Microscopic study of the processes of photosplitting and radiative casture of light nuclei, taking into account the interaction...

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MICROSCOPIC STUDIES OF PHOTOSPALLATION AND LIGHT-NUCLIDE RADIATIVE CAPTURE WITH ALLOWANCE FOR THE INTERACTION OF COLLECTIVE AND CLUSTER DEGREES OF FREEDOM

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1. A particular place is taken amongst the resonant nuclear states excited by electromagnetic radiation and charged particles by the dipole, monopole, and quadrupole giant resonances. Interest in these arose when various signs of the giant dipole resonance were observed [1-3], and Migdal [4] interpreted this resonance as the excitation of collective oscillations in the nuclear protons. Since then, there have been numerous theoretical studies on the dipole resonance [5,6] and also on the monopole [7] and quadrupole [8] ones. Basic tasks in giant-resonance theory are to explain the nature of the resonances and to identify the main factors determining their positions and widths. We therefore examine how far the published theoretical models are capable of doing this.

There are two alternative viewpoints on the nature of giant resonances. While Migdal [4] and then Goldhaber and Teller [5] considered the giant dipole resonance as a state in which collective nucleon motion is excited, in a long series of theoretical papers that have been reviewed in [9-11], this same resonance was identified with the direct excitation of one-particle degrees of freedom in the nucleon system. In fact, at least to a first approximation, collective dipole excitation is a coherent superposition of one-particle dipole ones [12], and, therefore, the two concepts are not mutually exclusive. However, during their development, there has so far been no substantial approach between the viewpoints.

The microscopic theory of collective excitations in nucleon systems [7,8,13-15] is based on the view that the collective modes of motion have a predominant role in producing the giant resonances, and it correctly predicts the positions of the resonances as well as the relatively large photospallation cross sections, but it is incapable of reproducing the observed widths. A theory based on the shell model and concepts on particle-hole states does not give such large absolute photospallation cross sections, but it enables one to estimate the widths of the giant resonances from the random-phase method. On that theory, the giant resonances should have fine structures, since the theory treats each such resonance as a set of a large number of particle-hole resonant excitations.

All known giant resonances lie in the region of the continuous spectrum for a nucleon system high above the threshold for decay on various channels. Therefore, in order to calculate the widths from the microscopic theory of collective excitation, it is necessary to include not only collective-motion modes but also modes related to nucleon-system decay on the open channels. So far, this step has not been taken, which has given rise to difficulties in the microscopic theory in the discussion of the observed resonance widths.

The main purpose of this paper is to consider together the collective degrees of freedom in the nucleus and the degrees of freedom of those channels on which the nucleus can decay. We restrict ourselves to p-shell nuclei and quadrupole resonances in order that the detailed calculations shall remain fairly simple. Consequently, it is possible to calculate the effective photospallation cross sections for ^{6}He, ^{6}Li, ^{7}Li, and ^{77}Be in various partial states, as well as the corresponding radiative capture cross sections, and it is also possible to show that the large widths of the giant quadrupole resonances in these nuclides are a direct consequence of the strong coupling between the collective degrees of freedom and the cluster ones in the open channels. Finally, our approach leads us to conclude that there are narrow quadrupole resonances, whose energies are some tens of megaelectron-volts. At such high excitation energies for the collective degrees of freedom, the coupling of them to the cluster ones is weak, and therefore there is a delay in the decay of the collective excitations over the open cluster channels.

2. According to the traditional shell model, each light nuclide should have a sizable number of particle-hole excitations. However, with minor exceptions, all the excited states predicted by the shell model lie in the continuous spectrum above the spallation threshold, where they can only be resonances. However, they are usually not observed by experiment even as resonances. One of the reasons for their absence from the spectrum is that the actual amplitudes of the cluster oscillations and the collective ones (quadrupole and monopole ones) in various states of light nuclides are much larger than is implied by estimates from the shell model. The cluster and collective oscillations disrupt the simple shell structure of the particle-hole excitations, which leads in particular to an appreciable increase in light-nuclide binding energies and substantial change in the ground-state wave functions.

Dominant-mode collectivization occurs also for those states in light nuclides that appear as resonances in reactions. Otherwise, it is difficult to explain why they do not decay instantly on open channels, which always include a nucleon-escape channel in the region of the giant resonances.

Clearly, the narrow resonances must be closed-channel mode excitations, and also weakly coupled to the open-channel modes. At relatively high energies, the only closed channels are those in which the excitation energy is uniformly distributed over all the nucleons, i.e., the channels for the collective degrees of freedom. However, if the amplitude of the collective oscillations is not too large, the collective resonances may be extremely broad (as occurs for the giant resonances), since the collective-mode channels overlap heavily with the open decay channels for small collective-oscillation amplitudes.

Therefore, in simulating giant resonances as large numbers of particle-hole resonant excitations, we should be able to answer a difficult question: why in general can particle-hole excitations become resonances at high energies above the nucleon-escape threshold? We note that the question does not arise in the microscopic theory of collective excitations.

The explanation for the widths of the giant resonances in the microscopic theory is as follows. The interaction between a nucleus and electromagnetic radiation or charged particles (electrons, protons, etc.) means that the energy of the γ rays or charged particles is transmitted directly to the collective degrees of freedom (dipole, quadrupole, or monopole ones), and, therefore, collective oscillations are excited.

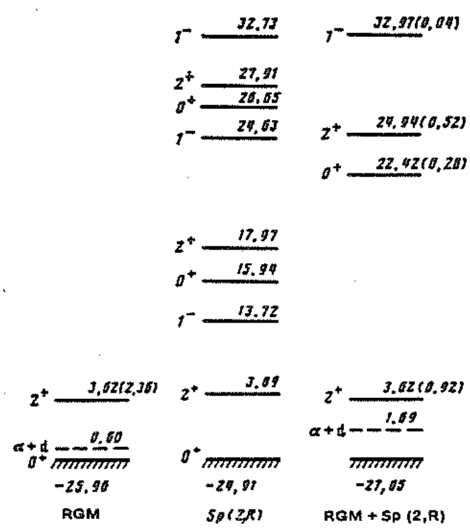

Fig. 1. Collective-excitation and resonant-state spectrum for $^{6}He(^{6}Li)$; RGM is calculation in the cluster basis, Sp(2,R) in the collective basis, and RGM + Sp(2,R) calculation incorporating the coupling between the cluster and collective modes. The energies of the levels and the resonance widths (numbers in parentheses) are given in MeV.

The energy required to excite the corresponding collective modes can be estimated if we neglect the transfer of excitation energy from the collective modes to all other modes within the framework of the microscopic theory. That procedure has been used repeatedly for monopole and quadrupole modes [7,8,13,16-18], and it gives the correct positions for the monopole and quadrupole resonances, but it leaves aside the question of their widths. Giant-resonance dissipation is a consequence of the nucleus going over to a state lying far above the threshold for decomposition on various channels as a result of the transferred energy. The collective-mode channel is closed. Therefore, while the excitation energy remains localized in the collective degrees of freedom, the nucleus does not break up, but this cannot last a long time. The collective channel is coupled to other channels, which are open at the excitation energy taken up by the collective mode. Also, the coupling is strong, which ultimately results in considerable widths for the giant resonances: the excitation energy passes rapidly from the collective modes to the open-channel ones and the nucleus rapidly breaks up.

In general terms, this is the interpretation of the giant resonances and their widths, which is confirmed by calculations for light nuclides. The main result from the microscopic theory that is accessible to experimental test is that a giant resonance is a state having a large width. Against the general background of such a state, there may or may not be peaks from a small number of narrow resonances responsible for a certain part of the sum rule. We have mentioned above the possible origins of the narrow resonances.

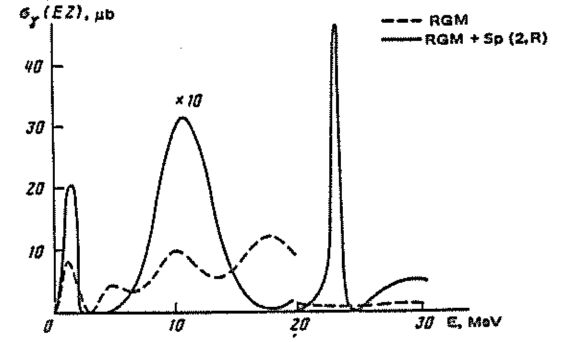

Fig. 2

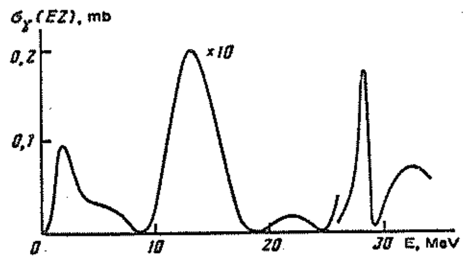

Fig. 3

Fig. 2. Cross section for the $\sigma_\gamma(E2;\ 0^+\to 2^+)$ quadrupole photospallation of ^{6}Li; E is the energy of the escaping α and d fragments. Dashed line RGM, solid line RGM + Sp(2,R).

Fig. 3. Cross section $\sigma_\gamma(E2;\ 1^-\to 3^-)$ of the quadrupole photospallation of ^{7}Li; E is the energy of the α and t fragments.

3. The nuclear wave function is represented as an expansion in terms of two sets of multiparticle oscillator functions:

$$\Psi = \sum_\nu C_\nu^{\mathrm{col}} |\nu,\ \mathrm{col}\rangle + \sum_n C_n^{\mathrm{cl}} |n,\ _{n,\ \mathrm{cl}}\rangle. \qquad (1)$$

The first set of functions $\{|\nu, \mathrm{col}\rangle\}$ constitutes the basis of the irreducible representation of the simplectic group Sp(2,R) and is adapted for describing collective quadrupole excitations. If we restrict ourselves to this basis, we get the Sp(2,R) microscopic model first realized by Arickx, et al., [15,17]. The second set of functions $\{|n, \mathrm{cl}\rangle\}$ is the cluster-model oscillator-function basis, or, in other words, the basis of the resonant group method RGM, which reproduces the motion of the fragments (clusters) on the relevant channel.

Before we discuss the theoretical calculations, we note that the expansion of (1) incorporates 25 collective-basis functions and 100 cluster-basis ones. Those numbers of basis functions enable one to reproduce the nucleon-system wave functions closely for the internal and external regions. The interaction between the nucleons is represented by the first form of the Brink-Boeker potential [19]. The oscillator radius is the same for the cluster and collective bases, and it was chosen for the condition for minimum threshold for each of the nuclides.

As the Coulomb interaction between the protons is not incorporated, and as the even and odd components are equal in the Brink-Boeker potential, the thresholds for the $\alpha + 2n$ and $\alpha + d$ reactions (and also for $\alpha + t$ and $\alpha + {}^3He$) are the same, and, consequently, the same applies for the oscillator radii r_0 for ${}^6He$ and ${}^6Li$ (${}^7Li$ and ${}^7Be$). For the same reason, the results obtained for ${}^6He$ (${}^7Li$) apply also to ${}^6Li$ (${}^7Be$).

Figure 1 shows the spectrum of resonances and collective excitations for ${}^6He$ (${}^6Li$) derived in various approximations. The cluster basis (RGM) enables one to describe the bound and resonant states (2^+ state in this case) due to the existence of a centrifugal barrier. The collective functions (Sp(2,R)) provide a set of vibrational excitations ($L^\pi = 0^+, 2^+$ for ${}^6He$) as well as the rotational excitations (2^+ for ${}^6He$), in addition to anomalous-parity states ($L^\pi = 1^-$). The first 0^+ and 2^+ vibrational excitations in even nuclides or the 1^- and 3^- ones in odd ones are usually identified in the microscopic theory with monopole and quadrupole giant resonances, because they are linked to the ground states by large matrix elements for the monopole and quadrupole transition operators and exhaust considerable fractions of the monopole and quadrupole sum rules with their energy weights.

If on the other hand we incorporate not only the collective mode but also the cluster one (RGM + Sp(2, R)), then the above vibrational collective excitations dissolve into the continuum, and the elastic-scattering phases in the corresponding cluster channel do not show resonant behavior at the energies where calculations show there should be a giant resonance on the basis of the collective functions with the cluster channel closed. Consequently, the giant resonances cannot make themselves felt explicitly in light-cluster interactions, and one has to seek other ways of recognizing them. The explanation of our theoretical results for the first 0^+ and 2^+ vibrational excitations is that these excited states have relatively small collective-oscillation amplitudes, and therefore there is strong coupling between the collective and cluster modes. This leads to rapid giant-resonance decay on the cluster channel.

As regards the higher-lying 0^+ and 2^+ vibrational excitations, they characteristically have large collective-oscillation amplitudes. The strength of the coupling between the collective and cluster modes in these excited states is less, and they do not broaden after incorporating the cluster basis, being instead narrow resonances clearly seen on the curves relating the elastic-scattering phases and partial effective cross sections in the open cluster channel to energy. The widths of these collective resonances do not exceed 1 MeV, i.e., they are much less than the width of the centrifugal 2^+ resonance. A similar picture occurs in the odd nuclides ${}^7Li$ and ${}^7Be$.

We now consider the energy dependence of the photospallation cross sections σ_γ for ${}^6He$ (${}^6Li$) and ${}^7Li$(${}^7Be$). As the radiative capture cross sections σ_c are related to the σ_γ by the detailed-balancing conditions, our conclusions apply equally to the σ_c; a characteristic feature of the calculated σ_γ (Figs. 2-4) is that there are resonant peaks, some of which belong to narrow collective resonances excited by the γ rays. The radiative widths of these resonances coincide with their α-decay ones. Also, the photospallation cross sections have clear-cut peaks near the threshold, which occur because the continuum functions have a structure similar to that in the ground-state wave function at small values of the energy in excess of threshold, and the ground state lies only a little way below the threshold, while the matrix elements for the electromagnetic-transition operators linking the ground state and the epithreshold ones in the continuum in fact are larger. This thus leads to epithreshold resonances. A detailed discussion of the monopole epithreshold resonances has been given in [21].

Finally, in ${}^6He$, ${}^6Li$, ${}^7Li$, and ${}^7Be$ at excitation energies of 12-15 MeV, there is a quadrupole-resonance peak of width about 5 MeV, which accounts for over 15% of the quadrupole sum rule with energy weights and can be considered as a giant quadrupole resonance, since its position coincides with that given by the Sp(2,R) collective model.

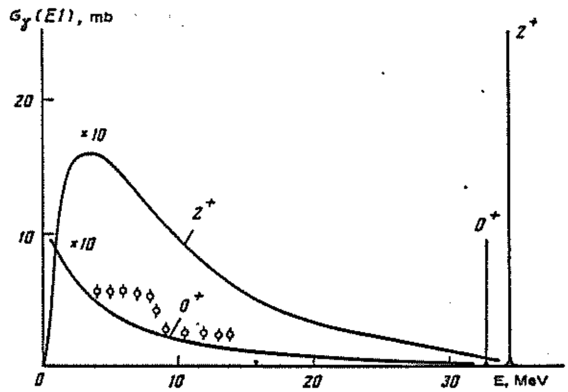

Fig. 4. Cross sections $\sigma_\gamma(E1;\ 1^-\to 2^+)$ and $\sigma_\gamma(E1;\ 1^-\to 0^+)$ for dipole photospallation of ^{7}Li; E is the energy of the α and t fragments. The experimental points are from [20].

As a result of the broadening in the quadrupole collective excitation in the continuum, the matrix element for the quadrupole transition from the ground state is large and goes not to one state but to a continuous series of states grouped around a certain center. The peak in the photospallation cross section distinguishes these states amongst others in the continuum.

Therefore, photonuclear reactions represent the most convenient means of identifying giant resonances in light nuclides in a natural fashion.

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