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Nucleon resonances in nuclei and quark exchange

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We investigate the photoexcitation of nucleon resonances in nuclei taking into account the quark structure of the nucleon. We calculate the total strength of the $M1$, $E1$, and $E2$ excitation in a two-nucleon system, considered as two three-quark clusters with a properly antisymmetrized wave function. The calculations show that the resonance excitation in the deuteron is not modified with respect to the free nucleon case. In contrast, when the nucleon relative distance assumes typical nuclear values, quark exchange leads to a ~11% damping of the D_{13} resonance and ~23% of the F_{15}, but it leaves the Δ excitation practically unaffected, in agreement with the recent photoabsorption measurements.

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The study of nucleon resonances in nuclei is believed to be relevant for the understanding of the interplay between nuclear structure and the internal degrees of freedom of the nucleon. Up to now, attention has mainly focused on the excitation of the $P_{33}(1232)$ (i.e., Δ resonance), but recently new data on the higher resonances have become available [1–3]. The total photoabsorption cross section has been measured for various nuclei, from ^{9}Be up to ^{238}U, using various methods (transmission techniques [1], total hadron reaction, and photofission [2,3]).

The new experimental results have confirmed the shape of a very evident Δ peak, and have shown that in this region the cross section per nucleon follows a universal behavior, which, even in the presence of nuclear medium effects, is not too different from the free proton behavior. By contrast, in the higher resonance region, the cross section has a flat trend. This is unexpected since in the photoabsorption cross sections the $D_{13}(1520)$ and $F_{15}(1680)$ resonances are clearly seen both in the proton and in the deuteron [4].

One could think that the depletion of the cross section is due to an enlargement of the resonance widths caused by the Fermi motion of the nucleons. In order to test whether this hypothesis is sufficient to explain the data, the photonuclear cross section can be computed by means of a simple folding formula:

$$\sigma_{\gamma A/A} = \int d^3 p n(\mathbf{p}) \sigma_{\gamma N}(W_p) \tag{1}$$

where $\sigma_{\gamma A}$ is the nucleus total photoabsorption cross section, $\sigma_{\gamma N}$ is the average photonucleon cross section, $n(\mathbf{p})$ is the nucleon momentum distribution in nuclei and W_p is the invariant mass of the incoming photon and the moving nucleon, $\sigma_{\gamma N}$ is taken from the phenomenological analysis [4] while $n(\mathbf{p})$ is computed from realistic NN potentials.

With the NN wave functions of the Paris [5] or Bonn [6] potentials, Eq. (1) reproduces the experimental deuteron cross section quite well [4]. Using the momentum distribution of ^{12}C evaluated in the correlated basis approach [7], the theoretical cross section reproduces the Δ peak very well and predicts a broad peak in the higher resonance region [8]. This prediction clearly exceeds the experimental data (see Fig. 1).

The fact that the higher resonances in nuclei are missing cannot therefore be attributed to kinematics but rather to dynamical nuclear effects: the excitation of each single nucleon seems to be affected by the presence of other nucleons. Since the resonance excitation involves the internal structure of the nucleon, it is quite natural to study these effects in the framework of quark models.

The constituent quark model (CQM) has provided a good description of the baryon spectrum [9] and of the electromagnetic excitation of baryon resonances [10]. It has also been used to describe the repulsive core in the short-range nucleon-nucleon interaction [11]. Therefore CQM seems to be a suitable means of investigating how

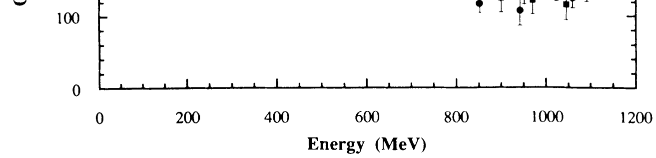

FIG. 1. The total photoabsorption cross section per nucleon, as a function of the photon energy; the experimental points are taken from [1]. The full curve is evaluated by means of Eq. (1), using the phenomenological fit of [4] for the single nucleon cross section and folding with a realistic nucleon momentum distribution [7]. The dot-dashed curve is the same as the full one, but reducing the D_{12} and F_{15} strength by the factor 0.88 and 0.77.

the excitation mechanism of isobar resonances is modified by neighboring nucleons. Moreover, it is convenient for the description of multinucleon systems, since, being a nonrelativistic model, it avoids any spurious contribution to the c.m. motion.

There are various aspects that have to be considered when two nucleons are close to one another [11,12]. In particular, when the internucleon distance is comparable with the confinement (or bag) radius, the wave functions of the two nucleons are strongly overlapped and, in accordance with the Pauli principle, there is a quark exchange between the two clusters. This effect has been shown to be relevant at such distances in previous investigations concerning the electromagnetic form factors of few nucleon systems [13–17]. In this work we examine how much quark exchange affects the excitation mechanism of correlated nucleons and compare the transition strength with the free nucleon one [18].

Since a definite electromagnetic multipole is involved for each resonance excitation, the transition probability can be fairly described by means of multipolar sum rules.

In the case of the Δ, the transition is a magnetic dipole and the corresponding cross section, integrated over the resonance width, is

$$\int d\omega\, \sigma_{\gamma}^{M1}(\omega) = \frac{4\pi}{3}\sum |\langle\psi^*|\mu_z|\psi_0\rangle|^2(M^* - M_0) \qquad (2)$$

where $\sigma_{\gamma}^{M1}(\omega)$ is the total $M1$ cross section, ψ_0 is the initial state of two nucleons in the nucleus, ψ^* is the final state in which one of the two nucleons is excited to the Δ resonance, μ_z is the magnetic dipole operator, and $M^* - M_0$ is the excitation energy.

For the electric dipole and quadrupole excitations, similar sum rules can be written which, in the nucleon, correspond to the $D_{13}(1520)$ and $F_{15}(1680)$ resonances, respectively. Equation (2) and similar equations for the other multipoles have already been used for the analysis of single nucleon excitation [19]. The states ψ_0 and ψ^* are taken from the Isgur-Karl model [9] and the transition strength is in agreement with the phenomenological values, provided that the confinement radius consistent with the helicity amplitudes [20] is chosen. This radius is $R = 0.48$ fm and corresponds to a harmonic oscillator (h.o.) constant for the three-quark wave function $\alpha = 0.41$ GeV [20].

The two-nucleon states to be used in Eq. (2) are constructed within the framework of the cluster theory [21] for the description of nucleon pairs. In this approach, each nucleon is regarded as a cluster of three quarks, as described by the Isgur-Karl model. The two-nucleon wave function for the initial state can be written as

$$\psi_0 = N_0\mathcal{A}\{\vartheta_A\vartheta_B[\psi_A \otimes \psi_B]^{[S,T]}\varphi(r)\} = N_0\mathcal{A}\psi_{NN}\ , \quad (3)$$

where ψ_A, ψ_B are the internal wave functions of the quarks in nucleon A and B respectively; $\vartheta_A\vartheta_B$ is the color singlet for six quarks and $\varphi(r)$ describes the relative motion of the two clusters; the spin-isospin parts of the quark wave functions are coupled to definite values of the total spin S and isospin T of the nucleon pairs; N_0 is a normalization factor. $\mathcal{A}$ is the antisymmetrization operator for the exchange of all six quark coordinates:

$$\mathcal{A} = \sum_{i<j} P_{ij}. \qquad (4)$$

Since $\vartheta_A\psi_A$ and $\vartheta_B\psi_B$ are already antisymmetrized with respect to the quark coordinates in each cluster, the operator $\mathcal{A}$ is simply $1 - 9P_{36}$.

The final state $\psi_f = N_f\mathcal{A}\psi_{NN^*}$ has the same form as in (3) but ψ_B is replaced by ψ_B^*, which is the wave function of three quarks in a resonance state.

For a given electromagnetic transition operator $O = \sum_{i=1}^{6} O(i)$ the total amplitude has the form

$$\begin{aligned} M_{\rm tot} &= N_fN_0\langle(1-9P_{36})\psi_{NN^*}|O|(1-9P_{36})\psi_{NN}\rangle \\ &= 3N_fN_0\{82[\langle\psi_{NN^*}|O_{(3)}|\psi_{NN}\rangle + \langle\psi_{NN^*}|O(6)|\psi_{NN}\rangle] \\ &\quad -18[\langle\psi_{NN^*}|O(3)P_{36}|\psi_{NN}\rangle + \langle\psi_{NN^*}|O(6)P_{36}|\psi_{NN}\rangle]\}. \end{aligned} \qquad (5)$$

The first matrix element in the curly brackets vanishes because ψ_{NN^*} is orthogonal to ψ_{NN}. The last two matrix elements describe the exchange contribution.

The electromagnetic operator O has the following form for the various multipoles

$$O_{M1} = \sum_i \frac{e_i}{2m}(\boldsymbol{\sigma}_i)_z, \qquad (6)$$

$$O_{EL} = \sum_i e_i\sqrt{\frac{4\pi}{2L+1}}r_i^L Y_{LO}(\Omega i), \quad L = 1,2, \qquad (7)$$

where the sum is over all six quarks; $e_i, \boldsymbol{\sigma}_i$ are the quark charge and spin, respectively; $\mathbf{r}_i$ is the quark coordinate relative to the total center of mass system; m is the quark mass, assumed to be 1/3 of the nucleon mass.

We first consider the excitation of two nucleons in the deuteron. To this end we take the realtive wave function $\varphi(r)$ from realistic potentials (in this preliminary evaluation we take into account only the S-wave part since the D-state percentage is of the order of 4–7%). The total transition strength is

$$S_{2N} = \sum |M_{\rm tot}|^2, \qquad (8)$$

where $\sum$ means sum over final states and average over initial states. Using S_N to denote the corresponding quantity for a single nucleon, we define the ratio

TABLE I. The ratio R [Eq. (9)] in the case of the deuteron, for various multipoles and NN potentials: Paris [5], Bonn [6], Argonne [22], De Tourreil-Sprung [23], and one-pion exchange.

R	$M1$	$E1$	$E2$
Paris	1	0.98	0.99
Bonn	1	0.99	0.99
Argonne	1	0.98	0.98
DTS	1	0.98	0.98
OPEP	1	0.97	0.98

$$R = S_{2N}/2S_N. \tag{9}$$

Without quark exchange R is 1 and therefore the occurring of $R \neq 1$ is an indication of quark exchange effects. In Table I we report the theoretical results for R, obtained using various realistic wave functions. One can see that for the deuteron there is practically no modification of the excitation strength of the Δ, D_{13}, and F_{15} resonances, in comparison with the free nucleon. Deviations are in the order of a few percent and mainly concern the electric multipoles. This is due to the fact that the deuteron is a loosely bound system and the excitation of each nucleon occurs fairly independently.

We now turn to the excitation of a nucleon pair in the nuclear medium.

As a first attempt, one can work, as it is customary in photonuclear physics, within the framework of a "quasideuteron" approach [24]. This means first of all that a real photon is absorbed by a correlated proton-neutron pair and the choice of the overall quantum numbers is the same as for the deuteron, that is S wave for the relative motion and $S = 1, T = 0$.

We also consider the case of an arbitrary nucleon pair with no restriction on the total spin and isospin, but in any case we restrict ourselves to a relative S-wave function since the higher angular momentum states are less relevant in the short range behavior of NN correlations.

We can derive $\varphi(r)$ from a h.o. shell model for a typical nucleus after separating the c.m. and relative motion of a nuclear pair with the technique of the Moshinsky coefficients [25]. In the case of ^{16}O we have

$$\varphi(r) = \left(\frac{4\beta^3}{\sqrt{\pi}}\right)^2 \left[\frac{31}{4} + 3(\beta r)^2 + (\beta r)^4\right] e^{-\beta^2 r^2}, \tag{10}$$

where $\beta = 0.55$ fm^{-1} is fixed by the charge rms radius.

The wave function (10) does not vanish for $r = 0$, as it is required by the repulsive core in the NN interaction. A more realistic wave function is then obtained introducing a Jastrow correlation factor $g(r)$. We choose the form [26]

$$g(r) = N(1 - e^{-\alpha^2 r^2}) \tag{11}$$

with $\alpha = 1.4$ fm^{-1}.

TABLE II. The ratio $R_{pn}^{S=1}$, R_{pn}^{av}, R_{NN} (for $N = Z = 8$) with the wave functions (10), (11), and (12), for various multipoles.

$M1$ excitation			
R_M (fm)	$R_{pn}^{S=1}$	R_{pn}^{av}	R_{NN}
≈0	0.99	0.99	0.99
1	0.99	0.99	0.99
2	1.00	1.00	1.00
4	1.00	1.00	1.00
7	1.00	1.00	1.00
Corrected wave-function Eqs. (10) and (11)	0.99	0.99	0.99
Without q exchange	1.00	1.00	1.00
$E1$ excitation			
R_M (fm)	$R_{pn}^{S=1}$	R_{pn}^{av}	R_{NN}
≈0	0.91	0.92	0.92
1	0.89	0.89	0.89
2	0.94	0.94	0.94
4	0.99	0.99	0.99
7	1.00	1.00	1.00
Corrected wave-function Eqs. (10) and (11)	0.90	0.90	0.90
Without q exchange	1.00	1.00	1.00
$E2$ excitation			
r_M (fm)	$R_{pn}^{S=1}$	R_{pn}^{av}	R_{NN}
≈0	0.79	0.81	0.81
1	0.77	0.79	0.79
2	0.89	0.81	0.84
4	0.99	0.99	0.99
7	1.00	1.00	1.00
Corrected wave-function Eqs. (10) and (11)	0.78	0.79	0.80
Without q exchange	1.00	1.00	1.00

In order to test the sensitivity of the results to the average internucleon distance and then to possible quark exchange, we also use the trial wave function

$$\varphi(r) = Ne^{-\beta(r-r_M)^2}. \tag{12}$$

The parameter r_M corresponds to the average distance between the two nucleons, and the coefficient β (~0.23 fm^{-1}) is taken in order to obtain a reasonable depletion of the wave function at short distances.

In this way we get the results reported in Table II as $R_{pn}^{S=1}$.

In order to analyze the effects related to the choice of the quantum numbers, we calculate also the ratio $R_{pn}^{S=0}$, corresponding to $S = 0, T = 1$ and the average, weighted with the standard spin factors:

$$R_{pn}^{\mathrm{av}} = \frac{3}{4}R_{pn}^{S=1} + \frac{1}{4}R_{pn}^{S=0}.$$

Furthermore, we also evaluate the ratio R_{NN} obtained by means of an average over all types of nucleon pairs.

In Table II we report the results for R_{pn}^{av} and R_{NN}, in correspondence of the $M1$, $E1$, and $E2$ excitations.

For large internucleon distances the results agree with those of the deuteron. As long as the distance r_M decreases, the magnetic transition strength remains unaffected; this is in qualitative agreement with the fact that the Δ peak is evident in all nuclei. By contrast, the electric multipoles show a significant depletion. At typical internucleon distances in nuclei (~1 fm), there is an 11% and 22% reduction for the $E1$ and $E2$ transition strength, respectively, and the situation practically does not change taking into account the contributions coming from different NN pairs and quantum numbers. This again agrees, at least qualitatively, with the depletion of the peaks in the higher resonance region, although it is not sufficient to reproduce the data (see Fig. 1).

These results show that the $M1$ transition behaves quite differently from the electric multipoles when the quark exchange mechanism is taken into account. This can be understood by observing that the $M1$ operator involves the quark spin, and the spin part of the wave function is only slightly affected by the exchange operator; in the case of the electric transitions there is a relevant modification of the space wave function and therefore a significant exchange contribution. In other words, the typical feature of a two-nucleon pair with quark exchange is to give rise to a deformed two-cluster structure [27]. The $M1$ transition is simply a spin-flip and therefore, unlike $E1$ and especially to $E2$ transitions, is not sensitive to deformation.

The numerical results are reasonable and present the correct phenomenological trend, both in finite nuclei and in the deuteron. This is, however, a preliminary calculation and several improvements are necessary in order to perform a detailed comparison with data.

In particular, one should consider more refined cluster wave functions, with a better description of the short range NN behavior. Also higher angular momentum states should be in principle considered, but the increasing importance of the centrifugal barrier certainly keeps nucleons far apart and the quark exchange effects are expected to be less relevant.

To conclude, we have shown that taking into account the quark structure of the nucleon and the nucleon resonances is beneficial for the description of resonance photoexcitation in nuclei. In particular, the quark exchange between two neighboring nucleons produces a depletion of the $E1$ and $E2$ transition strength in nuclei, while leaving practically unaffected the $M1$ absorption in nuclei and all multipole transitions in the deuteron.

The numerical results are not able to explain the data, but only their qualitative trend. The model, however, seems to be a reasonable basis for a more reliable description of the excitation of nucleon resonances in nuclei.

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