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New Type of Dipole Vibration in Nuclei

Yasuyuki SUZUKI,*),†) Kiyomi IKEDA*,†) and Hiroshi SATO**

Physics Department, University of Michigan, Ann Arbor, MI 48109
**Physics Department, Niigata University, Niigata 950-21*
***Radiation Laboratory, Institute of Physical and Chemical Research, Wako 351-01*

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Excess nucleons in neutron- or proton-rich nuclei are expected to play a distinctive role because of loose coupling to a core. The Steinwedel and Jensen hydrodynamic model is used to examine the possible existence of a new type of dipole oscillation in which the core and excess parts vibrate against each other.

Recently it has become possible through the systematic analysis of interaction cross sections to determine the sizes of p-shell nuclei including unstable nuclei.[1] Included among these are some neutron dripline nuclei, e.g., ^{11}Li, ^{14}Be and ^{17}B. All of these nuclei have been shown to have extremely large root mean square radii. The large radius is clearly related to the very small two-neutron separation energy: This suggests that several valence nucleons are coupled to a core very weakly. In those nuclei with neutron or proton excess it is tempting to explore a new type of motion in which the core part and the loosely bound excess part play a characteristic role.

Let us consider the electric dipole mode as an example. The Goldhaber-Teller (GT)[2] and Steinwedel-Jensen (SJ)[3] models are known as macroscopic models for the giant dipole resonance (GDR). The GT model treats a displacement mode of the bulk of protons against the neutrons assuming that the proton and neutron fluids are incompressible, while the SJ model considers the GDR as the acoustic mode of density oscillations assuming that both the fluids are compressible but the total fluid is incompressible. Both of the GT and SJ models consider the out-of-phase density oscillation of all the protons and all the neutrons, and relate the restoring force against the vibration to the energy of the GDR. It appears possible, however, that the neutrons inside the core of neutron-rich nuclei move together with the protons because of their tight binding but the excess neutrons move against the protons leaving the center-of-mass at rest. The restoring force corresponding to this kind of dipole vibration is expected to be smaller than that of the GDR. This dipole oscillation, which we call pygmy dipole resonance (PDR), will thus appear at lower excitation energy, although more detailed examination is needed to be definitive because the mass parameter of the vibration also becomes smaller. Hansen and Jonson[4] speculated about the existence of a similar mode, "soft dipole mode", in an attempt to discuss the possible enhancement of Coulomb dissociation cross sections in a loosely bound nucleus such as ^{11}Li.

*) Permanent address: Physics Department, Niigata University, Niigata 950-21, Japan.

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The purpose of this paper is to investigate the pygmy dipole mode for a system of two fluids, the core fluid and the excess fluid, using a classical hydrodynamic model[3),5)] of SJ type. Although it is shown that the SJ mode does not dominate the GDR[6)] and that the velocity field for the GDR of ^{40}Ca is closer to that of the GT model,[7)] we focus on the SJ model in the present investigation because the SJ model is known to account well for the observed energy and the electric dipole strength of the GDR and because the SJ model is appropriate to discuss the properties of the PDR without much recourse to ambiguous parameters, as will be seen later. Mohan, Danos and Biedenharn[8)] introduced a three-fluid model consisting of the protons, the blocked neutrons of the same orbitals as the protons and the excess neutrons, to account for the fact that the excess neutrons interact less strongly with the protons than the blocked neutrons. They recognized the possibility of two types of dipole modes, the GDR and the PDR. The resulting dipole strength of the PDR was, however, negligibly small compared with the classical sum rule. A new feature of the present approach to the PDR is to assume the simultaneous displacement of the protons and neutrons inside the core, thereby enabling us to eliminate ambiguous parameters such as those introduced in Ref. 8) for the symmetry energy between the three fluids.

The density of the core fluid, ρ_c, is a sum of the proton and neutron components, $\rho_c=\rho_{c,p}+\rho_{c,n}$. The excess fluid with the density ρ_e could be either neutron or proton but, to be definite, the neutron excess case is assumed. We neglect the neutron skin thickness which makes the hydrodynamic treatment harder and assume that the fluids are irrotational and confined inside a sphere with a radius R. The equilibrium densities of each fluid are assumed to be $\rho_{c,p}^{(0)}=Z/V$, $\rho_{c,n}^{(0)}=N_c/V$, $\rho_e^{(0)}=(N-N_c)/V$ ($V=(4\pi/3)R^3$), respectively, where N_c is the number of neutrons inside the core. The part of the Lagrangian, $L=T-U$, relevant to the present study is

$$\frac{1}{2}M\int_V(\rho_c\boldsymbol{v}_c^2+\rho_e\boldsymbol{v}_e^2)d\boldsymbol{r}-\kappa\int_V\frac{(\rho_p-\rho_n)^2}{\rho_0}d\boldsymbol{r}\,, \tag{1}$$

where $\boldsymbol{v}_c$ and $\boldsymbol{v}_e$ are the velocities of the volume elements of the fluids, M is the nucleon mass and the coefficient κ can be estimated from the symmetry energy term of the empirical mass formula. The proton density, ρ_p, is equal to $\rho_{c,p}$ but the neutron density, ρ_n, is given by $\rho_{c,n}+\rho_e$. The ρ_0, equal to A/V, denotes the nucleon density at equilibrium. The density vibrations from the equilibrium undergo the following conditions:

$$\rho_c+\rho_e=\rho_0=\text{const}\,, \tag{2}$$

$$\rho_{c,p}=\chi\rho_c, \qquad \rho_{c,n}=(1-\chi)\rho_c\,, \tag{3}$$

where $\chi=Z/(Z+N_c)$. Equation (2) assures the incompressibility of the total fluid, whereas Eq. (3) expresses the fact that the protons and neutrons of the core vibrate in phase. The velocity of the wave propagation is given by [3),5)]

$$u=\left(\frac{8\kappa}{M}\frac{\chi^2\rho_{\text{red}}^{(0)}}{\rho_0}\right)^{1/2}, \tag{4}$$

where $\rho_{\text{red}}^{(0)}=\rho_c^{(0)}\rho_e^{(0)}/\rho_0=(Z+N_c)(N-N_c)/AV$ is the reduced density at equilibrium.

The boundary condition for the dipole oscillation, $\partial j_1(kr)/\partial r|_{r=R}=0$, yields the lowest excitation energy ($kR=2.082$) of the PDR as

$$\hbar w=\hbar ku=\frac{2.082}{R}\hbar u=\left(\frac{Z(N-N_c)}{N(Z+N_c)}\right)^{1/2}\hbar w_{\mathrm{GDR}}\,, \tag{5}$$

where w_{GDR} is the eigenfrequency of GDR. Note that the GDR is a special case with $N_c=0$ in the present model. The dipole strength of the PDR is given by [3),5)]

$$0.857\times\frac{2\pi^2\hbar e^2}{Mc}\frac{\chi^2\rho^{(0)}_{\mathrm{red}}}{\rho_0}A=0.857\times\frac{Z(N-N_c)}{N(Z+N_c)}SR\,, \tag{6}$$

where $SR\equiv\int_0^\infty\sigma(E)dE=(2\pi^2\hbar e^2/Mc)(NZ/A)$ is the sum rule of the classical absorption cross section. For the case in which the ρ_e stands for the proton excess fluid, the role of N and Z should be interchanged in Eqs. (5) and (6) and N_c should read as Z_c. Note that in the electric dipole operator, $D_z=e\int_V z\rho_p d\boldsymbol{r}$, the ρ_p is given by $\chi\rho_c$ for the neutron excess case but is given by $\rho_0-\chi\rho_c$ with $\chi=N/(N+Z_c)$ for the proton excess case: This leads to the same expression of Eq. (6) for the dipole strength in both cases.

The measurement of slow neutron capture γ-ray spectra is of particular interest in connection with our model. The measurement on several nuclei with $70<N<120$ shows that an anomalous bump, a so-called pygmy resonance, appears systematically at low excitation energies of $2\sim6$ MeV in γ-ray spectra from (n,γ) and $(d,p\gamma)$ reactions with a typical γ-ray resolution of about 100 keV.[9),10)] Although the nature of the pygmy resonance has not yet been clarified, it seems that the pygmy resonance reflects a concentration of the electric dipole strength and indicates a neutron particle-hole collective mode. We feel tempted to identify the pygmy resonance with a manifestation of the pygmy dipole mode, although in nuclei near the stability line the motion of the core relative to the excess part may not be a well developed mode so that the PDR may not actually occur. The comparisons given below should therefore be qualitative. Our aim is just to see if our model has some realistic

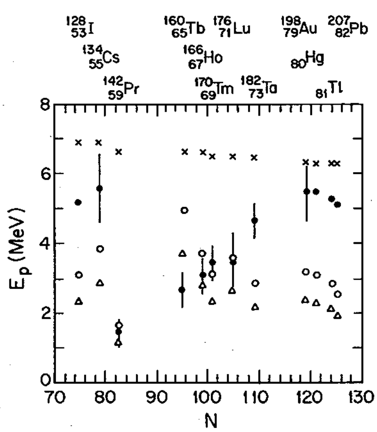

Fig. 1. Energies of the pygmy resonances. The experimental data denoted with the closed circle are taken from Ref. 10). See text for the theoretical results denoted with the symbols ×, △ and ○.

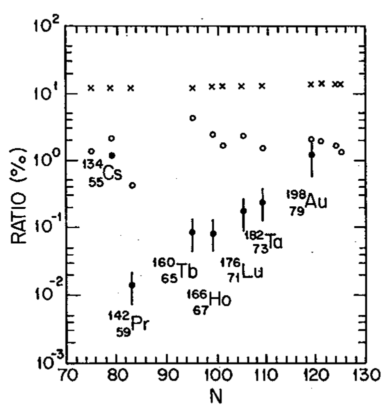

Fig. 2. The percentage ratio of the electric dipole strength of the pygmy resonance to the classical absorption cross section. See the caption of Fig. 1.

features. Figures 1 and 2 compare theory with the observed energies and dipole strengths of the pygmy resonances.[10] We have tested two extreme cases for the choice of N_c. In one case shown with the cross $\times$, N_c is set to Z and κ to 30 MeV. This choice of N_c leads to a structureless curve as a function of N, resonance energies $1\sim3$ MeV larger than experiment and one to two order-of-magnitude larger dipole strengths. The discrepancies between theory and experiment are most evident in the nuclei from Tb to Ta. Note, however, that the theory assumes spherical nuclei so that it has to be modified to apply for such well-known deformed nuclei as Tb to Ta. In the second case N_c is determined so as to make the binding energy per particle a maximum at N_c for a given Z. The experimental mass compilation[11] leads us to choose N_c=72, 74, 82, 84, 92, 96, 98, 104, 112, 114, 118, 120 for the nuclei I to Pb shown in Figs. 1 and 2. Note that the number of excess neutrons so determined becomes sometimes very small so that the hydrodynamic treatment may break down. The symbol $\triangle$ denotes results obtained with this choice of N_c and κ=30 MeV. The predicted resonance energies are lower by 3 MeV than experiment for the spherical nuclei but now follow very nicely the experimental trend. Finally, we used N_c of the second choice and the optimal values determined by Myers et al.[6] in their analysis of the GDR: $M=0.7\times M_f$(M_f=free nucleon mass), κ=36.8 MeV. Results denoted with the open circle $\circ$ clearly show improvement over the previous cases. The neutron number dependence of both the resonance energies and the ratio of the dipole absorption cross section to the sum rule is in fair agreement with experiment.

As we have seen that the PDR seems to correlate with the observation of the pygmy resonances despite the qualitative nature of the comparisons, we are encouraged to predict the PDR of nuclei with more excess nucleons. We choose the Ca isotopes as a prime example. Although the coefficient κ for the neutron-rich nuclei may be different from the one for the stable nuclei, we assume that κ does not change despite the increasing number of excess neutrons. If a smaller value of κ is to be used for very neutron-rich nuclei, we note that the energy of the PDR given below becomes lower. Figure 3 shows the energy of the PDR relative to that of the GDR and the contribution of the PDR to the sum rule value, SR, as a function of the number of excess neutrons. The nucleus ^{46}Ca is chosen as a core since the binding energy per particle becomes the biggest in ^{46}Ca among the Ca isotopes. It is seen that the resonance energy and the dipole strength increase with increasing number of excess neutrons. For the extremely neutron-rich nucleus, ^{61}Ca, the excitation energy of the PDR reaches about 8 MeV if the energy of the GDR is assumed as 20 MeV, and the electric dipole strength occupies a significant fraction of the sum rule amounting to

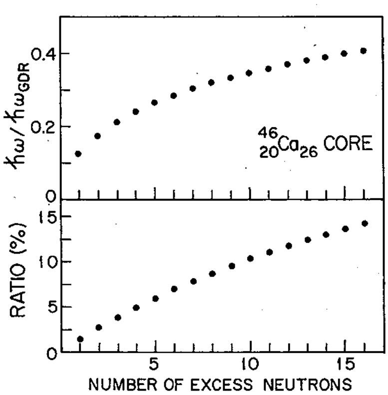

Fig. 3. The relative energy of pygmy dipole resonance vs giant dipole resonance and the ratio of the electric dipole strength of pygmy dipole resonance to the classical absorption cross section as a function of the number of excess neutrons in the Ca isotopes.

15%.

We have developed a two-fluid model of the core and excess fluids to envisage a unique dipole oscillation, the pygmy dipole resonance, which is expected to build up as the number of excess nucleons increases. This dipole mode in which the excess nucleons move against the core is found to take up a sizable amount of the classical electric dipole sum rule. We have applied our theory to the so-called pygmy resonances observed in β-stable nuclei with a small number of excess nucleons. The agreement between theory and experiment is rather encouraging in spite of the fact that many of these nuclei are ones for which the pygmy dipole resonance is not expected to be well developed. There are several points to be examined further; 1) to take into account the effects of skin thickness, non-sharp cutoff of the nuclear surface and the deformation of nuclei, 2) to consider the effects of the Pauli principle which tends to prevent the core neutrons from moving together with the protons as the number of excess neutrons increases, 3) to consider the coupling of the pygmy dipole mode with the giant dipole mode especially when there are many excess nucleons. We are currently investigating some of these effects in a microscopic framework.

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