Study of $B^- \to \Xi c \Lambda \bar{c}^-$ and $B^- \to c \Lambda \Lambda \bar{c}^- \bar{K}$ decays at BABAR

Permalink
https://escholarship.org/uc/item/2f9041qr

Journal
Physical Review D, 77(3)

ISSN
1550-7998

Authors
Aubert, B
Bona, M
Boutigny, D
et al.

Publication Date
2008-02-01

DOI
10.1103/physrevd.77.031101

License
https://creativecommons.org/licenses/by/4.0/ 4.0

Peer reviewed
Study of $\bar{B} \to \Xi_c \Lambda_c^{-}$ and $\bar{B} \to \Lambda_c^{+} \Lambda_c^{-} \bar{K}$ decays at BABAR

We report measurements of $B$-meson decays into two- and three-body final states containing two charmed baryons using a sample of $3.0 \times 10^8 \ U(4S) \rightarrow BB$ decays. We find significant signals in two modes, measuring branching fractions $B(B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-) = (1.14 \pm 0.15 \pm 0.17 \pm 0.60) \times 10^{-3}$ and $B(B^- \rightarrow \Lambda_c^- \bar{\Lambda}_c^+ K^-) = (2.90 \pm 0.26 \pm 0.38 \pm 0.24) \times 10^{-3}$. We also measure the branching fraction $B(B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-) = (1.15 \pm 0.15 \pm 0.20 \pm 0.20) \times 10^{-3}$ and find no significant evidence for $B(B^- \rightarrow \Lambda_c^- \bar{\Lambda}_c^+)$. These results are compared to the Standard Model predictions.

Deceased

Now at Tel Aviv University, Tel Aviv, 69978, Israel

Also with Università di Perugia, Dipartimento di Fisica, Perugia, Italy

Also with Università della Basilicata, Potenza, Italy

Also with Universitat de Barcelona, Facultat de Fisica, Departament ECM, E-08028 Barcelona, Spain
Bottom ($B$) mesons are heavy enough to decay into charmed baryons, and do so at a rate of roughly 5% [1,2]. The dominant decay mechanism is via $b \to c W^-$ transitions, with $W^-$ coupling to $\bar{c}s$ or $\bar{u}d$ [3], both of which are Cabibbo-allowed. Theoretical predictions for the branching fractions of $B$ mesons to baryon-antibaryon pairs have been made within the diquark model [4] and with QCD sum rules [5]. These suggest that decays to two charmed baryons ($B \to X_c \bar{X}_c$) and to one charmed baryon and one light baryon ($B \to X_c \bar{X}_d$) have comparable branching fractions, of the order of $10^{-3}$ for individual modes.

Several inclusive measurements of $B$-meson decays to charmed baryons have been made [1]. In particular, the BABAR Collaboration recently performed an inclusive analysis of $\Lambda_c^+$ production in which flavor tag information was used to identify whether the $\Lambda_c^+$ came from a $B$ or a $\bar{B}$ meson [6]. It was found that about a third of all $\Lambda_c^+$ were from $B$ mesons with anticorrelated flavor content (i.e. $b \to c$ rather than $b \to c$ transitions), consistent with a substantial rate of $b \to c\bar{c}s$ decays. Inclusive studies of the $\Xi_c^0$ and $\Lambda_c^+$ momentum spectrum [2,7,8] also support a substantial rate of baryonic $b \to c\bar{c}s$ decays such as $B^- \to \Xi_c^0 \Lambda_c^-$. However, inclusive studies alone cannot fully establish this, since the momentum distributions can also be reproduced with carefully tuned sums of $b \to c\bar{d}$ processes. Therefore, exclusive measurements are needed. These require very large samples of $B$-meson decays and have only recently become feasible.

The Belle Collaboration has reported results on $B$ decays to final states with two charmed baryons in both two- and three-body modes [9,10]. They measured $\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-) \times \mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ = $(2.08 \pm 0.65 \pm 0.29 \pm 0.54) \times 10^{-5}$, and $\mathcal{B}(B^0 \to \Xi_c^+ \bar{\Lambda}_c^-) \times \mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ = $(9.3^{+3.7}_{-2.8} \pm 1.9 \pm 2.4) \times 10^{-5}$ [9]. Assuming that $\mathcal{B}(\Xi_c^0 \to \Xi^- \pi^+)$ and $\mathcal{B}(\Xi_c^+ \to \Xi^- \pi^+ \pi^+)$ are of the order of $1\%$–$2\%$ [11], these results are compatible with the prediction that $\mathcal{B}(B^- \to \Xi_c^0 \bar{\Lambda}_c^-)$ and $\mathcal{B}(B^0 \to \Xi_c^+ \bar{\Lambda}_c^-)$ are $O(10^{-5})$. This is in stark contrast to the branching fractions of singly charmed decays, such as that of $B^0 \to \Lambda_c^- \bar{p}$ which is $(2.2 \pm 0.8) \times 10^{-5}$, smaller by 2 orders of magnitude [12].

The branching fractions of the three-body processes $B \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ were also found to be large: $\mathcal{B}(B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-)$ = $(6.65^{+0.10}_{-0.09} \pm 0.11 \pm 0.34) \times 10^{-3}$ and $\mathcal{B}(B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K^0)$ = $(0.78^{+0.09}_{-0.23} \pm 0.12 \pm 0.42) \times 10^{-3}$ [10]. Explanations for these widely varying values have been proposed [13,14]. It was suggested that a kinematic suppression may apply to decays in which the two baryons have high relative momentum, since this requires the exchange of two high-momentum gluons. The rate of $B \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ decays could also be enhanced by final-state interactions, or by intermediate charmonium resonances.

In this paper, we present measurements of the branching fraction of the decays $B^- \to \Lambda_c^+ \Lambda_c^- K^-$, $B^- \to \Xi_c^0 \bar{\Lambda}_c^-$, $B^0 \to \Xi_c^+ \bar{\Lambda}_c^-$, and $B^0 \to \Lambda_c^+ \bar{\Lambda}_c^- K^0$, and investigate three-body decays for the possible presence of intermediate resonances. The data were collected with the BABAR detector [15] at the PEP-II asymmetric-energy $e^+ e^-$ storage rings and represent an integrated luminosity of approximately 210 fb$^{-1}$ collected at a center-of-mass energy $\sqrt{s} = 10.58$ GeV, corresponding to the mass of the $Y(4S)$ resonance. The BABAR detector is a magnetic spectrometer with 92% solid angle tracking coverage in the center-of-mass frame. Charged particles are detected and their momenta are measured in a five-layer double-sided silicon vertex tracker and a 40-layer drift chamber, both operating in a 1.5 T magnetic field. Charged particle identification (PID) is provided by the average energy loss (dE/dx) in the tracking devices and by an internally reflecting ring-imaging Cherenkov detector. Photons are detected with a CsI(Tl) electromagnetic calorimeter. The instrumented flux return for the solenoidal magnet provides muon identification. Simulated events with $B$ mesons decaying into the relevant final states are generated with EVTGEN [16] and PYTHIA [17], while GEANT4 [18] is used to simulate the detector response. Inclusive Monte Carlo (MC) samples of $Y(4S)$ and $e^+ e^- \to q \bar{q}$ ($q = u, d, s, c$) events at $\sqrt{s} = 10.58$ GeV are also used, corresponding to more than 1.5 times the integrated luminosity of the data.

The $\Lambda_c^+$ candidates are reconstructed in the three decay modes $pK^- \pi^+$, $pK^0_S$, and $\Lambda \pi^+$; $\Xi_c^0$ candidates in the two decay modes $\Xi^- \pi^+$ and $\Lambda K^- \pi^+$; and $\Xi_c^+$ candidates in the decay mode $\Xi^- \pi^+ \pi^+$. We begin by reconstructing the long-lived strange hadrons: $K^0_S \to \pi^+ \pi^-$ and $\Lambda \to p \pi^-$ candidates are reconstructed from two oppositely charged tracks, and $\Xi^- \to \Lambda \pi^-$ from a $\Lambda$ candidate and a negatively charged track. In each case, we fit the daughters to a common vertex and compute their invariant mass. The mass is required to be within $3\sigma$ of the central value, where $\sigma$ is the experimental resolution and $3\sigma$ is approximately 4.0, 4.5, and 6.0 MeV/c$^2$ for $K^0_S$, $\Lambda$, and $\Xi_c^+$, respectively. Candidates with a $\chi^2$ probability below $10^{-4}$ are rejected. For $\Lambda$ candidates, we also require the daughter proton to satisfy PID criteria. The mass of the $K^0_S$, $\Lambda$, or $\Xi_c^+$ candi-

---

**DOI:** 10.1103/PhysRevD.77.031101

**PACS numbers:** 13.25.Hw, 11.30.Er, 12.15.Hh
date is constrained to its nominal value [1] for subsequent fits.

We suppress background by requiring the transverse displacement between the event and decay vertices to be greater than 0.2 cm for $K^0_S$, $\Lambda$, and $\Xi^-$, each of which travels several centimeters on average. We also require that the scalar product of the displacement and momentum vectors of each hadron be greater than zero, and that the transverse component of the displacement vector of a $\Xi^-$ candidate be smaller than that of its $\Lambda$ daughter.

Next, we reconstruct the charmed baryons $\Lambda^+_c$, $\Xi^0_c$, and $\Xi^+_c$ in the decay modes listed previously. In each case, we fit their daughters to a common vertex, require the invariant mass of the charmed baryon candidate to be within 18 MeV/$c^2$ (approximately 3 times the experimental resolution) of the nominal mass [1], reject candidates with a $\chi^2$ probability below $10^{-4}$, and then constrain the masses to their nominal values. We also require that daughter kaons and protons of the charmed baryons satisfy the PID criteria for that hypothesis.

We reconstruct $B$-meson candidates in the following final states: $\Lambda^+_c\bar{\Lambda}_c^-K^-$, $\Xi^0_c\bar{\Lambda}_c^-\bar{\Xi}_c^0$, and $\Lambda^+_c\bar{\Lambda}_c^-K^0_S$, fitting the daughters to a common vertex and requiring that the $\chi^2$ probability is at least $10^{-4}$. We also apply the kinematic and PID requirements mentioned above to the $K^0_S$ and $K^-$ daughters of the $B$ mesons. Because the branching fraction and efficiency are higher for $\Lambda^+_c \rightarrow pK^-\pi^+$ than for the other $\Lambda^+_c$ decay modes, we use only final states in which at least one $\Lambda^+_c$ or $\bar{\Lambda}_c^-$ decays to $pK^-\pi^+$ or $\bar{p}K^+\pi^-$. For each $B$-meson candidate, we compute the energy-substituted mass $m_{ES} \equiv (s/4 - p_B^2)^{1/2}$ and the energy difference $\Delta E \equiv E_B - \sqrt{s}/2$, where $p_B$, $E_B$, and $\sqrt{s}$ are the momentum and energy of the $B$ meson and the $e^+e^-$ collision energy, respectively, all calculated in the $e^+e^-$ center-of-mass frame. For a correctly reconstructed signal decay, the $m_{ES}$ distribution peaks near the nominal mass of the $B$ meson with a resolution of approximately 2.5 MeV/$c^2$, and $\Delta E$ peaks near zero with a resolution of 6.0–7.8 MeV depending on the final state. Figure 1 shows the $m_{ES}$ and $\Delta E$ distributions for $B^- \rightarrow \Lambda^+_c\bar{\Lambda}_c^-K^+$ candidates.

Background arises from several sources, including misreconstructed $B$ decays to two charmed baryons, $B$ decays to a single charmed baryon, $e^+e^- \rightarrow c\bar{c}$ events containing charmed baryons, and random combinations of tracks. We use inclusive MC simulations and events from the sidebands of $m_{ES}$, $\Delta E$, and charged baryon mass in data to study the background. We consider as background $B$-meson decays with the same final state that do not proceed via an intermediate charmed baryon—for example, $B^- \rightarrow \Xi^0_c\bar{p}K^+\pi^- \rightarrow \Xi^0_c\bar{\Lambda}_c^-$, or $\Xi^0_c\bar{\Lambda}_c^-\bar{\Xi}_c^0$, or a nonresonant multibody decay such as $B^- \rightarrow \Xi^0_c\bar{p}K^-\pi^-$. These events have similar distributions to the signal for $m_{ES}$ and the charmed baryon invariant masses, but are displaced in $\Delta E$ by an amount that depends on the final state but is generally more than 50 MeV. We remove these backgrounds by requiring that signal candidates satisfy $|\Delta E| < 22$ MeV. Finally, we require $5.2 < m_{ES} < 5.3$ GeV/$c^2$. The average number of reconstructed $B$ candidates per selected event varies between 1.00 and 1.14 depending on the final state. In events with more than one candidate, the one with the smallest $|\Delta E|$ is chosen. We verify with MC and events from data sidebands that this does not introduce any bias in the signal extraction. Studies of simulated events show that 1%–3% of signal events are incorrectly reconstructed with one or more tracks originating from the other $B$ in the event; this effect is taken into account implicitly by the efficiency correction described later.

In studies of the $\Xi_c$ and $\Lambda_c$ mass sidebands, we find no evidence for these processes and conclude that their contribution is negligible.

Another important source of background is feed-down from related processes. The $B$ meson can undergo a quasi-two-body decay via an excited charmed baryon such as $B \rightarrow \Xi^+_c\bar{\Lambda}_c^-$, or a nonresonant multibody decay such as $B \rightarrow \Xi_c^0\bar{p}K^+\pi^-$. These events have similar distributions to the signal for $m_{ES}$ and the charmed baryon invariant masses, but are displaced in $\Delta E$ by an amount that depends on the final state but is generally more than 50 MeV. We remove these backgrounds by requiring that signal candidates satisfy $|\Delta E| < 22$ MeV. Finally, we require $5.2 < m_{ES} < 5.3$ GeV/$c^2$. The average number of reconstructed $B$ candidates per selected event varies between 1.00 and 1.14 depending on the final state. In events with more than one candidate, the one with the smallest $|\Delta E|$ is chosen. We verify with MC and events from data sidebands that this does not introduce any bias in the signal extraction. Studies of simulated events show that 1%–3% of signal events are incorrectly reconstructed with one or more tracks originating from the other $B$ in the event; this effect is taken into account implicitly by the efficiency correction described later.

The signal yields are extracted from an unbinned extended maximum likelihood fit to the $m_{ES}$ distribution. We use separate probability density functions (PDFs) for sig-
The efficiency is determined by applying the same analysis procedure to simulated signal events. For the three-body $B$-meson decays, the efficiency depends upon the distribution in the Dalitz plane. We weight the simulated events to reproduce the efficiency-corrected, background-subtracted distribution seen in data for $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$. As a cross-check, we also compute the efficiency assuming a phase-space distribution and find a difference of less than 10% in each case.

We then obtain each branching fraction as

$$B(B \rightarrow X_c \bar{\Lambda}_c^- [K]) = \frac{\sum n_{s_j}}{N_{B} \prod_i B_{ij}}$$

where $X_c$ is the charmed baryon ($\Lambda_c^+$, $\Xi_c^0$, or $\Xi_c^+$), $n_{s_j}$ is the signal yield extracted from the fit to the data for the $j$th submode, $\prod_i B_{ij}$ is the product of the daughter branching fractions, $N_B$ is the number of neutral or charged $B$ mesons, and $\varepsilon_i$ is the signal detection efficiency. We assume equal decay rates of the $Y(4S)$ to $B^+ B^-$ and $B^0 \bar{B}^0$ [1].

The branching fraction $B(\Lambda_c^+ \rightarrow pK^- \pi^+)$ has been measured previously to be $(5.0 \pm 1.3)\%$ [1]. Because the branching fractions of $\Xi_c^0$ and $\Xi_c^+$ decays have not been determined experimentally, we quote the products of the

FIG. 2 (color online). The fitted $m_{ES}$ distributions observed for the decay modes (a) $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$, combining 5 exclusive final states; (b) $B^- \rightarrow \Xi_c^0 \bar{\Lambda}_c^-$, combining 2 exclusive final states; (c) $B^0 \rightarrow \Xi_c^+ \bar{\Lambda}_c^-$; (d) $B^0 \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- F^0$. Points with error bars represent the data, dashed lines the background PDF, and solid lines the sum of the signal and background PDFs.
branching fractions, \( B(B \rightarrow \Lambda_c^+ K^-) \times B(\Xi_c^0 \rightarrow \Xi^- \pi^+) \) and \( B(B \rightarrow \Xi_c^+ \bar{\Lambda}_c^-) \times B(\Xi_c^0 \rightarrow \Xi^- \pi^+ \pi^0) \). For the \( \Xi_c^0 \rightarrow \Lambda K^{+}\pi^{-} \) decay mode we scale the measured branching fraction by the ratio \( B(\Xi_c^0 \rightarrow \Xi^- \pi^+)/B(\Xi_c^0 \rightarrow \Lambda K^{-}\pi^{-}) = 1.07 \pm 0.14 \) \cite{[1]} so that its value can also be expressed as the product of the same two branching fractions.

For each decay mode, Table I gives the values of \( n_S, \varepsilon, \) the significance, and the branching fraction. For each mode with a significance below 2 standard deviations, we calculate the Bayesian upper limit \cite{[1]} on the branching fraction including systematic uncertainties and obtain \( B(\bar{B} \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^0) < 1.5 \times 10^{-3} \) and \( B(B \rightarrow \Xi_c^+ \bar{\Lambda}_c^-) \times B(\Xi_c^0 \rightarrow \Xi^- \pi^+ \pi^0) < 5.6 \times 10^{-5} \) at the 90\% confidence level.

Table II lists the main systematic uncertainties and their sum in quadrature. The largest uncertainty is from the charged track reconstruction efficiency, evaluated with control samples of \( \tau \) decays. A small correction is also included due to a known data/MC difference in tracking efficiency. Other sources of systematic uncertainty considered include: the number of \( B\bar{B} \) pairs in the data sample; the limited size of the signal MC sample; the PID efficiency, which is evaluated with control samples of \( \Lambda \rightarrow p \pi^-, D^{+} \rightarrow D^{0}(K^{-}\pi^{+})\pi^{+} \), and \( \phi \rightarrow K^{+}K^{-} \) decays; possible differences in \( \Delta E \) resolution between data and MC, which are estimated with control samples of \( B \rightarrow D^+ D^- K \) decays; charmed baryon branching ratios relative to the control modes \cite{[1]}; the \( \Lambda \) branching fraction \cite{[1]}; the presence of intermediate resonances in the charmed baryon decay and possible structure in the 3-body \( B \)-meson decays; and the assumption that \( B(Y(4S) \rightarrow B^0 \bar{B}^0) = B(Y(4S) \rightarrow B^+ B^-) = 0.5 \). For fit parameters which are fixed to values from fits to the signal MC, we vary the value by the uncertainty and take the largest change as a systematic uncertainty. Dividing out the absolute \( \Lambda_c^+ \) branching fraction also introduces a large systematic uncertainty, which we quote separately.

To investigate whether the three-body mode \( B \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^0 \) contains intermediate resonances, we examine the Dalitz plot structure of candidates in the signal region (\( m_{ES} > 5.27 \text{ GeV}^2 \)), shown in Fig. 3. After taking into account the expected background (estimated from the \( m_{ES} \) sidebands), the \( \Lambda_c^+ K^- \) mass spectrum of the data is inconsistent with a phase-space distribution (\( \chi^2 \) probability of \( 1.5 \times 10^{-7} \)).

### Table II. Summary of relative systematic uncertainties (%) on the branching fractions (BFs). The uncertainty on the \( \Lambda_c^+ \) BF is 26\% and is quoted separately.

<table>
<thead>
<tr>
<th>Source</th>
<th>( \Lambda_c^+ \bar{\Lambda}_c^- K^- )</th>
<th>( \Xi_c^0 \bar{\Lambda}_c^- )</th>
<th>( \Xi_c^+ \bar{\Lambda}_c^- )</th>
<th>( \Lambda_c^+ \bar{\Lambda}_c^- K^0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking efficiency</td>
<td>9.9</td>
<td>10.0</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>( B ) counting</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>MC sample size</td>
<td>0.8</td>
<td>1.6</td>
<td>2.4</td>
<td>1.5</td>
</tr>
<tr>
<td>PID efficiency</td>
<td>4.6</td>
<td>3.5</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>( \Delta E ) resolution</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Intermediate BFs</td>
<td>3.4</td>
<td>6.9</td>
<td>0.8</td>
<td>0.1</td>
</tr>
<tr>
<td>( \Lambda_c^+ \rightarrow pK^- \pi^+ ) Dalitz</td>
<td>2.9</td>
<td>1.8</td>
<td>1.8</td>
<td>3.6</td>
</tr>
<tr>
<td>( B \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K ) Dalitz</td>
<td>6.9</td>
<td>. . .</td>
<td>. . .</td>
<td>4.2</td>
</tr>
<tr>
<td>( Y(4S) ) BF</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Fit related</td>
<td>2.0</td>
<td>1.4</td>
<td>3.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Total</td>
<td>14.5</td>
<td>13.7</td>
<td>13.4</td>
<td>14.3</td>
</tr>
</tbody>
</table>
FIG. 3. Reconstructed $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ candidates in the signal region ($m_{\Sigma} > 5.27$ GeV/c$^2$, $\Delta E < 22$ MeV), shown as (a) the Dalitz plot, (b) the $\Lambda_c^+ K^-$ invariant mass distribution, and (c) the $\bar{\Lambda}_c^- \Lambda_c^+$ invariant mass distribution. Data from the signal region are shown as black points. Signal events from a phase-space simulation are shown as small gray points in (a) and as a histogram in (b) and (c). Data from the sideband region $5.20 < m_{\Sigma} < 5.26$ GeV/c$^2$ are shown as a shaded histogram in (b) and (c), normalized according to the expected background yield in the signal region. The masses of the $B$-meson candidates are not constrained.

In summary, we have studied $B$-meson decays to charmed baryon pairs in four decay modes using a sample of $230 \times 10^6$ $Y(4S) \rightarrow BB$ events. The measured branching fractions are consistent with the previous values within uncertainties [9,10]. The branching fraction of $B^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- K^-$ is found to be comparable to the $O(10^{-3})$ branching fraction predicted for two-body decays to a pair of charmed baryons. The data in the Dalitz plot and two-body mass projections are inconsistent with a phase-space distribution and suggest the presence of a $\Xi_c^0$ resonance in the decay.

We are grateful for the extraordinary contributions of our PEP-II colleagues in achieving the excellent luminosity and machine conditions that have made this work possible. The success of this project also relies critically on the expertise and dedication of the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and the kind hospitality extended to them. This work is supported by the US Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council (Canada), the Commissariat à l’Energie Atomique and Institut National de Physique Nucléaire et de Physique des Particules (France), the Bundesministerium für Bildung und Forschung and Deutsche Forschungsgemeinschaft (Germany), the Istituto Nazionale di Fisica Nucleare (Italy), the Foundation for Fundamental Research on Matter (The Netherlands), the Research Council of Norway, the Ministry of Science and Technology of the Russian Federation, Ministerio de Educación y Ciencia (Spain), and the Science and Technology Facilities Council (United Kingdom). Individuals have received support from the Marie-Curie IEF program (European Union) and the A. P. Sloan Foundation.

[3] Throughout this paper, for any given mode, the corresponding charge-conjugate mode is also implied.