Fano Resonances: A Discovery that Was Not Made 100 Years Ago

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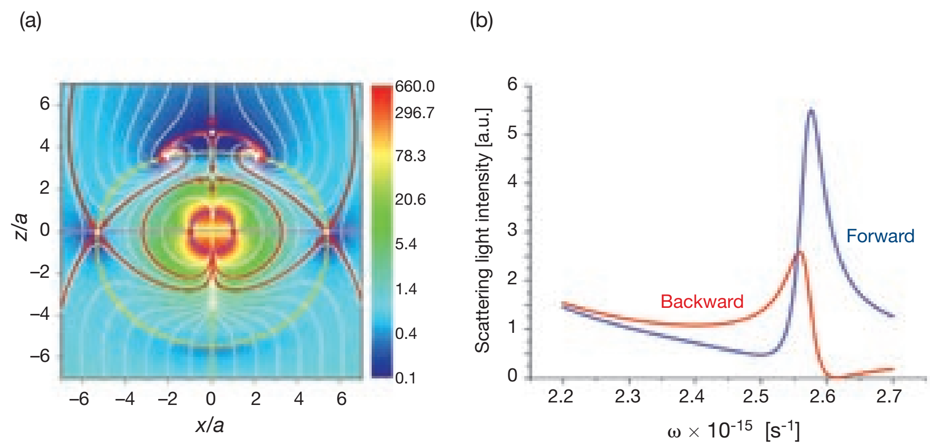
Rayleigh scattering is characterized by a sharp increase in scattering intensity with a rise in light frequency.[1] It explains why we can enjoy the blue color of the sky during the day (the intensely scattered blue component of the sunlight) and scarlet sunrises and sunsets at dawn and dusk (the weakly scattered red component). Lord Rayleigh's studies were generalized by the German scientist Gustav Mie, who, in 1908 (exactly 100 years ago!), obtained the complete analytical solution of Maxwell's equations for the scattering of electromagnetic radiation by a spherical particle valid for any ratio of diameter to the wavelength.[2]

A common belief is that the general Mie solution transforms into that of Rayleigh when particles are small. However, recent studies of resonant scattering by particles with negative dielectric susceptibility and a weak dissipation rate reveal that this may not be the case. The studies disclose new and unexpected features of Mie scattering by small particles, namely giant optical resonances with an inverted hierarchy (the quadrupole resonance is more intense than the dipole, etc.), a complicated near-field structure with vortices, unusual frequency and size dependencies of the scattered light, and other features that make such scattering anomalous.[3]

With this anomalous scattering, incident light excites localized electromagnetic modes (plasmons or polaritons) in a scattering particle. The modes oscillate with the frequency of the incident wave. The corresponding polarization oscillations of the particle result in the emission of electromagnetic waves with the same frequency, which then interfere with the incident light. Resonances correspond to cases when the frequency occurs close to (the real part of) the eigenfrequency of one of the localized plasmonic modes.



(a) The Poynting vector field in the vicinity of the dipole resonance for a particle with ratio of the radius over the wavelength $a/\lambda = 0.3/2\pi$.[3] (b) Line shapes for forward and backward scattering by a potassium nanocluster with radius 6.2×10^{-6} cm immersed in a crystal of KCl exhibiting typical Fano resonance asymmetric profiles.[5]

This physical picture recalls the well-known Fano resonances in quantum physics.[4] Recent research has revealed that this analogy is indeed exact,[5] and the anomalous light scattering does exhibit the quantum Fano resonances. In this case, the localized plasmons (polaritons), excited by the incident light in the scattering particle, are equivalent to quasi-discrete levels in Fano's approach, while the radiative decay of these excitations plays exactly the same role as that of tunneling from the quasi-discrete levels in quantum objects. As a result, the resonance may have a typical asymmetric profile with a local maximum and minimum situated close to one another. Such a line shape corresponds to constructive and destructive interference of different eigenmodes, respectively. In particular, the destructive interference may result in considerable or even complete suppression of the scattering along any given direction.

Thus, the famous Fano resonances[4] could have been discovered in 1908. Instead, they have remained hidden inside the exact Mie solution for 100 years!

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References

1. Lord Rayleigh. Phil. Mag. **41**, 107 (1871); **41**, 274 (1871); **41**, 447 (1871).
2. G. Mie. Ann. Phys. **25**, 377 (1908); P. Debye. Ann. d. Physik **30**, 57 (1909).
3. M.I. Tribelsky and B.S. Luk'yanchuk. Phys. Rev. Lett. **97**, 263902 (2006).
4. U. Fano. Phys. Rev. **124**, 1866 (1961).
5. M.I. Tribelsky et al. Phys. Rev. Lett. **100**, 043903 (2008).