COMPARATIVE DISCUSSION OF THE GIANT RESONANCE PHENOMENON IN NUCLEI, ATOMS, ATOMIC CLUSTERS, AND CONDENSED MEDIA *)

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Comparative discussion of the properties of giant resonances in nuclei, atoms, atomic clusters, and condensed media, are presented. The main conclusion: the existence of the giant resonance phenomenon does not depend on the nature of the particles and the interparticle forces. The necessary conditions are: the particles must be moving in a confining potential and the number of them should not be small.

1 Introduction

Such different physical objects as nuclei, atoms, clusters (including fullerenes), and condensed media are combined in one report because in all of them collective excited states can be created. Usually the resonance peak is broad (short lifetime) and exhausts a large part of the dipole oscillator strength.

These collective excitations were first discovered in 1947 in nuclei [1] and were called giant dipole resonances [2]. Their existence was anticipated in the two-fluid (protons and neutrons) hydrodynamical model by Migdal [3] and Goldhaber and Teller [4] before their experimental observation. The collective excitations of the free electron gas in metals were predicted by Bohr and Pines [5] and very soon were detected in metals and then in dielectric media (see references in [6]). In 1960 Fano [7] studied the coupled dipole model for collective excitations in dielectric media and noted the formal analogy with giant dipole resonances in nuclei. In the 60ies, broad collective peaks located above the ionization threshold were revealed in atoms [8,9]. Wendin [10] was the first who emphasized the similarity of these atomic collective excitations with the giant dipole resonances in nuclei. In the late 80ies the collective resonance states were also revealed in sodium clusters [11] and some other metal clusters [12,13], and even in fullerenes [14,15].

So, now it is well established that the phenomenon of giant resonance is not specific to nuclear systems but can also be observed in different physical objects. The energy of giant resonance peaks varies from $\approx 2\,\mathrm{eV}$ in metal clusters to $\approx 20\,\mathrm{MeV}$ in nuclei (in the range of 7 orders of magnitude!). A large number of reviews has been devoted to collective excited states in nuclei [16,17], atoms [18,19], condensed media [6,20,21], and clusters [22–25].

In this report I will try to give a comparative analysis of similarities and differences between collective excitations in all four types of physical objects mentioned

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in the title. Detailed description of the peculiarities of the giant resonance phenomenon in each physical object can be found in reviews mentioned above and in our publications [26,27].

2 Comparative discussion

In Table 1, I present some characteristics of the four physical objects under consideration and properties of the giant resonances in them. In all these objects, the giant resonance is characterized by strong broad peaks corresponding to a collective excitation of many particles. The resonance peak exhausts a large part of the dipole oscillator strengths (up to 80% in nuclei and up to 95% in some clusters). Although the energy of the resonance peak E_r varies from 2 eV for the sodium clusters to 15–20 MeV for nuclei, the ratio Γ_r/E_r is located between 0.1–1.0 for all the objects.

The dependence of E_r on the size of the physical systems shows the opposite trend even in the case of clusters: a blue shift for alkali-metal clusters and a red shift for silver clusters. This is an indication of the importance for a giant resonance in clusters of the peculiarities of the structure of constituent atoms. In the case of medium-sized and heavy nuclei, the approximate analytical dependence E_r on the nuclear mass A was found to be [28]

$$E_r = 79A^{-1/3}\text{MeV}\,. \qquad (1)$$

The heavier is the nucleus the lower is the resonance peak energy.

It is natural to consider clusters as an intermediate object between atoms and solids. But from Table 1 it follows that such properties as: 1) the constancy of the particle density, 2) the uniform charge distribution, 3) the importance of surface effects, 4) the possibility of the shape deformation, 5) the mechanism of the giant resonance damping in small metal clusters are common to nuclei and atomic clusters. This is the reason why in spite of the different nature of the interaction forces, the theoretical methods developed in nuclear physics are applicable in cluster physics [29–33].

The giant dipole resonance in nuclei can be modeled as a quantized oscillation of the neutron and proton densities in antiphase, the centre of mass remaining fixed. The main mechanism responsible for the damping arises from the interaction of the dipole resonance excitations with the quadrupole surface vibrations. In small metal clusters the physical picture is similar. The giant resonance can be described as collective dipole oscillations of the valence electron cloud against the positive background of cores. And the damping is caused by the interaction with the quadrupole surface vibrations. In condensed media, the resonance peaks are also based on the plasmon type oscillations of the valence electrons, although the damping mechanism is different. In atoms the fulfillment of conditions for formation of plasmon oscillations is not so evident as in the infinite condensed media, nevertheless, they are fulfilled for some electronic shells in heavy atoms (see [27]).

The crucial condition for the formation of the giant resonance is the form of the mean field in which the excited particles move. The mean field must guarantee the

Table 1. Comparative properties of giant resonances in different physical systems.[a]

Property	Nuclei	Atoms	Clusters	Condensed media
1. Number of particles, N	$N < 300$	$N < 115$	N has not the upper limit	$N \to \infty$
2. Mean density of particles (with increasing N)	unchanged	increases	unchanged	unchanged
3. Location of charge	approxim. uniform	positive charge at center	approxim. uniform	approxim. uniform
4. Shell structure	yes	yes	yes	no
5. Main type of interaction	strong interaction	screened Coulomb	screened Coulomb	screened Coulomb
6. Effective potential	short-range deep well	two-well potential	finite-range potential	finite-range potential
7. Surface effects	important	absent	important	non-important
8. Shape deformation	yes	no	yes	no
9. Dependence of E_r upon size	red shift, $\sim A^{-1/3}$	no	blue shift (alkali-metals), red shift (silver)	no
10. Γ_r/E_r	0.3–0.4	0.1–0.5	0.1–0.5	0.1–0.8
11. $\Sigma f_i/N_v$	0.6–0.8		0.7–0.95	0.2–0.3
12. Mechanism of giant resonance damping	a) coupling with quadrupole surface vibrations, b) direct escape of neutrons ($\approx 15\%$)	localization in 1p-1h excitation: a) autoionization, b) the Auger effect	*small clusters*: coupling with surface vibrations *large clusters*: localization in single-electron excitations, fragmentation	localization in 1p-1h excitation: a) interband transition, b) autoionization

[a]) Notation: E_r is the energy in the maximum of the resonance peak, Γ_r is its width, f_i is the oscillator strength, and N_v is the number of valence electrons (nucleons).

confinement. The effective potential in such field is characterized by a finite radius (it decreases with distance faster than $1/r$, note that the Coulomb potential has an infinite radius). Another important condition on the effective potential is the steepness of the boundaries. This results in the effective reflection of the excited particles which gives rise to the coherent oscillations. The short-range potential in nuclei fulfills these conditions. In atoms, it is the inner well [19] which leads to the confinement of excited electrons during the ionization process. If the potential boundaries are steep, the shape of the well bottom is not very important, it can be flat (as a square well for metals). It is only necessary that the effective potential provides a confinement during the excitation process.

The lifetime τ of a giant resonance must not be very short, at least, τ must not be less than the period T_r of resonance oscillations. The latter is equal

$$T_r = \frac{2\pi}{\omega_r} = \frac{2\pi\hbar}{E_r} \tag{2}$$

The lifetime τ of a resonance state cannot be defined in such unambiguous manner. Let us assume that a resonance state decays exponentially,

$$N(t) = N_0 e^{-t/\tau_0}, \tag{3}$$

where the effective lifetime τ_0 is connected with the resonance width Γ_r by uncertainty principle

$$\Gamma_r \times \tau_0 \approx \hbar \qquad \text{or} \qquad \tau_0 \approx \frac{\hbar}{\Gamma_r}. \tag{4}$$

Then we can define the mean lifetime τ as a time during which $1 - e^{-\pi}$ (or $> 90\%$) of the resonance states decay. From this follows,

$$\tau = \pi\tau_0 \qquad \text{and} \qquad \frac{\tau}{T_r} \approx \frac{E_r}{2\Gamma_r}. \tag{5}$$

Taking the values of E_r/Γ_r from Table 1, we find τ/T_r: 1.2–1.7 (for nuclei), 1–5 (for atoms), 1–5 (for clusters), and 0.6–5 (for condensed media).

Thus, for all four physical objects, at least, one oscillation occurs during the lifetime of the resonance state. This conclusion is in contradiction with the statement in review [19] that the lifetimes of the resonance states in atoms are less than one period of plasmon oscillations. According to our estimate, the lifetimes (measured in the oscillation periods) of resonance states in atoms are the same as in clusters and even larger than in nuclei, where the existence of the giant resonance phenomenon is well established.

Another important point is the requirement on the number of particles which participate in the resonance. When can we say that the system contains "many" particles? It seems that a rigorous answer to this question does not exist. It depends upon the system under consideration. Therefore, let us turn to experimental data.

For nuclei, the smallest nucleus in which the giant resonance is found is ^{6}Li [34], so for nuclei $N \geq 6$. In atoms, the giant resonance has been revealed in atoms with filled d-shell, i.e., $N \geq 10$. The giant resonance is very well established in such clusters as Na_8 and K_9^+. In these systems there are 8 valence electrons, so for clusters $N \geq 8$. Thus, the minimum number of particles needed for the giant resonance phenomenon can be estimated between 6 and 10.

When the many-particle system is exposed to electromagnetic radiation, the region of the instant excitation is about the mean wavelength λ_0. Evidently, for simultaneous excitation of several particles, the mean interparticle distance $\bar{r}_0$ must be smaller than λ_0.

3 Summary

From the discussion presented above follows that the existence of the giant resonance phenomenon does not depend on the nature of the particles and of interparticle forces [1]). The convincing evidence for this is the excitation of giant resonances both in nuclei and in different atomic systems. The sufficient conditions which the system must fulfil can be formulated in the following way:

1. The particles are moving in an effective potential which provides the confinement of excited particles.

2. The number of particles must not be small, $N \geq (6\text{–}10)$.

3. The mean wave length of the exciting field $\lambda_0 \geq \bar{r}_0$, where $\bar{r}_0$ is the mean distance between interacting particles.

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