Giant Resonances in Excited Nuclei

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Talk presented at the Workshop on "Chaos and Collectivity in Many Body Systems" at the PMIPKS, Dresden, Germany, March 5-8 2008.
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1. Synopsis

The purpose of these notes is to give some historical background about the Axel-Brink hypothesis and its relation to the experimental study of giant resonances in excited nuclei. The focus will be on the giant dipole resonance (GDR). Topics to be covered:

1. Giant dipole resonances based on nuclear ground states.

2. History of the giant dipole resonance.

3. Theory of the Γ-width of neutron resonances.

4. The GDR in excited nuclei.

2. Examples of giant dipole resonances

Many examples of photoneutron cross sections are given in the review article of Berman and Fultz (Rev. Mod. Phys. **47** (1975) 713). The photoneutron cross section for ^{208} Pb is the classical example of a giant resonance in a heavy spherical nucleus. The resonance is narrow and its shape can be fitted quite well a Lorentz resonance

$$\sigma \propto \frac{\Gamma^2 E^2}{(E^2 - E_m^2)^2 - \Gamma^2 E^2} \tag{1}$$

with a mean energy E_m =13.5 MeV and a width Γ = 4 MeV.

Another case is the photo-neutron cross section for ^{197} Au. The resonance peak is at E_m = 13.7 MeV, nearly the same as for ^{208} Pb, the width Γ = 4.76 MeV is a little larger.
The nucleus ^{160} Gd is non-spherical with a prolate deformation. The photonuclear cross section has two peaks; one corresponding to a dipole vibration

along the axis of deformation and the other perpendicular to the axis of deformation. This kind of cross section is typical for deformed nuclei. A fit to the cross section for ^{160} Gd as a linear combination of two Lorentz peaks gives $E_{m1} = 12.23$ MeV, $\Gamma = 2.27$ MeV and $E_{m2} = 15.96$ MeV, $\Gamma_2 = 5.28$ MeV.

The photo-neutron cross section in spherical nuclei with mass number $A > 60$ generally has one peak. Its width may be increased due to fluctuations in the nuclear shape. The Zr isotopes provide a good example. The giant resonance width in the double closed shell nucleus ^{90} Zr is $\Gamma = 4.1$ MeV. In ^{94} Zr, which is somewhat deformed, it is $\Gamma = 5.3$ MeV. The GDR in light nuclei is often fragmented. For example the experimental GDR in ^{28} Si has four well separated peaks. This splitting is probably due to shell effects.

The photoneutron cross section can be used to study the GDR only for photon energies above the neutron threshold. The photo-absorption cross section below the neutron threshold can be measured in photon scattering experiments. There is a very nice recent study of the even Mo isotopes with $A = 92$ up to $A = 100$ made using bremsstrahlung from the ELBE electron accelerator at Rossendorf. The photo-absorption cross section has been measured from about 4 Mev up to 16 MeV using photon scattering below the neutron threshold and the (γ, n) reaction above. The experiments show that the Lorentz-like variation of the cross section with energy extends well below the neutron threshold.

3. History

The first observation of a giant resonance was made by Baldwin and Klaiber in 1947 (Phys. Rev. **71** (1947) 3. They used bremsstrahlung from the 100-MeV betatron of the General Electric Research Laboratory to excite a uranium target. They measured the fission yield for photon energies between 10 and 100 MeV and observed a prominent peak in the cross section for photons of about 20 MeV. A year later (Phys. Rev. **73**, (1948) 1156) they observed the same peak in the $(\gamma$, n) cross section with a uranium target and similar peaks in other nuclei.

Goldhaber and Teller (Phys. Rev. **74** (1948) 1046). They proposed that the peak in the cross section was due to a nuclear resonance in which the protons in the nucleus move in one direction while the neutrons move in the opposite direction. the width of the resonance is due to transfer of energy from the orderly vibration into other modes of nuclear motion. Thus the breadth is due to a process analogous to damping by friction.

Two years later Steinwedel and Jensen (Phys. Rev. **79** (1950) 1019) proposed a two-fluid model of the giant resonance based on a similar idea. They assumed that the nucleus consisted of a nuclear fluid with consant density ρ_0 . In the giant dipole mode the variation of the neutron and proton density was governed by hydrodynamical equations. The theory predicted a mode similar to the Goldhaber Teller mode because the frequency was related to the nuclear symmetry energy. They predicted that the mean energy E_m should be proportional to $A^{1/3}$ was quite good. The absolute magnitude was too large by a factor of 1.4.

During the next few years there were systematic studies of the GDR with the (γ, n) reaction . For example a paper by Montalbetti, Katz and Goldemberg (Phys. Rev. **91** (1953) 659) presented results for more than 50 nuclei. At the same time there were studies of the ? widths of neutron resonances. Hughes and Harvey (Nature **173** (1954) 942) measured the radiation widths of neutron resonances in 20 nuclei from silver to uranium. They found that the widths were rather constant, decreasing from 1.5 mV to 0.3 mV from the light to the heavy nuclei. The resonance spins varied between 0 and 9/2 and the measurements showed no strong spin dependence. The measured values were a factor of 300 smaller than theoretical estimates by Blatt and Weisskopf.

4. The Radiation Widths of Neutron Resonances

Axel and Brink introduced a method for estimating the radiation widths of neutron resonances. They worked independently. Both methods related the radiation widths of the resonances to the giant dipole resonance. My result was presented in my Oxford Doctoral thesis submitted in May 1955 but was not published. Physicists at the Harwell Lab. knew about Brinks results and J.E. Lynn explained them in his book *Theory of neutron resonance reactions* (OUP) 1968, p.321. Peter Axels paper appeared in Phys. Rev. **124** (1962) 671.

The estimates of dipole radiation widths of neutron resonances in both Axel and Brink are based on several assumptions.

1. The processes of emission and absorption of photons are related by detailed balance.

2. The cross section for absorption of photons is well represented by a Lorentzian shape with strength determined by the dipole sum rule.

With these assumptions the average ground state radiation width of a resonance state with spin I is given by

$$\Gamma_{\gamma I}\rho_I(E_0) = \frac{4}{3\pi}\frac{NZ}{A}\frac{1+0.8x}{mc^2}\frac{\Gamma E^4}{(E^2-E_m^2)^2+\Gamma^2 E^2} \tag{2}$$

Here $\Gamma_{\gamma I}$ is the radiation width of the initial state with energy E_0, E is the gamma ray energy, $\rho_I(E_0)$ is the density of initial states with spin I, Γ and E_m are the width and position of the dipole resonance, $mc^2 = 931$ MeV is the atomic mass unit and $x \approx 0.8$ is an exchange force parameter. Putting in the numbers

$$\Gamma_{\gamma I}\rho_I(E_0) \approx 10^{-6}\frac{A\Gamma E^4}{(E^2-E_m^2)^2+\Gamma^2 E^2} \qquad \text{MeV} \tag{3}$$

where the energies are in MeV. This expression is sufficient to calculate the radiation width to the ground state. To obtain the total radiation width requires an additional assumption:

3. if it were possible to perform the photo effect on an excited state the cross section for absorption of a photon of energy E would still have an energy dependence given by equation (**??**).

This statement is made on page 101 of my thesis and is expressed in equation (11) of Axels paper. The assumption seemed reasonable in view of the macrascopic nature of the Goldhaber-Teller and Steinwedel and Jensen theories of the giant dipole resonance. If the resonance exists in a cold nucleus it should also exist if the nucleus is warm.

The total radiation width of a resonance state can be obtained by summing over all final states. With the additional assumption that the density states with spin I is proportional to $(2I+1)$ the predicted radiation width is independent of the spin of the neutron resonance. Calculation of the total radiation width of a neutron resonance requires an expression for the nuclear density of states. This depends on energy and on A. This influences the A dependence of the result. The numerical results have the same A dependence as the data of Hughes and Harvey but are a factor of three too large. The weakest link in the argument is probably the assumed form (**??**) of the dipole photoelectric cross section.

Oxford did not have a very large school of nuclear physics at the time when I was working on my thesis, but I was fortunate to have contact with the strong experimental group working on neutron resonances at the Harwell Laboratory. I also benefited from contacts with Prof. Hughes (Hughes and Harvey (Nature **173** (1954) 942) and Prof. Weisskopf who were visiting Oxford while I was working on gamma widths of neutron resonances for my thesis.

5. The Giant Dipole Resonance in Excited Nuclei

The work of Axel and Brink was concerned with the radiation width of neutron resonances. Observation of the giant dipole resonance in excited nuclei had never been considered at the time. The situation changed with the discovery of the dipole resonance in the gamma radiation emitted from highly excited nuclei by Newton and his collaborators at Berkeley in 1981 (Newton et al Phys. Rev. Lett. **46** (1981) 1383).

The authors observed gamma rays in Ar induced reactions leading to highly excited states in Th, Gd and Er. The gamma ray intensities fell exponentially as a function of energy. The main part of these gamma rays had a statistical origin due to the many possible decay paths of the compound nucleus. Superimposed on this statistical spectrum there was a shoulder for gamma rays with energies greater than 10 MeV. These were interpreted as gamma rays produced in the decay of a giant dipole resonance in the highly excited compound nucleus. The giant dipole spectrum was obtained by a subtraction procedure.

Since 1981 experimental techniques have become more sensitive and there have been many studies of the giant dipole resonance in excited nuclei. It has develop into a powerful technique for studying properties of highly excited nuclei as a function of excitation energy and angular momentum. An example is the search for the Jacobi shape transition in high angular momentum states of excited nuclei. It was predicted that spherical nuclei should become oblate, tri-axial and the prolate as the angular momentum increases. Experiments by Maj, et al (Eur. Phys. J. **20** (2004) 165) which measured the spectrum of giant dipole gamma rays provide evidence for the Jacobi transition.