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Фрагментация гигантского квадрупольного резонанса в ^{16}O

Распределение изоскалярной и изовекторной E2 спектроскопической силы в ^{16}O получено из смешивания конфигураций типа 1p1h и 2p2h. Оба изоспиновых мода четко разделены по энергии. Рассчитанные уровни с $J^{\pi}T=2^{+}0$ в области 17-25 МэВ исчерпывают 33-34% правила сумм, если учитываются корреляции в основном состоянии. Этот результат хорошо согласуется с последними экспериментальными данными (37-40% правила сумм). Распределение спектроскопической силы по отдельным уровням сильно зависит от выбора одночастичных энергий в 1p0f оболочке.

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Spreading of the Giant Quadrupole Resonance in ^{16}O

Isoscalar and isovector E2 strength distributions in ^{16}O were obtained from the mixing of 1p-1h and 2p-2h configurations. The two isospin modes are clearly separated in energy. The calculated $J^{\pi}T=2^{+}0$ levels in the 17-25 MeV energy region exhaust 33-34% of the EWSR if the ground state correlations are taken into account. This result is in nice agreement with the most recent experiments (37-40% of the EWSR). The strength attributed to the individual levels strongly depends on the choice of f-p shell parameters.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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The existence and possible specific features of the giant quadrupole resonance (GQR) in ^{16}O, as a representative of light nuclei, recently attracted very much attention. It is so particularly because of the contradictory earlier observations via reactions induced by gamma rays, protons, electrons and alphas [1]. Works on the inelastic scattering of the 104 MeV alpha particles [2] and 130 MeV ^{3}He [3] performed in the last year have shown unambiguously that GQR in ^{16}O differs from that in heavier nuclei. It does not appear as a single bump but rather is split into several ($\gtrsim$ 7) levels in the region of 17-25 MeV.

The simple 1p–1h calculation of GQR in ^{16}O results in a strong concentration of the E2 strength on a single level. The mixing of 1p–1h and 2p–2h configurations was shown by Knüpfer and Huber [4] and by Hoshino and Arima [5] to be responsible for the GQR spreading. Unfortunately, the calculated results for the strength distribution differ considerably [2] from the observed ones. Both calculations put the main E2 strength a little too high. Hoshino and Arima found 88% of the energy weighted sum rule (EWSR) to be exhausted between 20 and 30 MeV, Knüpfer and Huber quote 40% of the EWSR located between 20 and 40 MeV.

In this letter we extend the calculation of refs.[4] and [5] in several respects. We consider the 2p–2h admixtures in the construction of the ground as well as excited state wave functions. Instead of phenomenological interactions which may prove to be oversimplified for use in a large configuration space we introduce Tabakin's realistic potential for the residual interaction. This potential does not contain free parameters. At the same time, however, we have established an unexpectedly strong dependence of the E2 strength distributions on the single particle energies (s.p.e.) of the f–p shell nucleons. Finally, we extend the calculations to the $T=1$ case.

Diagonalization of the Hamiltonian was performed in the complete $2\hbar\omega$ bases of harmonic oscillator ($b = 1.67$ fm) orbitals. Such approach allows for an easy projection of the spurious states arising due to the centre-of-mass motion[6]. Namely, five (0^+) and thirteen (2^+) spurious vectors were explicitly constructed and the diagonalization was performed in the subspaces orthogonal to these vectors.

Let us first discuss the isoscalar E2 strength distribution. We use the energy weighted sum rule

$$S(L,T=0) = \sum_n (E_n - E_0) |\langle n | r^L Y_{L0} | 0 \rangle|^2 = \frac{\hbar^2 A}{8\pi m} L(2L+1) \langle r^{2L-2} \rangle ,$$

which is within 1% independent of the ground state admixtures. Our value of b implies $S(L=2, T=0) = 1642$ MeV.fm^4. At the same time, the individual transition probabilities are indeed very sensitive to the presence of ground state correlations (g.s.c.).

The inclusion of g.s.c. results in a 30% reduction of the EWSR fraction exhausted in our model space and also causes a considerable redistribution of the strength towards nuclear levels below 25 MeV. Indeed both features help to achieve better agreement with the experiment.

The calculated results are shown in table 1 together with the experimental data. As for the input values, it is needless to stress that little is known about the s.p.e. of the f-p shell nucleons. They may be assumed to be of minor importance since they influence only very few components which are strongly spread out over too many levels. Quantitatively, Knüpfer and Huber[4] state that the results exhibit a good stability against small modifications ($\approx$ 30%) of the f-p shell s.p.e. To elaborate upon this point we have performed the calculations twice, using first the s.p.e. set of table 2 and then a modified set obtained by a 25% reduction of the s.p.e. for the f-p shell orbitals. Indeed the energies of the calculated nuclear levels remain practically unchanged in the two series. At the same time the distribution of the spectroscopic strength shows an enormous sensitivity to s.p.e. parameters.

The observed collective levels below 17 MeV are known[7] to have predominantly 4p-4h structure and cannot be accounted for within the present model. Therefore, let us proceed directly to the levels in GQR region. In the above mentioned experiments[2,3] transitions to the individual $2^{+}T=0$ levels of ^{16}O were observed. The two

Table 1

Distribution of isoscalar quadrupole strength in ^{16}O

Present calculations				$(^3He, ^3He')$[c]		(α,α')[d]	
Energy[a] (MeV)	EWSR[a] (%)	Energy[b] (MeV)	EWSR[b] (%)	Energy (MeV)	EWSR (%)	Energy (MeV)	EWSR (%)
16.1	5.3	15.3	8.7	<17	17.8	<17	25.2
17.9	0.1	17.8	0.5	17.2±0.15	1.8	18.0	2.8
19.8	2.5	19.3	7.9	18.4±0.1	9.4	18.5	6.6
20.6	0.8	20.5	1.5	20.2±0.2 }	7.0	20.15	3.4
21.8	2.6	21.4	11.2	doublet }		20.9	4.6
22.2	0.1	22.2	1.5	21.6±0.2	4.7	21.8	5.8
22.4	0.3	22.3	3.7			(22.5)[e]	(5.2)
23.0	0.4	22.5	2.8	23.1±0.3	6.8	(23.25)[e]	(6.0)
23.5	17.5	24.1	0.8	23.5±0.15	7.1	(23.85)[f]	(4.8)
24.7	9.4	24.3	3.1			(24.4)[e]	(4.8)
17-25	34.2		33.1		37.0		40^{+20}_{-10}
25-30	10.5(17 levels)		2.9		-		-
30-60	3.5 (76levels)		3.4		-		-

[a] s.p.e. of tab.2; [b] s.p.e. of tab. 2; f–p shell values reduced by 25%; [c] ref. /3/, $E(^3He)=130$ MeV; [d] ref. /2/ $E(^4He)=104$ MeV, energy resolution 150 keV; [e] uncertain multipolarity $(2^+,3^-)$; [f] uncertain multipolarity $(2^+,0^+)$.

Table 2

The single particle spectrum (MeV)

$0s_{1/2}$	$0p_{3/2}$	$0p_{1/2}$	$0d_{5/2}$	$1s_{1/2}$
-45.0	-21.8	-15.65	-4.15	-3.27
$0d_{3/2}$	$0f_{7/2}$	$1p_{3/2}$	$0f_{5/2}$	$1p_{1/2}$
0.93	11.7	17.7	18.7	24.7

measurements agree nicely with each other as for the partial transition strengths. The total percentage of the EWSR observed in the GQR region is 37% for the ^{3}He scattering [3] and 40^{+20}_{-10} % for the α scattering [2]. The latter value includes, however, several transitions to the levels of poorly identified (2^+?3^-?0^+?) spin-parities. In the calculations which include g.s.c. we have obtained 33-34% of the EWSR located between 17 and 25 MeV in close correspondence to the measured values. Still, most interesting is the dramatic redistribution of the E2 strength among the individual nuclear states which appears when the traditional s.p.e. are slightly changed (columns 2 and 4 of tab. 1). This effect may well account for the unsatisfactory results obtained earlier [4,5] since those are based on s.p.e. sets similar to that of table 2.

Indeed, under these circumstances, an independent estimate of the s.p.e. for the f-p shell orbitals is needed before agreement of the theory with experiment is claimed. Unfortunately, the set of tab. 2 though repeatedly used in the literature is quite unsuitable for the given problem since it is based on an "ad hoc" choice [8] intended for use in very simple 1p–1h estimates without configuration mixing. Similarly, our modified set lacks foundation and should be considered a purely modelistic one.

The isovector nuclear levels in $N=Z$ nuclei are not excited (^4He) or strongly hindered (^3He) in the discussed experiments. Other projectiles (e.g. electrons) excite both isospin modes. To elucidate the possible separation of the isoscalar and isovector mode we have calculated also $T=1$ quadrupole strength distribution within the above $2\hbar\omega$ model. The results are summarized in table 3. The g.s.c. again bring about a strong (36%) reduction of the EWSR fraction* exhausted in our model space. Unlike the $T=0$ case, the isovector E2 strength is almost completely fragmented. Only the structure around 50 MeV($\approx$10% EWSR) shows the properties of a collective level. Our calculation predicts no overlap of the isoscalar and isovector spectroscopic strength: the collective isoscalar levels always lie below 25 MeV, accumulation of the isovector strength starts above 30-35 MeV excitation energy.

To conclude we put forth that the experimental-theoretical discrepancies [2] in the isoscalar E2 strength distribution

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* Isovector EWSR cannot be calculated in the model independent way. Relative numbers are of interest only, we assume therefore a rough enhancement factor $\kappa=0.3$. We have then $S(2,T=1)=(1+\kappa)S(2,T=0) \approx 2138$ MeV.fm^4.

Table 3

Isovector quadrupole strength distribution in ^{16}O

Energy (MeV)	20-25	25-30	30-35	35-40
% EWSR[a]	1.0	1.1	9.1	21.2(2)[c]
% EWSR[b]	2.0	3.4	14.0	20.0(1)[c]
Number of levels	9	19	27	30
Energy (MeV)	**40-45**	**45-50**	**50-60**	**20-60**
% EWSR[a]	10.7	13.7	11.5(1)[c]	67.0
% EWSR[b]	6.6	7.1	10.4(1)[c]	64.0
Number of levels	25	17	11	138

[a] s.p.e. of tab. 2; [b] s.p.e. of tab. 2; f–p shell values reduced by 25%; [c] number of collective states exhausting more than 5% EWSR given in parenthesis.

in the GQR region of the ^{16}O nucleus may easily be resolved if ground state correlations are properly taken into account and a responsible choice of the single particle energies for the f–p shell orbitals is made.

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