M1 RESONANCE AND COMPARATIVE STUDY OF E1, E2 AND M1 RESONANCES IN NEAR-THRESHOLD REGION

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The finite Fermi-system theory (FFST) is applied to M1 resonance properties of even spherical nuclei. The absolute and relative contributions of E1, E2 and M1 resonances to the integral γ-ray absorption cross section in the near-threshold region are calculated for ^{90}Zr, ^{120}Sn, ^{208}Pb.

After the discovery of the M1 resonance in lead isotopes in the near-threshold photoneutron reactions [1] the direct observations of the M1 resonance in medium and heavy nuclei through inelastic electron scattering [3, 4] were reported. The first method gives spectroscopic information about the 1^+ levels properties in the narrow region above the neutron binding energy. The second one is less accurate, but a wide energy region is available for investigation of the integral M1 resonance properties.

Except [5, 6] the microscopic calculations of the M1 resonance in medium and heavy nuclei were carried out only for ^{90}Zr [7] and double-magic ^{208}Pb in the Tamm-Dankoff [8], and Random Phasa [9, 10] approximations and the Finite Fermi-Systems Theory [11]. The realistic forces [8] or various sets of phenomenological parameters describing effective interaction have been used. In [11] the slightly modified strength constants of the FFST and the effective magnetic operator with the parameters adjusted to magnetic properties in near-lead region have been used.

The investigation of the M1 resonance, interesting for the nuclear structure theory, is also important for studying different reactions, for example, the slow neutron radiative capture. First of all, the M1 resonance is observed in the vicinity of neutron binding energy. The low-energy tail of the E1 resonance and the isoscalar E2 resonance with the energy of 63—65 $A^{-1/3}$ MeV and the width of 3—6 MeV [13, 14] are also observed in this region. The M1 resonance was also discussed in connection with the nature of the pigmy-resonance at 6—8 MeV (see, for example, [15]). Therefore one must know at least the relative contributions of the E1, E2 and M1 resonances to the integral γ-ray absorption cross section. In fact, it is impossible to compare the results of different calculations in

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the same nucleus, and the special comparison in the framework of a single scheme has not been performed.

It seems natural to use the particle-hole treatment to calculate and compare the properties of the above resonances. One can think that as in the case of the E1 resonance. this method will give a correct explanation at least of the new giant resonances integral properties. In our case it would be most desirable to have a variant of the particle-hole method with the parameters already known and practically independent on A, multipolarity and the excitation energy in a wide excitation spectrum region. The FFST [16], in principle, satisfies these requirements.

We have calculated the properties of M1 resonance in one-closed-shell nuclei and in ^{208}Pb using a general approach to the magnetic dipole polarizability problem in the framework of the FFST, as outlined in [17, 18]. The pairing has been taken into account in all the nuclei except for ^{208}Pb. The l-favoured single-particle transitions only are taken into consideration (our estimates and experiment show that the l-forbidden transitions contribution, arising in unclosed-shell nuclei, is small). The single-particle energies and their wave functions have been obtained for the Saxon–Woods potential [19]. The following set of the FFST dimensionless constants describing the spin-spin interaction of quasiparticles in nuclei was used [12]:

$$g^{nn} = g^{pp} = 1.3, \qquad g^{np} = -0.3$$

(together with the normalizing factor[1] $(dn/d\mathscr{E}_F)^{-1} = 386$ MeV fm^3).

The results of our calculations are presented in Table I. Denoted by q_s are the oscillator strengths, determined in such a way that $\sigma_{int} = \int \sigma(E)dE = \sum_s q_s$, where the sum is taken over the excited levels. In Table II the nuclei are listed for which the direct experimental evidence of the M1 resonance exists at present. We see immediately that except B(M1) for ^{90}Zr[2] our results are in a good agreement with the experiment on the whole. A comparison with the spectroscopic data for ^{208}Pb [1] is most interesting. As in all particle-hole calculations, ours give only two 1^+ levels, their integral strength being in a good agreement with the available experimental data. However, the possible existence of the "extra" levels indicates that the 1^+ levels in ^{208}Pb have a more complicated nature than the 1p−1h one.

There are one or two high lying 1^+ levels, arising from neighbouring shell transitions, which give the main contribution to the integral M1 absorption cross section. The pair correlations are mainly responsible for the appearance of low lying 1^+ levels in the region of 2—5 MeV.

In Fig. 1 we give a comparison of the E1, E2 and M1 resonance contributions to the photoabsorption cross section. The E1 and E2 resonances have been calculated within the above scheme using the well-known FFST scalar constants [21, 22, 14]. We conclude

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[1] In our preliminary calculations of E1 and E2 resonances the value of the normalizing factor was $(dn/d\mathscr{E}_F)^{-1} = 469$ MeV fm^3. This corresponds to $r_0 = 1.28$ fm used in the single particle scheme calculations [19]. For this reason all the results of Fig. 1 were obtained with $(dn/d\mathscr{E}_F)^{-1} = 469$ MeV fm^3. The difference between these two variants is small, on the whole (for the details see [22]).

[2] For information on M1 resonance search in ^{90}Zr through the (p, p$'\gamma_0$) reaction see also [20].

TABLE I

Calculated M1-resonance characteristics in spherical nuclei

Nuclei	E^{sp} (MeV)	$\hbar\omega_s$ (MeV)	$B(M1, 0^+ \to 1^+)$ μ_N^2	q_s^i (MeV · mb)
	2.40	2.84	0.87	0.11
^{88}Sr	6.31	8.28	0.23	0.09
	8.04	9.25	8.61	3.58
	11.29	11.52	1.64	0.85
	2.85	3.01	0.33	0.05
^{90}Zr	6.31	9.16	5.85	2.41
	9.53	9.56	0.05	0.02
	9.66	10.15	4.50	2.06
	2.69	3.81	2.35	0.40
^{114}Sn	5.58	7.20	0.09	0.03
	7.00	8.20	13.18	4.86
	10.23	10.31	0.60	0.28
	2.93	3.83	1.98	0.34
^{116}Sn	5.58	8.07	4.57	1.66
	8.07	8.26	7.38	2.74
	9.23	9.45	1.62	0.69
	3.56	3.97	0.96	0.17
^{120}Sn	8.26	8.05	8.49	3.08
	9.36	8.89	6.51	2.60
	4.24	4.43	0.39	0.08
^{124}Sn	7.64	7.98	5.61	2.01
	10.36	8.88	11.43	4.57
	4.49	4.59	0.20	0.04
^{126}Sn	7.35	7.94	4.56	1.63
	10.76	8.90	13.54	5.42
	3.57	3.85	1.03	0.18
^{140}Ce	5.74	6.97	1.29	0.40
	6.08	8.42	11.45	4.34
	10.96	11.05	0.90	0.45
	1.57	2.03	0.39	0.04
^{202}Pb	3.46	3.68	0.87	0.14
	4.99	6.96	5.40	1.69
	5.91	8.11	20.97	7.65
	1.77	1.55	0.69	0.05
^{204}Pb	3.38	3.64	0.51	0.08
	4.99	6.97	5.67	1.78
	5.95	8.20	21.21	7.83
^{208}Pb	4.99	6.91	3.48	1.08
	5.49	7.95	23.52	8.41

TABLE II

Comparison of calculated M1 resonance properties with experimental values

Theory			Experiment			
Nuclei	$\langle \hbar\omega \rangle$ MeV	$\sum G\uparrow$ S.P.U.	E MeV		$\sum G\uparrow$ S.P.U.	Ref.
^{90}Zr	9.6	5.8	9		—	[4]
^{120}Sn	8.4	8.3	8.3		—	[13]
^{140}Ce	8.4	7.8	8.7±0.2		19.5±9.7	[3]
Nuclei	$\hbar\omega_s$ MeV	G_s S.P.U.	E MeV		$\sum G\uparrow$ S.P.U.	G_s S.P.U.
^{208}Pb	6.91	1.9	7.41 — 8.24 (7 levels, see [1])	7.56	$14.6^{+4.1}_{-2.9}$ see [1]	3.3
	7.95	13.1		7.99 see [2]		5.5 see [2]

that the E2 and M1 resonance positions differ by 2–4 MeV. In the region of the calculated M1 resonance in ^{208}Pb the contribution of the E1 resonance is by an order of magnitude higher than that of the M1 resonance, while for ^{90}Zr the 1^- levels are absent in the narrow

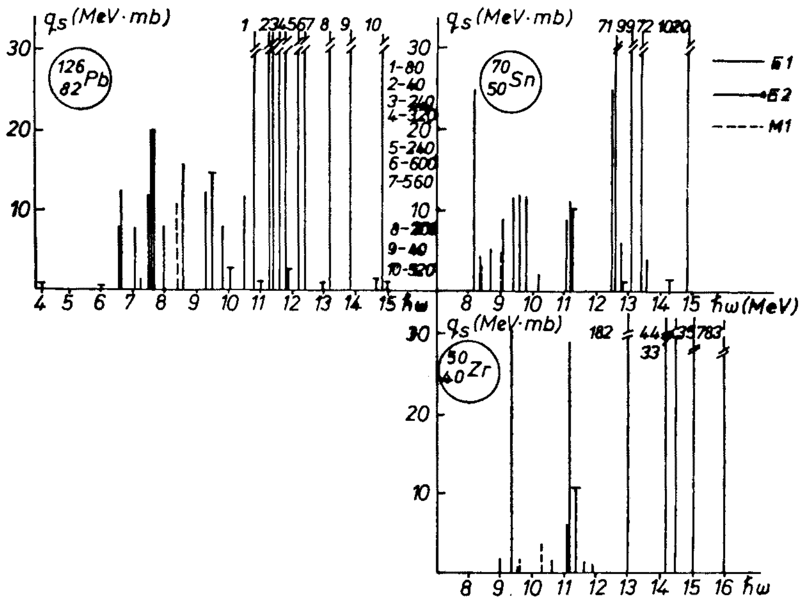

Fig. 1. The integral γ-ray absorption cross sections for the 1^-, 2^+ and 1^+-levels in 0 — 15 MeV region. Only the levels with $q_s \geqslant 0.2$ MeV · mb are plotted

region of the M1 resonance. More information may be obtained by the comparison of the contributions of various resonances in a wider energy interval. For instance, at 4 MeV interval the M1, E2 and E1 resonances give the following contributions to the photoabsorption integral cross section (in MeV · mb):

Nucleus	M1	E2	E1	Energy interval (MeV)
^{90}Zr	6	11	254	9 — 13
^{120}Sn	7	10	103	8 — 12
^{208}Pb	12	17	196	7 — 11

As it is evident from Fig. 1, though the integral photoabsorption cross sections at individual 1^-, 2^+ and 1^+ levels are comparable, the main contribution for a wider interval (higher than 2–3 MeV) is from the E1 resonance.

It is known [23] that the most intensive levels of the isoscalar E2 resonance coincide with the positions of the peaks on the low-energy tail of the photoabsorption curve for ^{208}Pb. Similarly one may try to assume the M1 resonance to be responsible for the structure of the ^{208}Pb (γ, n) reaction cross section in 7–8.5 MeV excitation region. The calculations show that the E1 resonance gives the main contribution to the integral cross section (E1–85%, M1–15% in the 7–8.5 MeV region and E1–99%, E2–1% in 9.5–12 MeV region) and that the total contribution of the E2 and M1 resonances in these two regions is $\sim$1% of the integral cross section $\sigma_{int} = 60_{NZ}/A$ MeV · mb. The latter is in rough agreement with the experimentally determined ratio of the area under fine structure peaks relative to the area under the Lorenz curve for ^{208}Pb.

However, at present we cannot assert anambiguously that the structure of the photoabsorption cross section is caused by the M1 resonance or (and) the isoscalar E2 resonance. The main reason is that we have rather poor knowledge of the 2p–2h configurations influence (see [24]). For the same reason we have not taken into account such fine effects as the separation of the spurious state in the E1 resonance, particle-particle forces in the particle-particle channel, the influence of the spin-spin forces on E2 resonance properties, the influence of the continuum. We think that consideration of these effects would be an overrating of the methods accuracy.

The following general conclusions can be made:

1. The variant of the particle-hole method used (the finite Fermi-systems theory) allows to explain the integral properties (the maximum position and total strength) of the M1 resonance in medium and heavy spherical nuclei without using any parameters but those known before.

2. The main result of the E1, E2 and M1 resonances comparison in the near-threshold region is that individual 1^-, 2^+, and 1^+ levels have comparable integral γ-ray absorption cross sections. Thus in a narrow energy interval (less than 1.5–2 MeV) different multipolarity levels may compete with each other in their contributions to the photoabsorption cross section.

3. The pairing correlation has small influence on the integral resonance properties but it leads to enrichment of low-energy spectra of 1^+ and 2^+ levels. In particular, consideration of pairing is necessary for the explanation of the first 2^+ level properties in ^{90}Zr [22].

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Note added in proof: The systematic study of the M1 resonance in the wide region of spherical nuclei with unclosed shells ($A \sim 70-140, 200$ was perfomed recently (I. N. Borzov, V. N. Tkachev, *Izv. Akad. Nauk USSR Ser, Fiz.* **41**, N6 (1977)). The total M1 resonance strength in $Z = 30-40$ nuclei was shown to be influenced by the number of nucleons in the unclosed shells in contrast with $Z = 42-60$, 78 nuclei. An extension of Kurath sume rule for the medium and heavy nuclei was obtained. The mean energies of M1 resonance are in a good agreement with the empirical formula (40—50) $A^{-1/3}$ MeV.

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