IL NUOVO CIMENTO Vol. ?, N. ? ?

Results of $B_S^0 \to$ CP Eigenstates at Belle

F. Thorne(1), C. Schwanda(1) for the Belle Collaboration
(1) *Institute of High Energy Physics, Austrian Academy of Science, Vienna*

Summary. — We report the measurement of the absolute branching fraction for $B_S^0 \to J/\psi\, \phi$, for $B_S^0 \to J/\psi\, K^+K^-$ and a determination of the s-wave contribution in the ϕ mass range as well as a first observation of $B_S^0 \to J/\psi\, \eta$ and $B_S^0 \to J/\psi\, \eta'$. These results are based on a 121 fb^{-1} data sample collected with the Belle detector at the KEK-B asymmetric e^+e^- collider near the $\Upsilon(5S)$ resonance.

PACS 13.25.Hw – Decays of bottom mesons.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

During its operation, the Belle experiment collected over 700 fb^{-1} of data near the Υ (4S) resonance and 121 fb^{-1} near the Υ (5S) resonance. This second data sample is unique at B factories and provides the opportunity to study decays of $\mathrm{B_S^0}$ mesons.
To extract the $\mathrm{B_S^0}$ signal, two nearly independant kinematic variables, $\Delta\mathrm{E}$ and $\mathrm{M_{bc}}$, are used:

$$(1) \qquad \Delta \mathrm{E} = \mathrm{E_B^*} - \mathrm{E_{beam}^*} \qquad \text{and} \qquad \mathrm{M_{bc}} = \sqrt{\mathrm{E_{beam}^2} - \left(\mathrm{p_B^*}\right)^2}$$

where $\mathrm{E_{beam}^*}$ is the beam energy in the center of mass frame and $\mathrm{E_B^*}$ and $\mathrm{p_B^*}$ denote the energy and the momentum of the reconstructed $\mathrm{B_S^0}$ meson, respectively, given in the center of mass system.
In the analyses presented below, the $\mathrm{B_S^0}$ meson is fully reconstructed. However, the photon from a possible $\mathrm{B_S^*} \to \mathrm{B_S^0}\gamma$ decay is not included. As the energy information from the photon from the $\mathrm{B_S^*}$ decay is lost, the signal region plotted in the $\mathrm{M_{bc}}$-$\Delta\mathrm{E}$ plane splits up into three areas, depending on the number of $\mathrm{B_S^*}$ mesons in the initial state. As these areas are not overlapping in $\mathrm{M_{bc}}$, they can easily be separated during the analysis by a cut on $\mathrm{M_{bc}}$ (fig. 1(b)).

The Belle detector (fig. 1(a)), located at the asymmetric $\mathrm{e^+e^-}$ collider KEK-B in Tsukuba Japan, is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM). The detector is described in detail elsewhere [1].

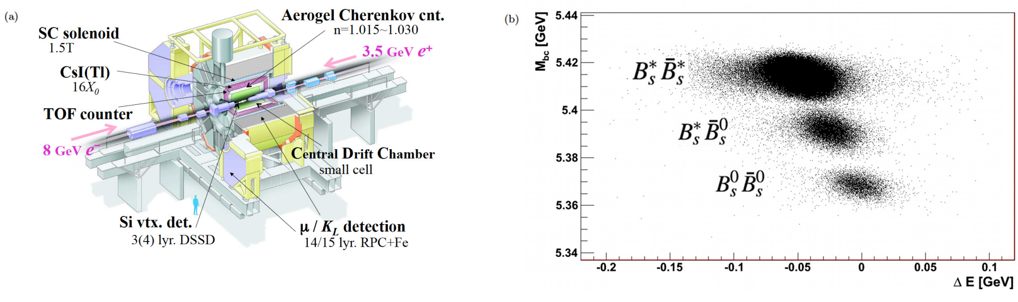

Fig. 1. – (a) Schematic view of the Belle detector. (b) Signal regions shown as a scatter plot in the $\mathrm{M_{bc}} - \Delta\mathrm{E}$ plane.

2. – Precise measurement of $\mathcal{B}\left(\mathbf{B_S^0} \to \mathbf{J}/\psi\,\phi\right)$ and $\mathcal{B}\left(\mathbf{B_S^0} \to \mathbf{J}/\psi\,\mathbf{K^+K^-}\right)$

The decay $B_S^0 \to J/\Psi\ \phi$ is an important mode for measuring the CP violating phase β_S in the $B_S\overline{B}_S$ mixing, which is of particular interest as it is expected to be sensitive to physics beyond the Standard Model [2]. Therefore, regarding the current PDG value of $\mathcal{B}\left(B_S^0 \to J/\psi\ \phi\right) = (1.4 \pm 0.5)\ 10^{-3}$ [3] measured by the CDF experiment [4], which provides a relative error of 35.7%, a precise measurement of this branching fraction is essential.
Furthermore, in this analysis the branching fraction of the decay $B_S^0 \to J/\psi\ K^+K^-$, which has not been measured so far, is determined together with the branching ratio of $B_S^0 \to J/\psi\ \phi$. The study of this nonresonant mode is crucial, as it is the main background for the investigation of the decay $B_S^0 \to J/\psi\ \phi$. By separating these two final states, it is also possible to calculate the s-wave contribution within the ϕ mass region.

In both final states, the same particles have to be identified: Two oppositely charged leptons and two oppositely charged kaons. To reconstruct the J/ψ meson, the invariant mass of the leptons and a possible bremstrahlung gamma is required to lie within $2.946\text{ GeV} \leq m(\ell\ell)_{e^+e^-(\gamma)} \leq 3.133\text{ GeV}$ and $3.036\text{ GeV} \leq m(\ell\ell)_{\mu^+\mu^-} \leq 3.133\text{ GeV}$, respectively.
In case of the invariant kaon mass, only a lower cut of $m(K^+K^-) \geq 0.95\,\text{GeV}$ is applied, so that the full $m(K^+K^-)$ distribution can be investigated.
Finally, to extract the B_S^0 meson, signal requirements on the kinematic parameters ΔE and M_{bc} are performed. In this analysis a region with $M_{bc} > 5.4\,\text{GeV}$ is used, which means only the dominant $B_S^*\overline{B}_S^*$ signal region is investigated as this provides the best signal to background ratio.

To determine the branching ratios for $B_S^0 \to J/\psi\,\phi$ and $B_S^0 \to J/\psi\,K^+K^-$ a two dimensional unbinned likelihood fit in ΔE and $m(K^+K^-)$ is performed.
For these two channels, the probability density functions (pdfs) for the ΔE distribution are adjusted using a real data control sample. For this purpose the decay $B^0 \to J/\psi\ K^*(892)$ was chosen, as its final state is very similar to the final state of $B_S^0 \to J/\psi\,\phi$ and $B_S^0 \to J/\psi\,K^+K^-$, except that one kaon is replaced by a pion.
As for the K^+K^- invariant mass, the pdfs for $B_S^0 \to J/\psi\,\phi$ and $B_S^0 \to J/\psi\,K^+K^-$ are determined from generic Monte Carlo (MC) data. The simulation of this data basically includes all known contributions that can be found in the PDG. Investigating the $m(K^+K^-)$ distribution, the peak of the ϕ meson can be clearly identified at the low energy part of the spectrum, while the nonresonant decay $B_S^0 \to J/\psi\,K^+K^-$ provides a flat distribution up to the high energy part of the $m(K^+K^-)$ spectrum which can be modeled by an Argus function. As a consequence, the two decay modes are distinguishable via the distribution of the invariant kaon mass, rather than by performing an angular analysis.

The fit results obtained from the full $121\,\text{fb}^{-1}$ Belle data sample are presented in tab. I . The description of the ΔE and the $m(K^+K^-)$ distribution with the applied pdf model is in good agreement with the data for the muon channel (fig. 2) as well as for the electron channel (fig. 3).
With 158±13 (168±14) events for $B_S^0 \to J/\psi\,\phi$ in the muon (electron) channel the corresponding branching fraction can be calculated to be

$$\mathcal{B}\left(B_S^0 \to J/\psi_{\mu^+\mu^-}\ \phi\right) = \left(1.19 \pm 0.10_{\text{stat}} \pm 0.19_{\text{sys}}\right) 10^{-3} \tag{2}$$

channel	$J/\psi\,\phi$	$J/\psi\,K^+K^-$	combinatorial background
$\mu^+\mu^-$	158±13	89±13	304±20
e^+e^-	168±14	110±16	239±20

TABLE I. – *Fit results for the $\mu^+\mu^-$ and the e^+e^- channel on 121 fb^{-1}.*

(3) $$\mathcal{B}\left(B_S^0 \rightarrow J/\psi_{e^+e^-}\ \phi\right) = \left(1.33 \pm 0.11_{\text{stat}} \pm 0.22_{\text{sys}}\right) 10^{-3}$$

with the weighted mean value of

(4) $$\mathcal{B}\left(B_S^0 \rightarrow J/\psi\ \phi\right) = \left(1.25 \pm 0.07_{\text{stat}} \pm 0.20_{\text{sys}}\right) 10^{-3}$$

The obtained results for the branching fractions for the muon and the electron channel are comparable with each other within their statistical errors and are in good agreement with the current PDG value.
Summarizing all contributions to the systematic error that are presented in tab. II, the total systematic error is determined to be 16.3%. The dominant contribution to the systematic error is the uncertainty in f_S, the ratio of $B_S^*\overline{B}_S^*$ events within all produced $b\overline{b}$ pairs, which is therefore limiting the accuracy of the analysis at the present time.
The fit result for the nonresonant component $B_S^0 \rightarrow J/\psi K^+K^-$ is 89±13 (110±16) events in the muon (electron) channel, which leads to

(5) $$\mathcal{B}\left(B_S^0 \rightarrow J/\psi_{\mu^+\mu^-}\ K^+K^-\right) = \left(0.33 \pm 0.05_{\text{stat}}{}^{+0.06}_{-0.07}{}_{\text{sys}}\right) 10^{-3}$$

(6) $$\mathcal{B}\left(B_S^0 \rightarrow J/\psi_{e^+e^-}\ K^+K^-\right) = \left(0.43 \pm 0.06_{\text{stat}}{}^{+0.10}_{-0.11}{}_{\text{sys}}\right) 10^{-3}$$

with the weighted mean value

(7) $$\mathcal{B}\left(B_S^0 \rightarrow J/\psi\ K^+K^-\right) = \left(0.39 \pm 0.04_{\text{stat}} \pm 0.08_{\text{sys}}\right) 10^{-3}$$

This measurement has a significance of $5.3\,\sigma$. The sources of the systematic error are the same as for the measurement of $B_S^0 \rightarrow J/\psi\ \phi$.

Another result that can be obtained from this analysis is the s-wave contribution in the mass region of the ϕ meson. For this purpose, the following assumptions are made:

- The p-wave contribution originates from the decay $B_S^0 \rightarrow J/\psi\ \phi$.
- The s-wave contribution originates from the decay $B_S^0 \rightarrow J/\psi\ K^+K^-$.

The two states are distinguishable via the m(KK) distribution and the s-wave contribution (S) is calculated as the rate of the fitted number of events of the nonresonant decay compared to the total number of fitted events of the resonant and nonresonant decay within a specific mass range:

(8) $$S = \frac{\alpha \cdot N\left(J/\psi\ K^+K^-\right)}{\alpha \cdot N\left(J/\psi\ K^+K^-\right) + \beta \cdot N\left(J/\psi\ \phi\right)}$$

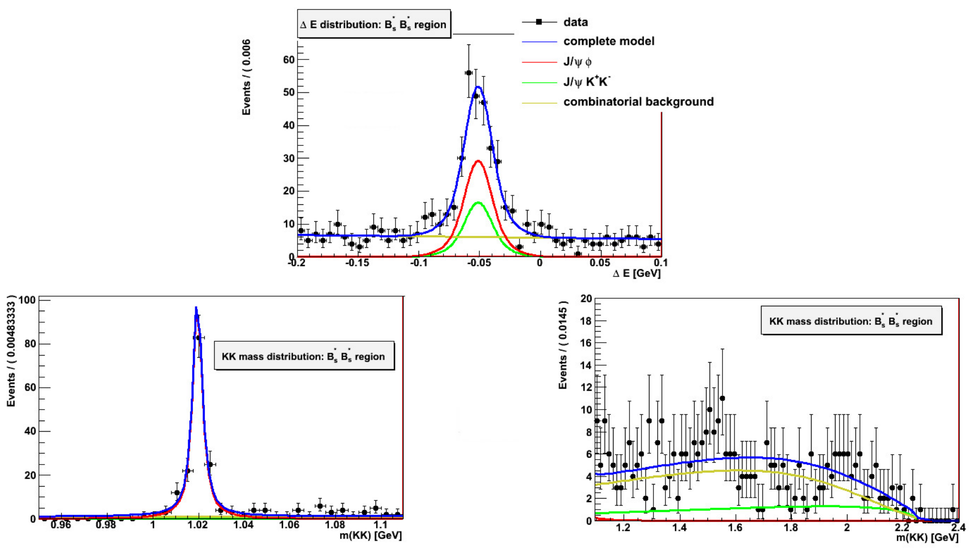

Fig. 2. – Fitted ΔE and m(K^+K^-) distribution for the $\mu^+\mu^-$ channel on 121.061 fb^{-1}.

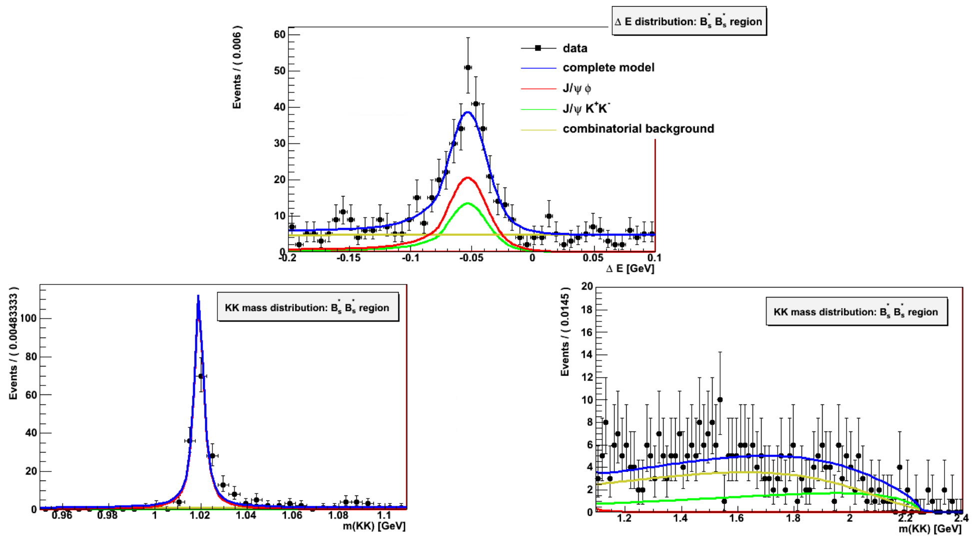

Fig. 3. – Fitted ΔE and m(K^+K^-) distribution for the e^+e^- channel on 121.061 fb^{-1}.

In eq. 8, N $\left(J/\psi\, K^+K^-\right)$ and N $\left(J/\psi\, \phi\right)$ are the fitted number of events for the $B_S^0 \rightarrow J/\psi\, K^+K^-$ and the $B_S^0 \rightarrow J/\psi\, \phi$ channel, respectively. The parameters α and β denote the percentage of the two components within the considered mass range.
The mass ranges that are investigated are the same as used by CDF and LHCb (see table III) and the obtained results are in agreement with the contributions calculated by these experiments. The statistical error originates from the statistical uncertainty of the

Parameter	Value	Error	%
Luminosity	121.061 fb^{-1}	0.847 fb^{-1}	0.7
$\sigma_{b\bar{b}}^{\Upsilon(5S)}$ [5]	0.302 nb	0.014 nb	4.6
f_S [6]	0.193	0.029	15.0
$\mathcal{B}\left(\phi \rightarrow K^+K^-\right)$ [3]	0.489	0.005	1.0
$\mathcal{B}\left(J/\psi \rightarrow \mu^+\mu^-\right)$ [3]	0.0593	0.0006	1.0
$\mathcal{B}\left(J/\psi \rightarrow e^+e^-\right)$ [3]	0.0594	0.0006	1.0
$\epsilon_{\text{MC statistic}}\left(\mu^+\mu^-\right)$	0.325	0.001	0.2
$\epsilon_{\text{MC statistic}}\left(e^+e^-\right)$	0.307	0.001	0.3
$\epsilon_{\text{Polarisation}}\left(\mu^+\mu^-\right)$	0.325	0.005	1.5
$\epsilon_{\text{Polarisation}}\left(e^+e^-\right)$	0.307	0.004	1.3
tracking	-	-	1.4
lepton and kaon ID	-	-	2.0
PDF shape $\left(\mu^+\mu^-\right)$	158 events	3.7 events	2.3
PDF shape $\left(e^+e^-\right)$	168 events	4.6 events	2.7
sum $\left(\mu^+\mu^-\right)$	-	$0.19 \cdot 10^{-3}$	16.0
sum $\left(e^+e^-\right)$	-	$0.22 \cdot 10^{-3}$	16.5

TABLE II. – *Values and systematic errors for the parameters used to calculate $\mathcal{B}\left(B_S^0 \rightarrow J/\psi\ \phi\right)$.*

	CDF [7]	LHCb [8]
mass range	1.009 GeV -1.028 GeV	1.007 GeV -1.031 GeV
hadron collider results	< 6.0% at 95% CL	$4.2 \pm 1.5 \pm 1.8\%$
Belle result	$0.61 \pm 0.07_{\text{stat}} \pm 0.06_{\text{sys}}\%$	$0.75 \pm 0.09_{\text{stat}} \pm 0.09_{\text{sys}}\%$

TABLE III. – *Results for the s-wave contribution in different mass regions around the ϕ peak. The numbers are in agreement with the results from CDF and LHCb.*

fit results for $N\left(J/\psi\, K^+K^-\right)$ and $N\left(J/\psi\ \phi\right)$, while the systematic error is given by the uncertainty of the parameters α and β due to the uncertainty in the pdf shape.

3. – First observation of $B_S^0 \rightarrow J/\psi\,\eta$ and $B_S^0 \rightarrow J/\psi\,\eta'$

The measurement of the decays $B_S^0 \rightarrow J/\psi\,\eta$ and $B_S^0 \rightarrow J/\psi\,\eta'$ provide the possibility to investigate new CP-even eigenstates. Furthermore, the SU(3) flavor symmetry predicts the ratio of these two branching fractions to be close to one and therefore, a measurement of these decay channels would allow to test the SU(3) symmetry as well as the $\eta - \eta'$ mixing (for more detail, see *e.g.* [9, 10, 11, 12]).
However, these decays have not been observed so far. The L3 experiment published an upper limit of $\mathcal{B}\left(B_S^0 \rightarrow J/\psi\,\eta\right) < 3.8 \cdot 10^{-3}$ at a 90% confidence level [13].

To determine the branching fractions of $B_S^0 \rightarrow J/\psi\,\eta$ and $B_S^0 \rightarrow J/\psi\,\eta'$ the B_S^0 meson

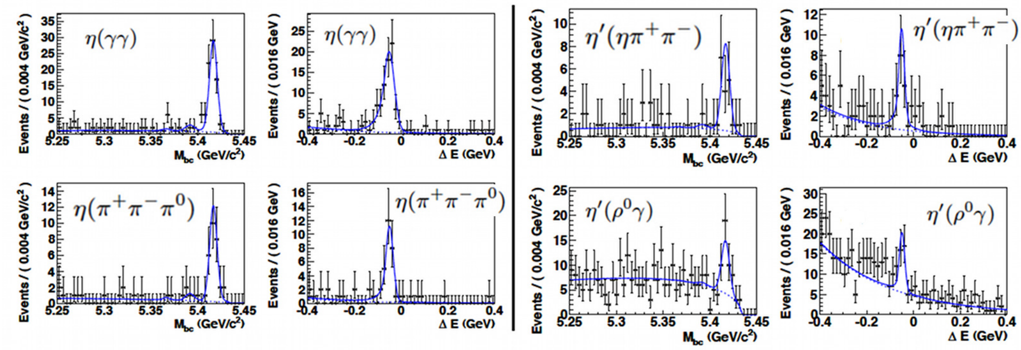

Fig. 4. – Fitted M_{bc} and ΔE distributions for $B_S^0 \to J/\psi\,\eta$ (left) and $B_S^0 \to J/\psi\,\eta'$ (right). The solid lines present the projection of the fit results, while the dotted curves illustrate the background component.

is reconstructed in five different final states. While the J/ψ meson is identified via two oppositely charged leptons, the η meson is reconstructed from a $\gamma\gamma$ or $\pi^+\pi^-\pi^0$ state and the η' meson is expected to decay into a $\rho^0\gamma$ or a $\eta\pi^+\pi^-$ final state. For more detailed information on the reconstruction and the fitting method in this analysis see [14].
The fit is performed as a two dimensional unbinned, extended maximum likelihood fit in ΔE and M_{bc}, simultaneously for all five final states. The fit results are presented in fig. 4 where the applied pdf model shows a good agreement with the data in all subchannels. With 141 ± 14 (86 ± 14) events found for $B_S^0 \to J/\psi\,\eta$ ($B_S^0 \to J/\psi\,\eta'$), the corresponding branching fractions are calculated to

$$\mathcal{B}\,(B_S \to J/\psi\,\eta) = \left(5.10 \pm 0.50_{\mathrm{stat}} \pm 0.25_{\mathrm{sys}}\ {}^{+1.14}_{-0.79}(N_{B_S^{(*)}\overline{B}_S^{(*)}})\right) \cdot 10^{-4} \tag{9}$$

$$\mathcal{B}\,(B_S \to J/\psi\,\eta') = \left(3.71 \pm 0.61_{\mathrm{stat}} \pm 0.18_{\mathrm{sys}}\ {}^{+0.83}_{-0.57}(N_{B_S^{(*)}\overline{B}_S^{(*)}})\right) \cdot 10^{-4} \tag{10}$$

and their ratio is

$$\frac{\mathcal{B}\,(B_S \to J/\psi\,\eta')}{\mathcal{B}\,(B_S \to J/\psi\,\eta)} = 0.73 \pm 0.14_{\mathrm{stat}} \pm 0.02_{\mathrm{sys}} \tag{11}$$

While the result for $B_S^0 \to J/\psi\,\eta$ is in agreement with the upper limit obtained from the L3 experiment, the determined ratio shows a deviation at a $2.1\,\sigma$ level with respect to the prediction.

4. – Summary

We presented the measurement of the absolute branching fraction for $B_S^0 \to J/\psi\ \phi$, for $B_S^0 \to J/\psi\ K^+K^-$ and a determination of the s-wave contribution in the ϕ mass range. The results concerning the branching fraction of $B_S^0 \to J/\psi\ \phi$ and the s-wave contribution are in good agreement with previous measurements from other experiments.

The branching fraction of $B_S^0 \rightarrow J/\psi\ K^+K^-$ was determined for the first time with a significance of $5.3\,\sigma$.
Furthermore, we presented the first observation of $B_S^0 \rightarrow J/\psi\ \eta$ and $B_S^0 \rightarrow J/\psi\ \eta'$. While the result for the branching fraction of $B_S^0 \rightarrow J/\psi\ \eta$ is in agreement with the upper limit of a former measurement, the ratio of the two branching fractions shows a deviation of $2.1\,\sigma$ level with regard to the prediction.

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This work is supported by the Austrian Science Fonds (FWF), under grant number P22742-N16.

We thank the KEKB group for the excellent operation of the accelerator, the KEK cryogenics group for the efficient operation of the solenoid, and the KEK computer group and the National Institute of Informatics for valuable computing and SINET3 network support. We acknowledge support from the Ministry of Education, Culture, Sports, Science, and Technology of Japan and the Japan Society for the Promotion of Science; the Australian Research Council and the Australian Department of Education, Science and Training; the National Natural Science Foundation of China under contract No. 10575109 and 10775142; the Department of Science and Technology of India; the BK21 program of the Ministry of Education of Korea, the CHEP SRC program and Basic Research program (grant No. R01-2005-000-10089-0) of the Korea Science and Engineering Foundation, and the Pure Basic Research Group program of the Korea Research Foundation; the Polish State Committee for Scientific Research; the Ministry of Education and Science of the Russian Federation and the Russian Federal Agency for Atomic Energy; the Slovenian Research Agency; the Swiss National Science Foundation; the National Science Council and the Ministry of Education of Taiwan; and the U.S. Department of Energy.

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