A new scissors mode on the skin of deformed neutron rich nuclei

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Covariant density functional theory is used to analyze the evolution of low-lying M1 strength in superfluid deformed nuclei in the framework of the self-consistent Relativistic Quasiparticle Random Phase Approximation (RQRPA). In nuclei with a pronounced neutron excess two scissors modes are found. Besides the conventional scissors mode, where the deformed proton and neutron distributions oscillate against each other, a new soft M1 mode is found, where the deformed neutron skin oscillates in a scissor like motion against a deformed proton-neutron core.

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Since the discovery of the of the Giant Dipole Resonance (GDR) in the photo absorption spectra of nuclei and its interpretation as an oscillation of protons against neutrons\textsuperscript{1}, many other collective excitations have been found, and much has been learned about the bulk properties of nuclei from such resonances. The interpretation of such modes is closely linked with the symmetries of the underlying system, and the phase transitions connected with their spontaneous breaking. The simplest example is the translational motion of the entire nucleus, protons and neutrons in-phase, with the quantum numbers \(J^\pi = 1^-, T = 0\). Because of translational invariance, this mode is not really an excitation, but it shows up in the theoretical excitation spectra as a Goldstone mode connected with the symmetry violation by the mean field approach. Closely related is the vibration of neutrons against protons, with the quantum numbers \(J^\pi = 1^-, T = 1\). It is, of course, not spurious and corresponds to the Giant Dipole Resonance (GDR).

A similar pattern has been observed in deformed nuclei. Rotational symmetry is spontaneously broken and the corresponding Goldstone mode with the quantum numbers \(K^\pi = 1^+, T = 0\) in the intrinsic system is connected with the collective rotation of protons and neutrons in-phase. Since thirty years it is also known that there is a vibrational mode with the quantum numbers \(K^\pi = 1^+, T = 1\), corresponding to a scissors-like rotational motion of neutrons against protons\textsuperscript{2,3,4,5,6}. It can be excited by the magnetic dipole (M1) operator and has been found in many nuclei at energies of a few MeV by scattering of proton, electrons or photons (for reviews and recent applications see Refs.\textsuperscript{2,3,4,5}).

In recent years, new experimental facilities have permitted the study a variety of new phenomena connected with the isospin degree of freedom. Systems with large neutron excess show a pronounced neutron skin and much experimental and theoretical interest has been devoted to the study of collective modes connected with this skin. The Pygmy Dipole Resonance (PDR) identified in the E1-strength distribution at low energies has been interpreted as a resonant oscillation of the neutron skin against the remaining isospin saturated neutron-proton core. It has been observed not only in light systems\textsuperscript{7,8}, but also in heavy nuclei with neutron excess in and far from the valley of \(\beta\)-stability\textsuperscript{9}. This mode is also expected to play an important role in astrophysical applications in neutron rich systems, where the presence of a low-lying resonant component of the E1 strength has a strong influence on the radiative neutron-capture rates in the r-process\textsuperscript{10}.

On the theoretical side, the pygmy mode was first predicted in hydrodynamical models\textsuperscript{13,14} and, later, in the context of density functional theory\textsuperscript{15}. More recently, it has been studied with the aid of RPA and QRPA calculations, as well as large scale shell model applications (for a recent review see Ref.\textsuperscript{16} and references given therein). Since the pygmy mode has translational character, its quantum numbers are \(J^\pi = 1^-\). The isospin is mixed. In the nuclear interior protons and neutrons move in phase, forming a \(T = 0\) core, while near the nuclear surface, build up predominantly by neutrons, one has a superposition of \(T = 0\) and \(T = 1\).

In the PDR, the neutron skin describes a translational motion with respect to a core composed of neutrons and protons. It is natural to expect that, in a similar way, the skin plays also a role in the scissors mode in deformed nuclei with rotational character. This has been investigated in Ref.\textsuperscript{17} in a boson model with three degrees of freedom (protons, core neutrons and neutron skin) and it has been shown that group theory allows several possible modes. One of them is the normal scissors mode, where the protons oscillate against the combined system of neutrons (core and skin). In addition a new mode is possible, where the protons form together with the neutrons a deformed core system with \(T = 0\), which oscillates in a scissors like motion against the deformed neutron skin. However, there are further modes possible and in a group theoretical model it is hard to decide which of them is realized in actual nuclei.

In the present manuscript we investigate this question in a fully microscopic and self-consistent way using covariant density functional theory. As an example
we concentrate on the nucleus $^{154}$Sm, which has an excess of 30 neutrons. Density functional theory based on the mean field approach plays an important role in a fully microscopic and universal description of nuclei all over the periodic table. Covariant density functional theory (CDFT) is particularly successful because Lorentz invariance reduces the number of parameters considerably. Pairing correlations can be included in the framework of relativistic Hartree-Bogoliubov (RHB) theory. For recent reviews see Refs. [18-19]. Starting from the time-dependent version of CDFT, the same functionals can also be applied to investigate nuclear excitations. In the small amplitude limit one finds the relativistic Random Phase Approximation (RRPA) [20], suited for the description of excited states with vibrational character. It has been used with great success for the study of giant resonances and spin-or/and isospin-excitations as the Gamow-Teller Resonance (GTR) or the Isobaric Analog Resonance (IAR) [21]. Recently it also has been applied for a theoretical interpretation of the low lying E1 strength [22].

So far, applications of relativistic RPA and QRPA have been restricted to spherical systems. Here we report on the first theoretical investigation using a fully self-consistent implementation of relativistic QRPA for deformed nuclei with axial symmetry. We use the parameter set NL3 [23], which has been thoroughly tested and proven to successfully describe many nuclear properties. Pairing correlations are taken into account using a monopole pairing force with the strength parameters adjusted to the experimental pairing gaps obtained from odd-even mass differences.

First the relativistic mean field equations are solved in the basis of an anisotropic axial harmonic oscillator with 20 major shells [24]. The resulting Dirac spinors for the ground-state are subsequently used to construct two-quasiparticle pairs with the appropriate quantum numbers $K^\pi = 1^+$, and to evaluate the matrix elements of the effective interaction obtained from the second derivative of the original energy functional using a Fourier-Bessel decomposition in cylindrical coordinates [25, 26]. No new parameters are necessary. The solution of the QRPA equations provide the excitation spectrum, and allows the calculation of the dynamical M1-response $R_{M1}(\omega)$ and the corresponding strength function. Since the starting point is a deformed mean-field the calculated response function refers to the intrinsic frame. It has to be transformed to the laboratory frame by projection onto good angular momentum $I = 1$ using the needle approximation [27], which is valid for well-deformed nuclei.

The spontaneous breaking of rotational symmetry in the ground-state leads to a spurious $K^\pi = 1^+$ excitation at zero energy in the QRPA spectrum which corresponds to a rotation perpendicular to the symmetry axis. One the advantages of self-consistent QRPA is that, to the extent numerical errors are kept to a minimum, this spurious mode decouples exactly at zero energy. By taking into account all the mesons and their currents, as well as the electromagnetic fields, in the QRPA matrix elements, and by using a large two-quasiparticle space, the position of the spurious mode is in our calculations below 0.5 MeV, and this excitation exhausts more than 99% of the total spurious $J_{\pi \uparrow \downarrow}$ strength in $^{154}$Sm, i.e. its admixture with physical states is negligible.

In Fig. 1 we show the low-lying M1 response in $^{154}$Sm obtained within RQRPA together with the experimentally known excitations [28]. The agreement is remarkable. In particular, the theoretically determined position and strength of the strongest peak at 3.2 MeV, and its orbital nature, coincide with the established experimental knowledge. Four out of the six most prominent theoretical peaks have mostly spin character. We concentrate in the following on the two remaining modes with orbital character. Besides the scissors mode at 3.2 MeV a second low-lying orbital excitation is found around 2.5 MeV. These two excitations with orbital nature can be interpreted in geometrical terms by analyzing their intrinsic transition densities $\delta \rho_\nu$ in cylindrical coordinates $r, z$ and $\varphi$, $r$ being the distance from the symmetry axis in $z$-direction. $\delta \rho_\nu$ is related, in the harmonic approximation, to the time-dependent density distribution for a given excitation mode $\nu$ with quantum numbers $K^\pi$

$$
\rho(r,t) = \rho^{(0)}(r,z) + \sum_\nu (\delta \rho_\nu(r,z)e^{iK\varphi}e^{-i\omega_\nu t} + \text{h.c.}),
$$

where $\rho^{(0)}$ is the axially symmetric ground state density and $\hbar \omega_\nu$ are the peak energies of the various excitations $|\nu\rangle$. The quantities $\delta \rho_\nu$ are the so-called intrinsic transition densities. These quantities provide an intuitive
understanding of the geometrical nature of the excitation modes and they shall be used in the following for a discussion of their internal structure.

Figures 2 and 3 show the intrinsic transition densities $\delta \rho_\nu(r, z)$ for the two orbital peaks at $\hbar \omega_\nu = 3.2$ MeV and at $\hbar \omega_\nu = 2.5$ MeV as contour plots in the $(r, z)$-plane. In Fig. 2 we observe the typical structure of the normal scissors mode. Neutrons and protons are out of phase over most of the space, with a concentration near the caps ($z > 5$ fm) of the prolate nuclear shape. Effects of the mixing of orbital and spin strength can be seen in the region around $z \approx 2.5$ fm and $r \approx 4$ fm in the proton intrinsic transition density. A rough schematic representation of such a mode is shown on the left hand side of Fig. 4.

On the other hand, the low lying mode at 2.5 MeV, whose intrinsic transition density is plotted in Fig. 3 shows a completely different spatial excitation pattern. Like the scissors mode, it is mostly a surface vibration. However, unlike the normal scissors mode in Fig. 2 which is clearly a $T = 1$ mode, its isospin is mixed, closer to being $T = 0$; over the entire area protons and neutrons are in phase. However there is a clear distinction between the outer part of the nucleus with $z > 5$ fm representing the skin and the inner region with $z < 5$ fm representing the core. These two parts clearly oscillate against each other. We also find that the skin consists mainly of neutrons. In a first approximation we therefore have an neutron skin oscillating against the proton-neutron core. Of course the details are more complicated and there are small admixtures of protons in the skin.

The schematic representation on the right side of Fig. 4 portrays such a situation. The shaded region ($z < 5$ fm) represents the nuclear core composed of neutrons and protons rotating in phase. The full line represents the extended mostly neutron skin at the cap which rotates out of phase against the core.
Peak at 2.5 MeV \( E_1 + E_2 \)

| \( \pi \) | \( \Omega \) | \( N \) | \( P \) | \( E \) |
|---|---|---|---|---|
| \( \frac{3}{2}^- \) | 0 | 20% | 58% | 3.13 |
| \( \frac{5}{2}^- \) | 6 | 20% | 65% | 3.05 |
| \( \frac{7}{2}^- \) | 2 | 3% | 3% | 3.00 |
| \( \frac{9}{2}^- \) | 3 | 3% | 20% | 3.00 |

Peak at 3.2 MeV \( E_1 + E_2 \)

| \( \pi \) | \( \Omega \) | \( N \) | \( P \) | \( E \) |
|---|---|---|---|---|
| \( \frac{3}{2}^- \) | 0 | 65% | 3% | 3.10 |
| \( \frac{5}{2}^- \) | 6 | 9% | 20% | 3.06 |
| \( \frac{7}{2}^- \) | 2 | 7% | 2% | 3.13 |
| \( \frac{9}{2}^- \) | 3 | 1% | 2% | 3.06 |

TABLE I: Quasiparticle structure of the two lower QRPA excitation modes with orbital character in the M1 response

whereas the lower peak at 2.5 MeV corresponds to a new type of resonance: the loosely bound neutron skin oscillates in a scissor like motion against the proton-neutron core with pronounced \( T = 0 \) character. This provides a new understanding of the splitting of low lying orbital \( K = 1^+ \) modes observed in many deformed nuclei. Further investigations of this mode in nuclei of the periodic table are in progress. In particular it has to be clarify to which extend this mode depends on the underlying single particle structure.

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