Identified nearly a century ago by early workers in quantum mechanics, bound states can dramatically reduce radiation from optical resonators, opening up new application prospects in nanophotonics.
Recent work led by Hatice Altug, EPFL, has used bound states to create ultrasensitive biosensing devices targeted for personalized medicine.

EPFL / Bionanophotonic Systems laboratory
The physics of resonant nanostructures, which can trap light at the subwavelength scales and form high-density concentrations of electromagnetic energy, are driving advances in nanophotonics and metamaterials, taking the world closer to schemes for all-optical communication and data processing. For dielectric nanoscale structures in particular, the optical response depends on Mie resonances that not only strongly enhance light’s electric- and magnetic-field components, but also enable complex wavefront control, including modulation of amplitude, phase, dispersion and polarization of light (see “Meta-optics with Mie resonances,” OPN, January 2017, p. 24).

Until recently, though, Mie-resonant optical structures have suffered from a shortcoming—leakage of light, which significantly reduces the efficiency of their light–matter interaction and nonlinear response. Fortunately, a nearly century-old concept from quantum mechanics, so-called bound states in the continuum (BICs), is showing a way out of this quandary.

BICs are unique states of light that facilitate a sharp resonant response in subwavelength optical structures, associated with extremely high values of the resonance quality (Q) factor. These light states could help enable a new generation of ultrathin, versatile optical elements for enhancing nonlinear and quantum effects, developing low-threshold lasers and realizing strong-coupling regimes in subwavelength resonators. And BICs are not just confined to electromagnetic waves—they are, instead, a general wave phenomenon also found in acoustics, fluid mechanics and many other fields.

From quantum mechanics to photonics

In practice, any open resonant system is coupled to external radiation states and inevitably loses its energy. BICs constitute an intriguing exception. In a BIC, the resonator energy becomes completely localized—even though the state is embedded into the continuous spectrum of the environment. BICs are thus sometimes referred to as trapped states with embedded eigenvalues.

The prospect of such exotic trapped states was first discovered in 1929, in the context of quantum mechanics—but the specific proposal was somewhat artificial and not realized in experiment (see “The birth of BICs,” p. 41). Much later, the theory of atomic resonances offered alternative, more practical routes to design BICs. In 1985, H. Friedrich and D. Wintgen demonstrated that the evolution of continuous parameters of a system can induce destructive interference between a pair of resonances. This, in turn, would result in an avoided crossing of their energy dispersion spectra—and an exact vanishing of the linewidth for one of the resonances, which is transformed into (in theory) an infinite-Q-factor BIC. Subsequently, simpler approaches to construct electronic BICs were proposed, and the BIC concept also rapidly entered other fields of wave physics.

After the late 1970s, theoretical studies revealed the existence of exotic “leaky” modes with vanishing radiation for different configurations of guided waves in optical resonators. These studies (including explorations of corrugated dielectric waveguides and 2D photonic crystals) did not associate the observed effects with the BIC phenomenon and did not recognize the connection with quantum mechanics. The first analysis

Two types of BICs

Symmetry-protected BICs arise from a symmetry mismatch, as in arrays of coupled optical waveguides with two defects that support a decoupled antisymmetric mode (left). A second BIC type, accidental BICs, arise due to the continuous tuning of parameters (for example, the wavevector) in systems such as a photonic-crystal slab (right).

BICs—unique states of light that facilitate a sharp resonant response in subwavelength optical structures—could help enable a new generation of ultrathin, versatile optical elements.

uncovering the physics of BICs in optics (specifically, for an array of coupled optical waveguides)—by Dana-Codruta Marinica, Université Paris-Sud, France, and colleagues—came only a dozen years ago, in 2008.

A few years later, in 2011, Yonatan Plotnik and colleagues at the Technion, Israel, went beyond theory, performing specifically targeted experiments on optical BICs. The team used femtosecond direct laser writing in fused silica to fabricate an array of coupled optical waveguides, with two additional waveguides fabricated above and beneath the array. In the coupled array, the modes of individual waveguides interact and form a continuous-spectrum energy band, while the additional waveguide pair supports an antisymmetric mode embedded into that continuous energy spectrum. The symmetry mismatch completely decouples the guided mode—a “symmetry-protected” bound state—in the waveguide pair from the continuous spectrum of the waveguide modes in the array, allowing the antisymmetric state of the waveguide pair to propagate without losses. The symmetric mode of the waveguide pair, in contrast, is recoupled to the array spectrum, and the energy leaks to the array.

Two years after that, Chia Wei Hsu and colleagues at the Massachusetts Institute of Technology, USA, exploited Friedrich–Wintgen-style parameter tuning to observe another type of optical BICs in periodic photonic structures—so called accidental BICs. The demonstration involved a photonic-crystal slab with 2D periodic holes made in a silica substrate, immersed in an optical liquid index-matched to silica. The result is an optically symmetric environment, required for observation of accidental BICs. Numerical analysis of the slab's band structure predicted that the slab’s radiative $Q$ factor, which governs optical losses and field enhancement, would diverge for certain wave-vector values of certain photonic bands. The experimental spectra confirmed the numerical analysis, revealing sharp resonances and the measured radiative $Q$ factor of $10^6$.

An origin in interference

Clearly, the experiments outlined above suggest that BICs have great potential for trapping electromagnetic...
energy with high density and avoiding the leakage of energy out of waveguides and resonators. But what is the origin of BICs, and how do they work?

Fundamentally, BICs originate from destructive wave interference, when two or more waves superpose to completely suppress radiative losses. In periodic photonic structures such as gratings, photonic-crystal slabs or metasurfaces, the periodicity of the medium results in the coupling of guided modes in the medium to the continuum of propagating modes in the surrounding free space—causing the guided modes to become leaky. At the same time, the periodicity also causes backscattering of leaky modes and their strong coupling in high-symmetry points of the momentum space (for example, in the origin).

For structures with in-plane inversion symmetry, this coupling is precisely balanced at such high symmetry points, which allows constructing a symmetric leaky mode, via constructive interference, and an antisymmetric bound mode—a BIC—that remains localized. Depending on the design, such symmetry-protected BICs can belong to a high-frequency or low-frequency band. Accidental BICs can appear at nonzero wave vectors for structures with certain additional symmetries.

For periodic photonic structures, the continuum of modes of the surrounding space is “discretized”—meaning that radiation is allowed only to a finite number of directions, known as open diffraction channels. When the unit cell of the structure reaches the subwavelength size, there is a single open diffraction channel, equivalent to specular reflection. Thus, for those structures, a BIC appears when the coupling constant to this single radiation channel vanishes—something that can be engineered via symmetry mismatch (for symmetry-protected BICs) or by continuous parameter tuning of the system (for accidental BICs).

**From ideal BICs to quasi-BICs**

The hallmark of a BIC is that its radiative $Q$ factor diverges, becoming theoretically infinite, at specific points in the momentum space. In principle, this enables the boundless enhancement of both electric and magnetic fields. Pure nonradiative BICs, however, exist only as a mathematical ideal—for structures of infinite size, or made of materials with zero or infinite permittivity.

In practice, BICs instead manifest themselves as “quasi-BICs,” leaky modes whose $Q$ factors are limited by parameters related to material absorption, sample finiteness, fabrication imperfections, structural disorder and energy leakage into the substrate. To achieve dramatic field enhancement inside a real-world structure, it is vital to balance radiative and nonradiative losses, which can be done by adjusting the radiative $Q$ factor of the BIC by breaking structural symmetries or through parameter tuning.

Other essential features associated with optical BICs and quasi-BICs include a unique multipolar structure. Symmetry-protected BICs are associated with the multipole moments of the meta-atoms that do not radiate in the normal direction. Accidental BICs originate due to the simultaneous destructive interference of all multipole components in the direction of the open diffraction channel.

Finally, BICs relate fundamentally to Fano resonances—a kind of resonance with a characteristic asymmetric scattering profile, which results from interference between sharp resonant and broad non-resonant modes. In experiments, quasi-BICs are observed as sharp

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**How BICs form in periodic structures**

A pair of leaky guided modes is strongly coupled at the momentum space origin if the slab includes periodicity. Strong coupling induces constructive and destructive interference. The former produces a leaky mode with strong radiation losses; the latter leads to a BIC with an infinite radiative $Q$ factor.
The hallmark of a BIC is that its radiative $Q$ factor diverges, becoming theoretically infinite, at specific points in the momentum space.

asymmetric peaks with a Fano lineshape. Ideal or mathematical BICs, meanwhile—in which the resonance width completely vanishes—manifest themselves as a “collapse” of the Fano resonance, with the Fano feature disappearing from the spectrum.

**BICs in the subwavelength realm**

These characteristics are opening the door for new applications in sensors, lasers and more in a variety of subwavelength material systems. We offer a few examples in the paragraphs that follow.

**Optical gratings and photonic-crystal slabs**

Narrow resonances in most common periodic photonic structures, such as gratings and photonic-crystal slabs, have found applications in areas such as spectral and angular filtering of optical signals, directive outcoupling of the radiation, diffractive optics, and surface wave excitation. In 2014, for example, BICs in subwavelength dielectric gratings were shown to enable large-area narrowband transmission filters for normal incidence.

While most surface-emitting distributed-feedback lasers developed in the 1980s and 1990s exploit the modes formed at the origin of the momentum space, they operate not on the symmetry-protected BIC but on the complimentary bright mode—the leaky state formed due to constructive interference. Recent work from the group of Boubacar Kanté at the University of California, San Diego, USA, proposed the first BIC-based laser designed for telecommunication wavelengths and built on a CMOS-compatible semiconductor platform. The cavity of this system consists of an array of coupled semiconductor nanoscale disks, interconnected by bridges and arranged in a thin, submicron membrane suspended in the air. Lasing was experimentally demonstrated for a nanosecond pulsed laser at room temperature, showing perfect agreement with theoretical predictions. The same group also demonstrated a BIC-based laser that uses polarization singularities, which enables the generation of powerful coherent beams carrying orbital angular momentum (OAM).

Another platform supporting BICs is chains of dielectric scatterers, a system with potentially big prospects for vector beam sources transferring OAM. Key

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**Symmetry-protected BICs in metasurfaces**

All-dielectric metasurfaces consisting of subwavelength resonators, or meta-atoms, with broken in-plane inversion symmetry give rise to sharp resonant features—with the radiative $Q$ factor tied to an asymmetry parameter, $\alpha$, via an inverse-square law.

contributions to the theory of dielectric chains came from Almas Sadreev and colleagues at the Kirensky Institute of Physics, Russia, who have also obtained pioneering results on BICs in quantum, optical and acoustic systems.

**Metasurfaces**

Metasurfaces based on dielectric nanostructures with electric and magnetic Mie-type resonances have resulted in the best efficiency to date for functional flat optics. The generalized Huygens principle, with a superposition of the scattering contributions from several electric and magnetic multipolar modes of the systems' constituent meta-atoms, allows destructive interference in reflection or transmission over a large spectral bandwidth. This novel concept has allowed demonstrations of reflectionless (around 90% transmission) half-wave plates, quarter-wave plates, and vector beam q-plates that can operate across multiple telecom bands with around 99% polarization conversion efficiency.

All-dielectric metasurfaces composed of meta-atoms with broken in-plane inversion symmetry are known to have sharp resonant responses in normal-incidence reflection and transmission. As was recently shown by Kirill Koshelev of the Australian National University, Australia, and colleagues, the BIC concept can unify all of these high-Q resonances across seemingly different metasurfaces with asymmetric unit cells. Specifically, an asymmetry induces an in-plane dipole moment (or, if it is zero, the next allowed multipole moment), resulting in radiation in the vertical direction, giving rise to the normal-direction resonant response. Breaking the out-of-plane symmetry of meta-atoms also allows control of the properties of high-Q resonances originating from the BIC physics.

Recent research built on this idea targets the application of BIC-supporting metadevices in biosensing. At present, available biosensing methods are cumbersome, requiring laboratory infrastructure, trained personnel and complex bioassay protocols, making them unsuitable for point-of-care and lab-on-a-chip applications. Nanophotonic biosensors, on the other hand, hold great promise for detecting biomolecules in a label-free, and nondestructive manner based on the enhanced light-matter interactions with nanoengineered metasurfaces. Recent work led by Hatice Altug of EPFL, Switzerland, has shown how leveraging BICs can enable high-Q dielectric metasurface biosensing and hyperspectral imaging for ultrasensitive biomolecule detections (see opening image, pp. 38-39).

**Subwavelength nanoparticles**

The parameter-tuning approach to BICs pioneered by Friedrich and Wintgen is not limited to extended photonic structures; it can also be directly applied to construct high-Q resonances in compact geometries at subwavelength scales. In very recent work, Mikhail Rybin of the ITMO University, Russia, and colleagues proposed realizing high-Q modes in an individual dielectric nanoscale resonator, via continuous tuning of the resonator's aspect ratio which enables destructive interference and strong coupling of pairs of leaky modes (radial and axial) with similar far-field profiles when their frequencies come close to degeneracy.

For such a localized resonator, any portion of trapped light is released through a continuum of radiation modes simultaneously, which makes a totally nonradiative state impossible in these compact geometries, unless one considers materials with either infinite or zero permittivity, as was done by the group of Andrea Alù,
The BIC—a phenomenon that occurs in the many fields of wave physics, including electromagnetism, acoustics, hydrodynamics and quantum mechanics—is finding a new life in optics as well.

CUNY, USA—something not yet common for optical frequencies. Therefore, at subwavelength scales, BICs manifest themselves as quasi-BICs, also known as supercavity modes. The concept of supercavity modes provides a versatile platform for optical resonators, with the nanoscale footprint offering a strong benefit over many implementations of resonators relying on alternative mechanisms of localization, such as whispering-gallery modes and cavities in photonic-bandgap structures, where efficient light trapping requires dozens of structural periods.

The study of nonlinear effects with quasi-BIC in individual nanoparticles has been initiated only very recently, with the experimental demonstrations yet to come. A team including Luca Carletti of the Università di Padova, Italy, for example, analyzed the efficiency of second-harmonic generation from individual subwavelength dielectric nanoparticles and predicted that nonlinear effects at the nanoscale can be boosted dramatically provided the resonator parameters are tuned to the supercavity regime.

Summary and outlook
The BIC—a beautiful phenomenon that occurs in the many fields of wave physics, including electromagnetism, acoustics, hydrodynamics and quantum mechanics—is finding a new life in optics as well. And, as even the work that has been done thus far has shown, that development could have important implications for engineering highly efficient resonances for photonics at the nanoscale.

One very recent demonstration, for example, goes beyond the traditional concept of the interference of leaky modes to create BICs, employing the interference of multiple BICs themselves in an optical resonator—thereby substantially suppressing optical scattering losses due to roughness and structural disorder of the material itself, by merging BICs with different propagation directions. This enables dramatic enhancement of the optical $Q$ factor to experimentally record-high values of $4.9 \times 10^5$—more than an order of magnitude higher than any earlier reported BIC observations.

The possibility of converting optical waves into BICs also allows the realization of supercavity modes characterized by extremely high $Q$ factors in resonators with very compact geometries. Many high-refractive-index dielectric materials involving the vectorial nature of electromagnetic waves could be employed to reduce the resonator dimensions, and to combine individual, high-$Q$ BIC resonators in structured arrays. We envision the rapid development of novel approaches in the electromagnetic theory of vectorial resonances in such arrays in the future. By engineering $Q$ factors in the BIC regime in this way, we believe that future technologists will be able to substantially enhance nonlinear and quantum effects—and thus to develop low-threshold lasers and realize strong-coupling regimes of nanoscale supercavities.

References and Resources