Nuclear Science and Techniques (2023) 34:189
https://doi.org/10.1007/s41365-023-01343-8

RESEARCH HIGHLIGHT

A novel way to study the nuclear collective excitations

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Received: 7 November 2023 / Revised: 7 November 2023 / Accepted: 8 November 2023 / Published online: 2 December 2023
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Typically, the unambiguous determination of the quantum numbers of nuclear states is a challenging task. Recently, it has been proposed to utilize to this aim vortex photons in the MeV energy region and, potentially, this could revolutionize nuclear spectroscopy because of the new and enhanced selectivity of this probe. Moreover, nuclei may become diagnostic tools for vortex photons. Still, some open questions have to be dealt with.

Nuclei exhibit intricate excitation spectra. Indeed, not all states within these spectra are equally significant. Some are not sensitive to specific terms in the nuclear Hamiltonian or do not display novel features, so that investigating them is not helpful to enhance our overall understanding of nuclear structure. On the other hand, there are states that manifest themselves as prominent peaks, e.g., in the inelastic scattering spectra. Among the best examples are the so-called Giant Resonances that lie at energies of the order of tens of MeV [1].

Giant resonances not only represent easily excitable states, but they are also deeply linked with our understanding of the nuclear collective phenomena and of the effective Hamiltonian that govern them. The large magnitude of their excitation cross-section stems from the fact that a significant fraction of the nucleons are excited. In brief, giant resonances are a clear example of nuclear collective motion. These resonances come in various forms and are associated with different quantum numbers. For instance, in a spherical nucleus, the total angular momentum J and the parity π are the exact quantum numbers, in principle; but $\vec{J}$ is the sum of the spatial angular momentum $\vec{L}$ and spin $\vec{S}$, and these latter are approximate quantum numbers but still are valid to classify giant resonances.

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The monopole ($J = 0$), dipole ($J = 1$) and quadrupole ($J = 2$) resonances have been known for some time and have proven to provide very specific and valuable insight. The giant monopole resonance, often referred to as the nuclear "breathing mode," has been shown to be correlated to, and inform us about, the incompressibility of nuclear matter [2]. In the dipole case, the predominant physical mode involves neutrons oscillating in opposition to protons and is known as the isovector giant dipole resonance (IVGDR). It is analogous to what takes place in molecules and clusters, where electrons oscillate with respect to the ions in the "plasmon" modes [3]. Just as plasmons are highly sensitive to the screening of the Coulomb interaction, in the very same way the IVGDR is sensitive to the neutron–proton interaction in the nuclear medium [4].

In short, giant resonances have been so far an extremely valuable source of information to solve some of the key questions related to the physics of the atomic nucleus, and it is highly probable that the discovery of new giant resonances will enrich this understanding. However, here comes the significant challenge: For many years, the absence of exclusive probes that can excite giant resonances has constituted a significant impediment. This is, to some extent, also true for other nuclear excited states. There exist low-lying excitations that are sensitive to nucleon correlations around the Fermi energy and excited states that are good probes of nuclear rotation, nucleon clustering, or coupling to the continuum. Last but not least, some specific states play a very important role in astrophysical phenomena like stellar stability and the synthesis of new elements.

Protons, α-particles, and heavier ions are often used in inelastic scattering experiments. α-particles, for instance, are essentially pure $S = 0$ states in their ground state; thus, they do not transfer spin to the nucleus when inelastically scattered, but they do transfer different values of L. From a semiclassical perspective, during a grazing collision where the α-particle and the nucleus barely make contact, corresponding to an impact parameter equal to the sum R of their radii, the transferred value of L can be estimated as

$$L = 2kR\,\sin\frac{\theta}{2} \approx kR\theta. \tag{1}$$

Here, k is the initial wave vector and θ is the scattering angle. However, the semiclassical argument is only a rough estimate: In fact, the partial cross sections associated with different L-transfers are smeared and overlap with one another. There is no unambiguous way to separate them, and this is a first source of uncertainty when using inelastic scattering to identify giant resonances or other excited states. An even more significant source of uncertainty arises from the incomplete knowledge of the α-nucleus interaction. As a consequence, extracting the properties of the giant resonances from the measured cross section becomes a highly model-dependent procedure.

Here comes the breakthrough, as detailed in Ref. [5]. Let us imagine we wish to investigate elusive Giant Resonances, like, e.g., the octupole ($J = 3$), and we ask ourselves how to do so. In [5], a novel method has been proposed to excite giant resonances having a given angular momentum, in a controlled way. The idea is to exploit the electromagnetic interaction using photons with good orbital angular momentum, rather than linear momentum. These are called *twisted* photons, or *vortex* photons.

An excellent introduction to photons with nonzero orbital angular momentum can be found in Ref. [6]. They have been used in optics [7] and atomic physics [8] for quite some time, since the pioneering work in Ref. [9]. Electron vortex states are reviewed in [10]. A recent review with many ideas related to possible, innovative applications to nuclear and high-energy physics of the vortex states of photons, electrons and neutrons can be found in Ref. [11]. A vortex state of a field propagates along a given direction, say the z-axis, and carries a nonzero projection of the angular momentum along that axis. In the case of photons, vortex states are solution of the wave equation in cylindrical symmetry.

Figure 1 provides an illustration of the vortex photon field, offering a visual representation of its features. The wave propagates, on average, along the z-axis, and Fig. 1a shows its spiralling Poynting vector. This wave is a linear combination, with given amplitudes, of plane waves components associated with wave vectors $\mathbf{k}$ that are situated on the surface of a cone and possess a transverse wave vector κ, together with a z-component equal to k_z. The opening angle of this cone is $\theta_k = \arctan\frac{\kappa}{k_z}$ [cf. Figure 1b]. In the case of a scalar field, the orbital angular momentum m_ℓ along the z-axis stems from the fact that the combination of wave vectors on the surface of the cone is characterized by a phase $e^{im_\ell \phi_k}$, where ϕ_k is the angle around z. In the case of a vector field, one has to take into account the spin quantum number and this leads to slightly more intricate mathematical formulas. Details can be found in

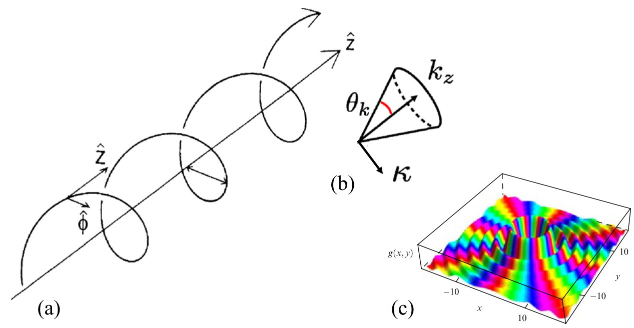

Fig. 1 (Color online) **a** Curve representing the propagation (i.e., the Poynting vector) along the z-axis of a vortex field. Taken from Ref. [9]. **b** The cone on which plane wave components of the vortex field lie. **c** Illustration of the vector potential on the xy-plane, in the case $m = 5$, $\theta_k = \arcsin 0.2$ and $\Lambda = 1$. Taken from Ref. [6]

[5, 6]. For our present discussion, what matters is the fact that one needs to introduces the spin of the photon: its projection σ on the z-axis, when combined with the projection of the orbital angular momentum m_ℓ, produces the total angular momentum along z, that is $m = m_\ell + \sigma$, whereas, at the same time, its projection on the direction of $\mathbf{k}$ is defined as the helicity Λ. Figure 1c displays the vector potential associated with such photon field, in the case of so-called Bessel modes, for specific values of m, θ_k and Λ.

Let us now consider a scenario in which the photon is absorbed by a nucleus lying precisely on the beam axis, that is, at zero impact parameter ($b = 0$). The z-component of the angular momentum of the photon, m, is transferred to the nucleus. Therefore, one can be sure that $J \geq |m|$. Coming back to our question above, we know how to excite selectively octupole or larger multipoles, eliminating the dipole and quadrupole contributions. That is in itself very relevant but, in addition, a more subtle feature displayed by the absorption process emerges. Conservation laws dictate that the angular momentum must be conserved along different axis that are rotated with respect to each other. As just mentioned, in addition to projecting angular momentum on the z-axis, we can project on the direction of $\mathbf{k}$. The overall result is expressed by a mathematical function [for those well-versed in quantum theory of angular momentum, this is a Wigner matrix $d^J_{m\Lambda}(\theta_k)$] that expresses the joint probability amplitude that the nucleus receives an amount of angular momentum J, by absorbing a photon with angular momentum m along z and with a spin Λ on a direction that forms an angle θ_k relative to z. Since this function has different zeros and maxima for different J, one can exploit this feature to enhance the selectivity and, for instance, excite $J = |m|$ while eliminating $J = |m| + 1$. The selectivity which was not possible with inelastically scattered particles, shows up as is evident from the simulations in Fig. 2.

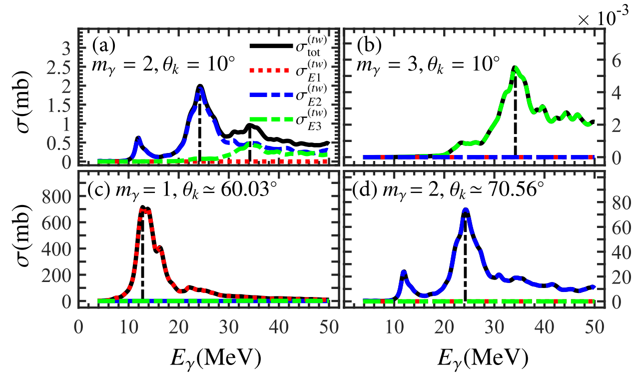

Fig. 2 (Color online) Theoretical photoabsorption cross sections of the nucleus ^{208}Pb, calculated in the case of vortex photons with various m and θ_k ($\Lambda = 1$). Details on the specific nuclear model used to calculate the $E1$, $E2$ and $E3$ transitions can be found in Ref. [5]. The figure is adapted from [5]

The devil lies in the details, as is said. Vortex photon beams with energies in the range of Fig. 2, tens of MeV, should be in principle doable but have not been prepared yet. Moreover, when doing experiments with a macroscopic target, one does not deal with a single nucleus at $b = 0$ and averaging over b is mandatory. This is discussed in [5] but has to be confronted with experimental constraints. A further point is the assumption, in the calculations of Ref. [5], of Bessel modes; most likely, using Gauss-Legendre profiles as is done when describing vortex photons in the optical regime [9] will not change the main conclusions of [5], but has to be dealt with. Despite these warnings, using vortex photons may definitely help nuclear physics in several ways, and further hints are in the work itself of Ref. [5]. Discussion in the experimental and theoretical communities should deepen all open questions.

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