbers: 13.66.Bc,12.38.Bx,14.40.Gx

Double charmonium production in $e^+e^-$ annihilation, first observed by Belle in 2002 [1], can be used to search for new charmonium states, recoiling against some known and easily reconstructed charmonium. The study of various double charmonium final states [2, 3] demonstrated that there is no significant suppression of the production of radially excited states: the cross-sections for $J/\psi\eta_c$, $\psi(2S)\eta_c$, $J/\psi\eta_c(2S)$ and $\psi(2S)\eta_c(2S)$ are very close to each other. These studies also show that scalar and pseudoscalar charmonia are produced copiously recoiling against $J/\psi$ or $\psi(2S)$. A new charmonium-like state, $X(3940)$, has been already observed in the spectrum recoiling against $J/\psi$, and reconstructed in the $D^*\overline{D}$ final state [5]. On the other hand, there has recently been a number of reports on observation of new charmonium or charmonium-like states above $D\overline{D}$ threshold [6]. Their properties are quite different from those expected from the quark model. These experimental results have renewed theoretical interest in spectroscopy, decay and production of charmonia [7].

In this Letter we present a new study of the $X(3940)$ resonance and report on the observation of a new charmonium-like state in the process $e^+e^- \rightarrow J/\psi D^{(*)}\overline{D}^{(*)}$ and the measurement of its parameters. The integrated luminosity used for this analysis is 693 fb$^{-1}$ collected with the Belle detector [8] near the $\Upsilon(4S)$ resonance at the KEKB asymmetric-energy $e^+e^-$ collider [9].

This study is performed using the selection procedure similar to that described in Ref. [1, 5]. All charged tracks are required to be consistent with originating from the interaction point. Charged kaon candidates are required to be positively identified, while no identification requirements are applied for pion candidates as the pion multiplicity is much higher than those of other hadrons. $K_S^0$ candidates are reconstructed by combining $\pi^+\pi^-$ pairs with an invariant mass within 10 MeV/$c^2$ of the nominal $K_S^0$ mass. We require the distance between the pion tracks at the $K_S^0$ vertex to be less than 1 cm, the transverse flight distance from the interaction point to be greater than 1 mm and the angle between the $K_S^0$ momentum direction and decay path to be smaller than 0.1 rad. Photons are reconstructed in the electromagnetic calorimeter as showers with an energy more than 20 MeV that are not associated with charged tracks. Photons of energy more than 50 MeV are combined to form $\pi^0$ candidates. If the mass of $\gamma\gamma$ pairs lies within 15 MeV/$c^2$ of the nominal $\pi^0$ mass, such pairs are fitted with a $\pi^0$ mass constraint and considered as $\pi^0$ candidates. $J/\psi$ candidates are reconstructed via the $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) decay channel. Two positively identified lepton candidates are required to form a common vertex that is less than 1 mm ($\approx 6\sigma$) from the interaction point in the plane perpendicular to the beam axis. A partial correction for final state radiation and bremsstrahlung energy loss is performed by including the four-momentum of every photon detected within a 50 mrad cone around the electron direction in the $e^+e^-$ invariant mass calculation. The $J/\psi$ signal region is defined by the mass window $|M_{\ell^+\ell^-} - M_{J/\psi}| < 30$ MeV/$c^2$ ($\approx 2.5\sigma$). $J/\psi$ candidates are subjected to a mass-vertex fit to improve their momentum resolution. QED processes are suppressed by requiring the total charged multiplicity in the event to be more than 4. $J/\psi$ mesons from $B\overline{B}$ events are removed by requiring a center-of-mass (CM) momentum $p_{T,J/\psi} > 2.0$ GeV/$c$. 

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We reconstruct $D^0$ mesons using five decay modes: $K^-\pi^+$, $K^-\bar{K}^+$, $K^-\pi^-\pi^+\pi^+$, $K_S^0\pi^+\pi^-$ and $K^-\pi^+\pi^-$. Candidate $D^+$ mesons are reconstructed using $K^-\pi^+\pi^+$, $K^-\bar{K}^+\pi^+$ and $K_S^0\pi^+\pi^-$ decay modes. A $\pm15\,\text{MeV}/c^2$ mass window is used for all modes except $D^0 \rightarrow K^-\pi^-\pi^0$ ($\pm20\,\text{MeV}/c^2$) ($\approx 2.5\,\sigma$ in each case). To improve their momentum resolution, $D$ candidates are refitted to the nominal $D^0$ or $D^+$ masses. To study the contribution of combinatorial background under the $D^0$ peak, we use $D$ sidebands selected from a mass window four times as large. For the study of the process $e^+e^- \rightarrow J/\psi D^*\overline{D}^{(*)}$ we use only the cleanest $D^{*+} \rightarrow D^0\pi^+$ channel. $D^{*+}$ candidates from the signal window, selected in the interval $\pm3\,\text{MeV}/c^2$ of the nominal $D^{*+}$ mass ($\approx 25\,\sigma$), are refitted to the nominal $D^{*+}$ mass. The $D^{*+}$ sideband region is defined by $2.016\,\text{GeV}/c^2 < M(D^{0}\pi^+) < 2.028\,\text{GeV}/c^2$. Only one $J/\psi D$ or one $J/\psi D^{*+}$ combination per event is accepted; the combination with the best sum of $\chi^2$ of the mass fits for $J/\psi$ and $D^{(*)}$ candidates is selected. In the $D^{(*)}$ sidebands a single candidate per event is selected as well. The sideband is divided into windows of the same width as the signal one, and the candidate with the smallest difference in mass from the center of its window is chosen.

The method for reconstructing the processes $e^+e^- \rightarrow J/\psi D^{(*)}\overline{D}^{(*)}$ was described in [3]. In addition to the fully reconstructed $J/\psi$, only one of the $D^{(*)}$'s is fully reconstructed (referred to below as $D^{(*)}_{\text{rec}}$: $D^\text{rec} = D^0$ or $D^+$, $D^{*\text{rec}} = D^{*+}$), and the other unreconstructed $D^{(*)}$ (referred to as associated $D \equiv \overline{D}^{(*)}_{\text{assoc}}$) in the event is observed as a peak in the spectra of masses recoiling against the reconstructed combination $J/\psi D^{(*)}_{\text{rec}}$. The recoil mass against the particle or combination of particles is defined as

$$M_{\text{recoil}}(X) = \sqrt{(E_{\text{CM}} - E_X^*)^2 - p_X^*},$$

(1)

where $E_X$ and $p_X$ are the CM energy and momentum of the (combination of) particle(s). The $M_{\text{recoil}}(J/\psi D^{(*)}_{\text{rec}})$ peak around the nominal mass of $\overline{D}^{(*)}_{\text{assoc}}$ with a typical resolution $\sim 30\,\text{MeV}/c^2$ is used to identify the studied process. As the resolution is smaller than $M_{D^0} - M_{D^+}$, the method allows the contributions from the processes $e^+e^- \rightarrow J/\psi D\overline{D}$, $J/\psi D^*\overline{D}$ and $D^*\overline{D}$ to be disentangled. The $M_{\text{recoil}}(J/\psi D_{\text{rec}})$ and $M_{\text{recoil}}(J/\psi D^{(*)}_{\text{rec}})$ spectra in the data are shown in Fig. 1 as points with error bars for the signal $D^{(*)}_{\text{rec}}$ windows; histograms show the scaled $D^{(*)}_{\text{rec}}$ sideband distributions. The signals for the processes $e^+e^- \rightarrow J/\psi D\overline{D}$, $D^*\overline{D}$ and $D^*\overline{D}^*$ are evident in Fig. 1(a) at the $D$ and $D^*$ nominal masses and at a mass $\sim 2.2\,\text{GeV}/c^2$, respectively. The latter peak is shifted and widened due to two missing pions (or photons) from $D^*$ decays. Another excess at $\sim 2.45\,\text{GeV}/c^2$ can be explained by the process $e^+e^- \rightarrow J/\psi D^*\overline{D}^*$. The processes $e^+e^- \rightarrow J/\psi D\overline{D}$ and $D^*\overline{D}^*$ are also clearly seen in Fig. 1(b) as distinct peaks around the $D$ and $D^*$ nominal masses. We use $D^{(*)}_{\text{rec}}$ sidebands to describe the combinatorial background contribution through simultaneous likelihood fits to the $\overline{D}^{(*)}_{\text{assoc}}$ signal and sideband spectra. The signal shapes are fixed from the Monte Carlo (MC) simulation. The background distribution is parameterized by a second-order polynomial function (linear function in case of $D^{(*)}_{\text{rec}}$). Only the region below $2.35\,\text{GeV}/c^2$ is used because of a possible contribution from $e^+e^- \rightarrow J/\psi DD\overline{D}^*$. The signal yields (including the tail due to initial state radiation [ISR]) and statistical significances are listed in Table 1.

| $J/\psi D^{(*)}_{\text{rec}}$ | $J/\psi D^{(*)}_{\text{rec}}$ |
|-----------------------------|-----------------------------|
| $e^+e^- \rightarrow J/\psi D^0$ | 162 $\pm$ 25 | 7.6 | 10 |
| $e^+e^- \rightarrow J/\psi D^+$ | 159 $\pm$ 28 | 6.5 | 19.0 $\pm$ 6.3 $\pm$ 5.3 | 5.8 |
| $e^+e^- \rightarrow J/\psi D^{*+}\overline{D}^*$ | 173 $\pm$ 32 | 5.6 | 47.2 $\pm$ 2.5 $\pm$ 8.5 | 8.4 |

We perform a study of these observed processes and search for new charmonium states $X_{c\bar{c}}$ that can be produced via $e^+e^- \rightarrow J/\psi X_{c\bar{c}}$ followed by the decay $X_{c\bar{c}} \rightarrow D^{(*)}\overline{D}^{(*)}$. Tagging the process $e^+e^- \rightarrow J/\psi D^{(*)}\overline{D}^{(*)}$ by the requirement $|M_{\text{recoil}}(J/\psi D^{(*)}_{\text{rec}}) - M_{D^{(*)}}| < 70\,\text{MeV}/c^2$ we thus divide each of selected $J/\psi D$ or $J/\psi D^{*+}$ combinations into two non-overlapping samples, each comprising $\sim 50\%$ of the signal events. The ISR tail causes an inefficiency for the tagging requirement as well as cross talk between different final states: the contribution of the process $e^+e^- \rightarrow J/\psi D\overline{D}$ ($D^*\overline{D}$) to the sample tagged as $e^+e^- \rightarrow J/\psi D^*\overline{D}$ ($D^*\overline{D}^*$) is $\sim 10\%$, the reverse cross talk is only $\sim 1.5\%$ and neglected. In our study we constrain $M_{\text{recoil}}(J/\psi D^{(*)}_{\text{rec}})$ to the $\overline{D}^{(*)}_{\text{assoc}}$ nominal mass. This improves the resolution on $M_{\text{recoil}}(J/\psi)$, which corresponds to the invariant mass of the produced $D^{(*)}$ meson pair, by a factor of $3 - 10$ with respect to the unconstrained value ($\sim 30\,\text{MeV}/c^2$). The $M(D^{(*)}\overline{D}^{(*)})$ resolution varies from 2 MeV/c^2 at threshold to 8 MeV/c^2.
FIG. 1: The distributions of masses recoiling against the reconstructed a) $J/\psi D$ and b) $J/\psi D^*$ combinations in the data. The histograms show the scaled $D^{(*)}$ sideband distributions. The solid curves are results of the fit, the dashed curves are the background functions.

at $M(D^{(*)}\bar{D}^{(*)}) = 5.0$ GeV/$c^2$ for all the processes except $e^+e^- \rightarrow J/\psi D^*\bar{D}$ with $D_{rec}\bar{D}_{assoc}$. In the latter case the resolution is worse because of the $D_{rec}$ from the $D^*$ decay ($\sim 10$ MeV/$c^2$ at $M(D^*\bar{D}) \sim 3.94$ GeV/$c^2$).

In the data the spectra of $M(D^{(*)}\bar{D}^{(*)})$ are shown in Figs. 2a), b), c), d) for $D_{rec}\bar{D}_{assoc}$, $D_{rec}\bar{D}_{assoc}$, $D_{rec}\bar{D}_{assoc}$, $D_{rec}\bar{D}_{assoc}$ cases, respectively. Points with error bars correspond to the $D_{rec}$ signal windows while hatched histograms show the scaled $D_{rec}$ sideband distributions. Excesses from the signal $D_{rec}$ window over the sideband distributions are seen around the threshold in all figures. The reflections ($D\bar{D} \rightarrow D^*\bar{D}$ and $D^*\bar{D} \rightarrow D^*\bar{D}$) estimated using the MC simulation are shown with open histograms. In the MC the $e^+e^- \rightarrow J/\psi D^{(*)}\bar{D}^{(*)}$ processes are generated with $M(D^{(*)}\bar{D}^{(*)})$ spectra tuned to the data.

We perform simultaneous likelihood fits to $D_{rec}^{(*)}$ signal and sideband distributions to fix the combinatorial background shapes. The accuracy of description of combinatorial backgrounds by $D_{rec}^{(*)}$ sidebands is validated with the MC simulation and with the data, where the $M(D^{(*)}\bar{D}^{(*)})$ spectra in the different sideband intervals are found to be in good agreement with each other. The combinatorial backgrounds are parameterized by the function $A\sqrt{M - M_{thr}} \cdot e^{-B\cdot M}$, where $A$ and $B$ are free parameters, except for the case $D_{rec}\bar{D}_{assoc}$, where this shape is found to describe poorly the behavior of the background. In the latter case we parameterize the background by a relativistic Breit-Wigner function with a free mass, width and amplitude. The signal functions are a sum of a relativistic s-wave Breit-Wigner function and a threshold function ($\sqrt{M - M_{thr}}$) to account for possible non-resonant production. The signal functions are convolved with the resolution functions and multiplied by the efficiency function obtained from the MC simulation. The reflections are taken into account in the fit.

The fitted parameters of the Breit-Wigner functions and significances of the resonance contributions are listed in Table III. We assess the significance of each signal using $-2\ln(L_0/L_{max})$, where $L_{max}$ is the maximum likelihood returned by the fit, and $L_0$ is the likelihood with the amplitude of the Breit-Wigner function set to zero. This quantity should be distributed as $\chi^2(n_{dof} = 3)$ in the absence of signal, as three signal parameters are free in the fit for $L_{max}$. The non-resonant contributions are consistent with zero within 1σ in all fits, except for the case $D_{rec}\bar{D}_{assoc}$ (1.6σ).
FIG. 2: The $M(D^{(*)}_{rec}D^{(*)}_{assoc})$ spectra for events tagged and constrained as a) $e^+e^-\rightarrow J/\psi D\bar{D}$, b) $e^+e^-\rightarrow J/\psi D^{*}\bar{D}$ and d) $e^+e^-\rightarrow J/\psi D^{*}\bar{D}^{*}$ in the data.

A fit to $M(D\bar{D})$ distribution finds a broad resonance near the threshold, which is tentatively denoted as $X(3880)$, with a statistical significance of 3.8 $\sigma$. However, the fit is not stable under variation of background parameterization as well as variation of the bin width. The fit with two resonances better describes the spectrum and is more stable, but the significance of the second resonance is lower than 3 $\sigma$. We conclude that the observed threshold enhancement is not consistent with non-resonant $e^+e^-\rightarrow J/\psi D\bar{D}$ production, but with the present statistics the resonant structure in this process cannot be reliably determined. The significance of the $X(3940)$ signal found by the fit to the $M(D^{(*)}_{rec}D^{(*)}_{assoc})$ spectrum is 6.0 $\sigma$. The fitted width of $X(3940)$ is slightly higher than that obtained in our previous analysis [5]. The
TABLE II: Summary of the signal yields, masses [MeV/c²], widths [MeV] and significances for $e^+e^-\rightarrow J/\psi(D^{(*)}\overline{D}^{(*)})_{res}$. 

| State                  | $N_{events}$ | $M$      | $\Gamma$ | $N_S$ |
|------------------------|--------------|----------|----------|-------|
| $X(3880)(D^0_{rec}D_{assoc}^*)$ | $63^{+41}_{-25}$ | 3878 $\pm$ 48 | $347^{+71}_{-14}$ | 3.8   |
| $X(3940)(D^0_{rec}D_{assoc}^*)$ | $52^{+24}_{-16}$ | 3942 $\pm$ 7  | $37^{+26}_{-15}$ | 6.0   |
| $X(3940)(D^+_{assoc}D^0_{rec}^*)$ | $5.2^{+3.4}_{-2.7}$ | 3934 $\pm$ 23 | $57^{+62}_{-34}$ | 2.8   |
| $X(4160)(D^+_{assoc}D^0_{rec}^*)$ | $23.8^{+12.3}_{-8.0}$ | 4156 $\pm$ 25 | $139^{+111}_{-61}$ | 5.5   |

TABLE III: Summary of the systematic errors in the masses (M in MeV/c²), widths (Γ in MeV) and production cross sections (σ in %) for $X(3940)$ [$X(4160)$] resonances.

| Source                  | $X(3940)$ | $X(4160)$ |
|-------------------------|-----------|-----------|
|                         | $M$       | $\Gamma$  | $\sigma$  | $M$       | $\Gamma$  | $\sigma$  |
| Fitting procedure       | $\pm 4$   | $\pm 6$   | $\pm 5$   | $\pm 12$  | $\pm 18$  | $\pm 2$   |
| Selection               | $\pm 4$   | $\pm 5$   | $\pm 4$   | $\pm 8$   | $\pm 11$  | $\pm 5$   |
| Momentum scale          | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   |
| Angular distributions   | $\pm 12$  | $\pm 12$  | $\pm 12$  | $\pm 12$  | $\pm 12$  | $\pm 12$  |
| Reconstruction          | $\pm 6$   | $\pm 6$   | $\pm 6$   | $\pm 6$   | $\pm 6$   | $\pm 6$   |
| Identification          | $\pm 4$   | $\pm 4$   | $\pm 4$   | $\pm 4$   | $\pm 4$   | $\pm 4$   |
| $B(D^{(*)})$            | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   | $\pm 3$   |
| Total                   | $\pm 6$   | $\pm 8$   | $\pm 16$  | $\pm 15$  | $\pm 21$  | $\pm 20$  |

mass of the state is in good agreement with the reported mass, and the signal yield scales with respect to the previous result in proportion to the luminosity. Separate fits to the $D^0_{rec}$ and $D^+_{rec}$ samples yield 42 $^{+10}_{-9}$ and 8 $^{+5}_{-4}$ signal events, respectively, in good agreement with the MC expectations (40 and 12) normalized to the integrated yield assuming equal branching fractions of $X(3940)$ decays into charged and neutral $D^+\overline{D}^*$ pairs. The $X(3940)$ signal is also seen in the $M(D^+\overline{D}^*)$ spectrum with a significance of 2.8 σ, with parameters in good agreement with those from the $M(D^0_{rec}\overline{D}^*_{assoc})$ fit. As this sample is a small subsample of the $D^0_{rec}\overline{D}^*_{assoc}$ case, we use the latter fit for only as a cross check. The $M(D^+\overline{D}^*)$ spectrum demonstrates a clear broad enhancement around the threshold, which we denote as $X(4160)$. The $X(4160)$ signal is seen above the small combinatorial background and the $X(3940)$ reflection with a statistical significance of 5.5 σ.

The Born cross sections for the processes $e^+e^-\rightarrow J/\psi X(3940)$ [$X(4160)$] multiplied by $B_{D^{(*)}\overline{D}^*}=B(X\rightarrow D^{(*)}\overline{D}^*)$ are calculated from the fitted $X(3940)$ and $X(4160)$ yields with the procedure used in the previous analysis [2]. Taking into account the reconstruction efficiencies obtained from the MC simulation, the calculated Born cross-sections are:

$$\sigma(e^+e^-\rightarrow J/\psi X(3940))B_{D^*\overline{D}^*} = (13.9^{+6.4}_{-4.1} \pm 2.2) \text{ fb}$$
$$\sigma(e^+e^-\rightarrow J/\psi X(4160))B_{D^*\overline{D}^*} = (24.7^{+12.3}_{-8.8} \pm 5.0) \text{ fb}.$$ (2)

The systematic errors of the parameters and production cross sections for $X(3940)$ and $X(4160)$ resonances are summarized in Table III. To estimate the fitting systematics we study the difference in $X(3940)$ [$X(4160)$] parameters returned by the fit to the Fig. (2b) and d) distributions under variation of the signal and background parameterizations, the fit ranges and the histogram bins as well as the resolution functions. We also vary the definitions of the signal and sideband regions to check the stability of the resonance parameters. Another uncertainty in the determination of the masses is due to possible momentum scale bias. This was estimated in the previous paper [2] to be smaller than 3 MeV/c². The systematic error for the cross section calculation is dominated by the uncertainty in the $J/\psi$ production and polarization angular distributions. In the MC both angular distributions are assumed to be flat and extreme cases ($1+\cos^2\theta$ and $\sin^2\theta$) are considered to estimate the systematic uncertainty in this assumption. In the case of the $X(4160)$ another source of the systematic uncertainty is the $D^+$ polarization, which is also taken into account by varying the $D^+$ helicity angle distribution. Other contributions come from the uncertainty in the track and $\pi^0$ reconstruction efficiencies; lepton and kaon identification and in the absolute $B(D^{(*)})$.

In summary, we have observed the processes $e^+e^-\rightarrow J/\psi D\overline{D}$ ($D^{(*)}\overline{D}^*$) and found significant enhancements in $M(D^{(*)}\overline{D}^{(*)})$ spectra around thresholds in all these processes. A broad enhancement in $M(D\overline{D})$ is not consistent
with non-resonant \( e^+e^- \to J/\psi D\overline{D} \) production, however the present sample is not large enough to allow the resonant structure in this process to be determined. We have confirmed our observation of the charmonium state, \( X(3940) \to D\overline{D}^* \), produced in the process \( e^+e^- \to J/\psi X(3940) \) with a significance of 5.7 \( \sigma \) including systematics. The \( X(3940) \) mass and width are \( (3942^{+7}_{-6} \pm 6) \) MeV/c\(^2\) and \( \Gamma = (37^{+26}_{-15} \pm 8) \) MeV. These measurements are consistent with our published results and supersede them. In this study we have found that the inclusive peak in the \( M_{\text{recoil}}(J/\psi) \) spectrum may consist of several states, thus our previous measurement of \( X(3940) \) branching fractions may be not reliable \[5\]. We report observation of a new charmonium-like state the \( X(4160) \) in the processes \( e^+e^- \to J/\psi X(4160) \) decaying into \( D^*\overline{D}^* \) with a significance of 5.1 \( \sigma \), including the systematic uncertainty of the fit. The \( X(4160) \) parameters are \( M = (4156^{+25}_{-20} \pm 15) \) MeV/c\(^2\) and \( \Gamma = (139^{+111}_{-61} \pm 21) \) MeV.

We thank the KEKB group for excellent operation of the accelerator, the KEK cryogenics group for efficient solenoid operations, and the KEK computer group and the NII for valuable computing and Super-SINET network support. We acknowledge support from MEXT and JSPS (Japan); ARC and DEST (Australia); NSFC and KIP of CAS (China); DST (India); MOEHRD, KOSEF and KRF (Korea); KBN (Poland); MES and RFAAE (Russia); ARRS (Slovenia); SNSF (Switzerland); NSC and MOE (Taiwan); and DOE (USA).

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