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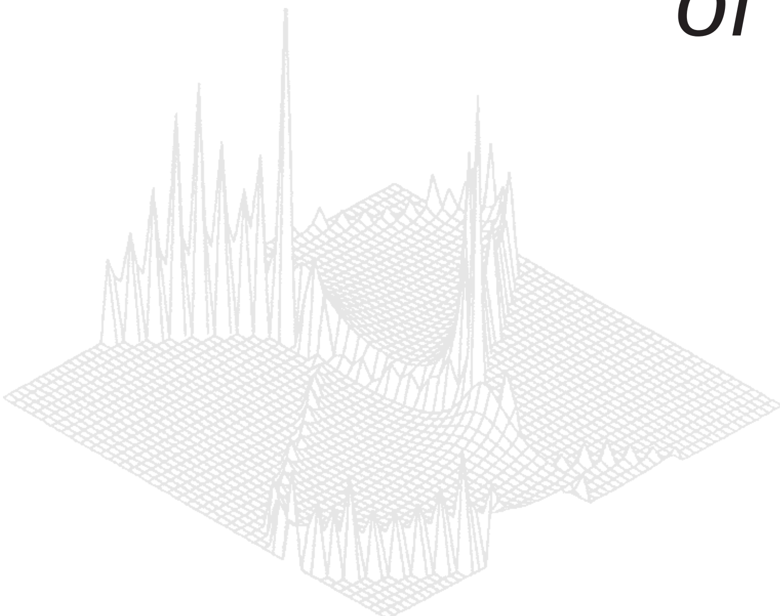

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Neutral Currents in the ^{16}O Nucleus

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Abstract

The aim of this paper is to investigate the parity and isospin forbidden α_0 decay from ^{16}O* ($J^\pi = 1^+$; $T = 1$; $E_x = 16.209$ MeV) to ^{12}C(g.s.) by calculating the longitudinal A_L and the irregular transverse A_b analysing powers of the reaction ^{15}N$(\vec{p}, \alpha_0)^{12}$C around the 1^+, $E_x = 16.2$ MeV resonance in ^{16}O*. The range for the expected interference effect has been estimated to be $A_L \approx 3.2 \times 10^{-5}$ and $A_b \approx 2.3 \times 10^{-5}$.

1. Introduction

The existence of neutral currents other than the familiar electromagnetic currents was predicted by Bludman (1958), who constructed a model based on a local $SU(2)$ gauge symmetry. This model incorporated both the charged (entering the β-decay interaction) and neutral currents. The space–time structure of the neutral currents in this first model was of a pure vector minus axial vector $(V - A)$ type. Thus they could not be identified with the electromagnetic currents which are of a pure vectorial and parity conserving type. There was no unification with electromagnetism in the Bludman model. A model truly unifying weak and electromagnetic interactions incorporating two kinds of neutral currents (electromagnetic and weak) was invented by Glashow (1961) and by Salam and Ward (1964). This model is the $SU(2) \otimes U(1)$ model. As stated in this model, there is no mechanism for the mass generation of the intermediate vector bosons. Thus, the relative strength of weak neutral-current interactions to that of charged-current interactions is a completely free parameter. This problem was settled by Weinberg (1967) who incorporated the idea of spontaneous breaking of local gauge symmetry (Higgs 1964; Englert and Brout 1964) into the $SU(2) \otimes U(1)$ model. The mass of the intermediate boson Z^0 that mediates the neutral current is related in a definite way to the mass of its charged counterpart $W^\pm$. The above relative strength was therefore fixed once and for all in this version of the $SU(2) \otimes U(1)$ model, predicting in this way the structure of the weak neutral currents (as a mixture of vector and axial vector currents) and its interaction strength. Thus, the $SU(2) \otimes U(1)$ model became a single parameter $\sin^2\theta_w$ theory. With the discovery of neutral currents (Hasert *et al.* 1973), this standard $SU(2) \otimes U(1)$ field theory stood out as a strong candidate for a unique theory of electroweak interactions. In the following years, great progress has been made in understanding the weak nucleon–nucleon (NN) interactions, especially after the

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experimental detection (Arnison *et al.* 1983; Banner *et al.* 1983) of $W^{\pm}$ and Z^0 bosons, mediators of the weak force.

The weak interactions between the nucleons and especially those components with a dominant contribution of the neutral currents can be studied only when the strong and electromagnetic interactions between the nucleons are forbidden by a symmetry principle, such as flavour [i.e. strangeness S or charm C] conservation. According to the standard theory, the neutral current contribution to $\Delta S = 1$ and $\Delta C = 1$ weak processes is strongly suppressed (Glashow *et al.* 1970; Kobayashi and Maskawa 1973) and, therefore, the neutral current weak interaction between quarks can only be studied in flavour conserving processes which can only be met in low energy nuclear physics.

The search for parity nonconservation (PNC) in complex nuclei, and especially in cases where an enhanced effect is expected from the existence of parity mixed doublets (PMD), has a long history (Adelberger and Haxton 1985; Brandenburg *et al.* 1978; Desplanques 1983, 1984; Desplanques *et al.* 1980; Desplanques and Dumitrescu 1993; Dubovik and Zenkin 1986; Dubovik *et al.* 1987*a*, 1987*b*; Dumitrescu 1991; Dumitrescu *et al.* 1990; Dumitrescu and Clausnitzer 1993; Kaiser and Meissner 1988, 1989, 1990*a*, 1990*b*; Haxton *et al.* 1980; Brown *et al.* 1980; Kniest *et al.* 1983, 1990, 1991; Ohlert *et al.* 1981). The enhancement of any PNC effect is predicted for several reasons, the most important being the small level spacing between states of the same spin and opposite parity in the compound nucleus involved. The second one arises from the expected increase of the ratio between parity-forbidden and parity-allowed transition matrix elements caused by the nuclear structures of the states involved. Usually such enhancements are offset due to correspondingly large theoretical uncertainties in the extraction of the PNC-NN parameters from the experimental data. In fact the same conditions which generate the enhancement complicate a reliable theoretical determination of the nuclear matrix elements. Therefore, it is necessary to select exceptional cases in which the nuclear structure problem can be solved. This is the case for closely spaced doublets of the same spin and opposite parity levels situated far away from other similar levels. In this case the parity impurities are well approximated by simple two state mixing, which simplifies the analysis and isolates specific components of the PNC-NN interaction.

The effects related to the PMD should help to determine the relative strengths of the different components of the PNC-NN interaction (Adelberger and Haxton 1985; Desplanques *et al.* 1980; Dubovik and Zenkin 1986; Dubovik *et al.* 1987*a*, 1987*b*; Kaiser and Meissner 1988, 1989, 1990*a*, 1990*b*). Due to generally small values of most of the contributing terms to the PNC matrix elements, PNC dealing with the low energy nuclear spectrum should essentially involve the strength of the nucleon–nucleus weak force. As weak interactions do not conserve the isospin, this strength may be characterised by two numbers, relative to the proton and neutron forces respectively, or equivalently to its isovector and isoscalar components. Moreover, the main contribution coming from the isovector part is assumed to be due to the one-pion exchange term, while the main contribution coming from the isoscalar part is assumed to be due to one ρ-meson exchange term. At present no experiment is possible to investigate other contributions to the weak hadron–hadron interaction potential. Therefore, in principle two independent experiments should be sufficient for the determination of the above nucleon–nucleus weak forces. They may be those looked at in ^{19}F, where theoretical analysis (Adelberger and Haxton 1985; Haxton *et al.* 1980; Brown *et al.* 1980) shows it is dominated by the strength of the proton–nucleus weak force (Desplanques 1983, 1984), and in ^{18}F which is well known to be dominated by the isovector part of this force. The first effect, experimentally observed (Adelberger *et al.* 1983; Elsener *et al.* 1982, 1984) is accounted for by the *best DDH values* (Desplanques *et al.* 1980) of the meson–nucleon weak coupling constants. The second one is not, although it is compatible (Barnes *et al.* 1979; Mak *et al.* 1981; Bini *et al.* 1981, 1984, 1985; Bizzeti *et al.* 1980; Maurenzig *et al.* 1979; Afrens *et al.* 1982), with the largest range of their expectations.

Besides, there are several theoretical and experimental investigations which are not necessarily related to the PMD. For instance, the value of h_π has also been extracted from evaluations of the nuclear anapole moment (Flambaum and Murray 1997; Auerbach and Brown 1999) and octupole moments (Flambaum *et al.* 1997). Also, some new aspects in the PNC phenomenology have been considered recently (Mitchell *et al.* 1999; Flambaum and Vorov 1993).

Investigating the PNC meson–nucleon vertices within the framework of a chiral effective Lagrangian for π, ρ and ω meson exchange and treating nucleons as topological solitons, the weak πNN coupling constant h_π is found (Kaiser and Meissner 1988, 1989, 1990*a*, 1990*b*) to be considerably smaller (2×10^{-8}) than the standard quark model results (1.3×10^{-7}) (Dubovik and Zenkin 1986; Dubovik *et al.* 1987*a*, 1987*b*), both restricting the often used Desplanques–Donoghue–Holstein (DDH) values significantly (Desplanques *et al.* 1980). Such a controversy stimulates us to investigate experiments sensitive to h_π with greater interest.

In the present paper the α_0 transition from the $J^\pi T = 1^+1$ state in ^{16}O ($E_x = 16.209$ MeV, $\Gamma_{cm} = 19 \pm 3$ keV), populated by the resonance capture of polarised protons ($E_p = 9.047$ MeV), to ^{12}C(g.s.) is investigated. This transition is forbidden by parity and isospin selection rules. It, therefore, can mainly be described theoretically by one-pion exchange, thus being sensitive to the weak πNN coupling constant h_π, the size of which may be related to the presence of neutral currents in the hadronic weak interaction, if using a quark picture.

The excitation functions of the PNC longitudinal A_L and PNC transverse A_b analysing powers are expected to show an energy anomaly at 1^+1 resonance energy due to the interference of the forbidden (PNC: 1^+1, 16.209 MeV) and allowed (PC: 1^-0, 16.200 MeV) resonance transition amplitudes as well as a (PC: 0^+0) background transition amplitude. The level structure of the ^{16}O nucleus enhances the interference effect because of the close lying ($\Delta E = 9$ keV) broad overlapping 1^-0 state at $E_x = 16.200$ MeV ($\Gamma_{cm} = 580 \pm 60$ keV) (Ajzenberg-Selove 1986).

The above-mentioned PNC α_0 transition from the theoretical point of view may be a better candidate than the recently investigated (Kniest *et al.* 1983, 1990, 1991; Ohlert *et al.* 1981) similar cases of parity and isospin forbidden α_0 decay from: (1) ^{16}O (2^-1, 12.2686 MeV) to ^{12}C(g.s.) via the ^{15}N($\vec{p}, \alpha_0$)^{12}C resonance reaction wherein a close lying ($\Delta E = 51$ keV) 2^+0 state is involved in the PNC transition and (2) ^{20}Ne(1^+1, 13.482 MeV) to ^{16}O(g.s.) via the ^{19}F($\vec{p}, \alpha_0$)^{16}O resonance reaction, wherein a close lying ($\Delta E = 20$ keV) 1^-0 state is involved in the PNC transition, respectively.

One explanation sustaining this affirmation could be the small energy difference entering the PMD (9 keV). On the other hand, the closest $1^\pm$ states to the PMD differ by more than ≈ 1 MeV in energy, while in the previous cases this energy difference is smaller than 0.5 MeV. Furthermore, the PNC α_0 transition can be studied via the ^{15}N($\vec{p}, \alpha_0$)^{12}C resonance reaction with two observables, independently, namely the PNC longitudinal A_L and the PNC transverse A_b analysing powers. The aim of this paper, therefore, is to give an estimation for these observables.

Section 2 is devoted to the weak interaction models, while Section 3 is devoted to the large scale shell model predictions for the PNC matrix elements. In Section 4 we reproduce the basic formulae used to calculate the energy anomalies in the excitation functions of the analysing powers. Discussions concerning the numerical results are presented in Section 5, while the conclusions are presented in Section 6.

2. Weak Interaction Models

The calculations of the PNC longitudinal A_L and the PNC transverse A_b analysing powers have been performed with the standard PNC potential, arising from the exchange of π, ρ and ω mesons, together with various descriptions of the effective NN interaction.

The expression for the above PNC-NN potential is well known. Nevertheless, we give it here especially to our precise conventions:

$$H_{PNC} = \sum_{s=\pi,\rho,\omega,\Delta T} V_s^{PNC}(\Delta T) = \sum_k \sum_{s=\pi,\rho,\omega} F_{k,s}\, f_{k,s}, \tag{1}$$

where $V_s^{PNC}(\Delta T)$ are different meson exchange contributions to the total PNC-NN potential H_{PNC}, defined by Desplanques and Dumitrescu (1993). A sample of the values for the weak coupling constants $h_{meson}^{\Delta T}$ are given in Table 1, while the values for the $F_{k,s}$ coefficients are given in Table 2. The abbreviations DDH, KM, AH and DZ stand for the models developed by Desplanques *et al.* (1980), Kaiser and Meissner (1988, 1989, 1990*a*, 1990*b*), Adelberger and Haxton (1985) and Dubovik and Zenkin (1986) respectively.

Corresponding to the above definitions, we may define the following matrix elements:

$$M_{k,s} = \langle I^\pi T | f_{k,s} | I^{-\pi} T' \rangle, \tag{2}$$

so that some matrix of the PNC interaction (1) reads

$$\langle I^\pi T | H_{PNC} | I^{-\pi} T' \rangle = \sum_k \sum_{s=\pi,\rho,\omega} F_{k,s}\, M_{k,s}. \tag{3}$$

The advantage of the M quantities is that their ratios in the case of the single particle approximation, without short range correlations (SRC) and for a zero range force, are quite simple rational numbers (0, 1, $\frac{1}{2}$, $\frac{3}{2}$).

Table 1. Weak meson–nucleon coupling constants (in units of 10^{-7}) calculated within different weak interaction models

KM (Kaiser and Meissner 1988, 1989, 1990*a*, 1990*b*), DDH (Desplanques *et al.* 1980), AH (Adelberger and Haxton 1985) and DZ (Dubovik and Zenkin 1986; Dubovik *et al.* 1987*a*, 1987*b*)

$h_{meson}^{\Delta T}$	KM	DDH	AH(fit)	DZ
h_π^1	+0.19	+4.54	+2.09	+1.30
h_ρ^0	−3.70	−11.40	−5.77	−8.30
h_ρ^1	−0.10	−0.19	−0.22	+0.39
h_ρ^2	−3.30	−9.50	−7.06	−6.70
$h_{\rho'}^1$	−2.20	0.00	0.00	0.00
h_ω^0	−6.20	−1.90	−4.97	−3.90
h_ω^1	−1.00	−1.10	−2.39	−2.20

Table 2. The coefficients $F_{k,s}$ multiplying the matrix elements $M_{k,s}$ given in Table 3

Numerical values (in units of 10^{-6}) are given for the 'best values' of the PNC meson–nucleon couplings in the DDH approach (Desplanques *et al.* 1980), as well as for the values obtained by Kaiser and Meissner (1988, 1989, 1990*a*, 1990*b*), Adelberger and Haxton (1985) and Dubovik and Zenkin (1986). The strong coupling constants values ($g_\pi = 13.45$, $g_\rho = 2.79$, $g_\omega = 8.37$) are taken from Adelberger and Haxton (1985)

$F_{k,s}$	KM	DDH	AH(fit)	DZ
$F_{0,\pi} = \frac{1}{2\sqrt{2}} g_\pi h_\pi^1$	0.090	2.16	0.995	0.617
$F_{1,\rho} = -\frac{1}{2} g_\rho h_\rho^1$	0.014	0.027	0.805	−0.544
$F_{2,\rho} = -\frac{1}{2} g_\rho h_\rho^1 (1+\mu_v)$	0.066	0.127	0.144	−0.256
$F_{3,\rho} = \frac{1}{2} g_\rho h_\rho^1$	−0.014	−0.027	−0.031	0.054
$F_{1,\omega} = -\frac{1}{2} g_\omega h_\omega^1$	0.437	0.480	1.000	0.921
$F_{2,\omega} = -\frac{1}{2} g_\omega h_\omega^1 (1+\mu_s)$	0.384	0.423	0.880	0.810
$F_{3,\omega} = -\frac{1}{2} g_\omega h_\omega^1$	0.437	0.480	1.000	0.921
$F_{4,\rho} = -g_\rho h_\rho^0 (1+\mu_v)$	4.850	14.94	7.566	10.884
$F_{5,\rho} = -g_\rho h_\rho^0$	1.032	3.180	1.610	2.316
$F_{6,\omega} = -g_\omega h_\omega^0 (1+\mu_s)$	4.568	1.408	3.661	2.872
$F_{7,\omega} = -g_\omega h_\omega^0$	5.190	1.6	4.160	3.264
$F_{0,\rho} = -\frac{1}{2} g_\rho h_\rho^1$	0.307	0.00	0.00	0.00
$F_{8,\rho} = -\frac{1}{2\sqrt{6}} g_\rho h_\rho^2 (1+\mu_s)$	0.886	2.542	1.888	1.792
$F_{9,\rho} = -\frac{1}{2\sqrt{6}} g_\rho h_\rho^2$	0.189	0.541	0.402	0.381

Due to the short range of the operators $\vec{u}(\vec{r}, m_s)$ and $\vec{v}(\vec{r}, m_s)$ [see equations (20) and (21) from Desplanques and Dumitrescu 1993], the estimations of their matrix elements are expected to be very sensitive to SRC. To take them into account, we introduce into the calculations the correlation function of Miller and Spencer (1976), for even as well as for odd parity components:

$$f(r) = 1 - \exp(-ar^2)(1 - br^2); \quad a = 1.1\,\mathrm{fm}^{-2}; \quad b = 0.68\,\mathrm{fm}^{-2}. \tag{4}$$

This choice is consistent with results obtained by using more elaborate treatments of SRC such as the generalised Bethe–Goldstone approach (Dumitrescu *et al.* 1971, 1972; Gari 1973) and should roughly correspond to an NN interaction close to the Reid soft-core model for the $^1S_0$ and $^3P_0$ components. The comparison with more recent models of the NN strong interactions (Machleidt 1987, 1989) indicates that the Miller and Spencer approach (4) overestimates the effect of short range repulsion. From inspection of the ${}^3S_1$ component of the deuteron wave function, one thus expects that the correlation function does not vanish at the origin. With the same asymptotic normalisation as in (4), it would be close to 0.1 for the Paris model (Lacomb *et al.* 1980) and 0.5 for the Bonn model (Machleidt 1987, 1989). Moreover, the correlation function (4) neglects the effect of the tensor force which admixes to the ${}^3S_1$ state a ${}^3D_1$ component that has also a short range character. This effect is large and, depending on the transition amplitude, it is constructive or destructive (Desplanques 1975; Desplanques and Missimer 1978). In the case of the π meson-exchange contribution, dominated by the ${}^3P_1{-}{}^3S_1(+{}^3D_1)$ transition, it compensates a large part of the short-range repulsion (Desplanques 1975; Desplanques and Missimer 1978). On the contrary, in the case of the isoscalar ρ-exchange contribution, *a priori* dominated by the ${}^1P_1{-}{}^3S_1(+{}^3D_1)$ transition, it provides further suppression.

The above improvements should be incorporated into definite predictions. We will not do this and will stick to (4). Finally, we make some remarks. First, there is no end to playing with different models of SRC. Second, there are other possible improvements due, for instance, to the part of the exchange of a 2π contribution not included in the ρ, to vertex form factors, to heavier meson exchanges, etc. Furthermore, the corresponding uncertainties will add to those on the PNC coupling constants themselves. In our mind, it is more important to make predictions that can be compared to other ones than to multiply them by looking at modifications of rather minor relevance at the present time.

The essential point is that the PNC potential given by (1) can account independently for the various contributions expected to dominate at low energy which are due to PNC-NN transition amplitudes ${}^1S_0{-}{}^1P_0$ (three amplitudes: pp, nn and pn or $\Delta T = 0, 1$ and 2) ${}^3S_1{-}{}^1P_1(pn,\ \Delta T = 0)$ and ${}^3S_1{-}{}^3P_1(pn,\ \Delta T = 1)$. A few clues as to the relevance of these amplitudes will be given when discussing the results.

3. Strong Interaction Models

In order to estimate the PNC effects in the case of the PMD investigated in ^{16}O, we need to compute the appropriate PNC matrix element,

$$\begin{aligned} M_{PNC} &= \langle 1^+,\ T = 1(16.209\,\text{MeV})|H_{PNC}|1^-,\ T = 0(16.200\,\text{MeV})\rangle \\ &= \sum_{k,s} F_{k,s}\, M_{k,s}. \end{aligned} \tag{5}$$

To facilitate the comparison between different models of strong interaction, we calculate first (see Table 3) the nuclear structure matrix elements

$$M_{k,s} = \langle 1^+,\ T = 1(16.209\,\text{MeV})\ |f_{k,s}|1^-,\ T = 0(16.200\,\text{MeV})\rangle, \tag{6}$$

where the operators $f_{k,s}$ are defined by equations (10)–(19) from Desplanques and Dumitrescu (1993). In Table 3 the first column contains the expressions for the $F_{k,s}$ coefficients multiplying the $M_{k,s}$ matrix element values listed in the next six columns. Besides the total contribution, we give the separate contribution of the core presently built by filling its orbits $1s_{\frac{1}{2}}$ and $1p_{\frac{3}{2}}$. It corresponds in the present case to a single particle transition involving nucleons in orbits $1p_{\frac{1}{2}}$ and $2s_{\frac{1}{2}}$. As a benchmark, we also give the result corresponding to a pure case, where the $\frac{1}{2}^-$ and $\frac{1}{2}^+$ states can be considered as made of one neutron moving in the field of an inert core (^{12}C) and occupying respectively the above orbits $1p_{\frac{1}{2}}$ and $2s_{\frac{1}{2}}$. The

Table 3. The matrix elements $M_{k,s}$ values (in MeV) for different descriptions of the nucleus

The first column gives the coupling constants multiplying these matrix elements, while the next columns contain results corresponding to models described in the text. The results corresponding to the oversimplified model, where the states $\frac{1}{2}^+$ and $\frac{1}{2}^-$ are described by one neutron occupying the $2s_{\frac{1}{2}}$ and the $1p_{\frac{1}{2}}$ orbits (with a ^{12}C core), are given in the second last column. The last column gives the dominant character of the transition for the component under consideration. For each component the contribution corresponding to the ^{12}C core is given in the first row, while the second row incorporates the contributions from valence nucleons

Coupling constant	ZBM-I	WM (Z)	REWIL (F)	ZBM-II	ZBMO	Valence particle (^{12}C)	Dominant transition
$\frac{g_\pi h_\pi^1}{2\sqrt{2}}$	−0.0670 −0.0038	−0.1594 −0.1065	−0.0354 −0.0966	−0.0355 +0.0057	−0.2796 −0.0668	0.6889	$(^3S_1 - ^3P_1)$
$-\frac{g_\rho h_{\rho'}^1}{2}$	−0.0038 −0.0091	−0.0091 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0160 −0.0030	0.0372	$(^3S_1 - ^3P_1)$
$-\frac{g_\rho h_\rho^1(1+\chi_v)}{2}$	−0.0042 −0.0055	−0.01 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0177 −0.0035	0.0436	$(^1S_0 - ^3P_0)$
$\frac{g_\rho h_\rho^1}{2}$	−0.0034 −0.0017	−0.00 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0143 −0.0027	0.0351	$(^3S_1 - ^3P_1)$
$-\frac{g_\omega h_\omega^1}{2}$	−0.0047 −0.0050	−0.01 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0196 −0.0036	0.0349	$(^3S_1 - ^3P_1)$
$-\frac{g_\omega h_\omega^1(1+\chi_v)}{2}$	−0.0040 −0.0052	−0.00 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0168 −0.0033	0.0144	$(^1S_0 - ^3P_0)$
$-\frac{g_\omega h_{\omega'}^1}{2}$	−0.0032 −0.0016	−0.00 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0133 −0.0025	0.0329	$(^1S_0 - ^3P_0)$
$-\frac{1}{2}g_\rho h_{\rho'}^1$	−0.0042 −0.0020	−0.01 −0.00	−0.00 −0.00	−0.00 +0.00	−0.0177 −0.0037	0.0437	$(^1S_0 - ^3P_0)$

comparison with full calculations may give evidence of specific nuclear structure effects such as depopulation of these single particle states, pairing, possible departures to the single particle approximation together with some suppression or enhancement of particular contributions of the weak force. In reporting the results for various strong interaction models, we gave particular attention to the intrinsic sign of the weak matrix element M_{PNC}. Obviously, this sign is not measurable since it depends on the sign conventions used to describe the states $|1^-, T = 0(16.200\,\text{MeV})\rangle$ and $|1^+, T = 1(16.200\,\text{MeV})\rangle$. However, the comparison of signs obtained with different strong interaction models may be relevant and some change may indicate a strong sensitivity to particular features of the nucleus description. We, therefore, carefully examined this result. The task is not *a priori* straightforward. One may imagine, for instance, that the sign of the isovector contribution is not settled, as stated by Brandenburg *et al.* (1978) in the ^{21}Ne case, while the sign of the isoscalar contribution would be well determined, or vice-versa. Moreover, there are eight contributions to the isovector matrix element and one should be sure whether the corresponding signs depend on the strong NN effective interactions. For the strong interaction models used here, it has been found (Dumitrescu 1991) that the sign of the largest contribution [at the levels of the two-body matrix elements (TBME)] was the same up to a common phase, leaving no doubt that the origin of a difference in sign is the result produced from the computer. Differences in sign between some of these results reflect, therefore, differences in the physical description of the nucleus.

The present calculations give a fortunate example where all $M_{k,s}$ have the same sign, except for those calculated with the ZBM-II interaction (see Table 3) whereas in the previous case (Dumitrescu 1991) an ambiguous result is obtained.

The microscopic structure of the nuclear levels of the PMD has been obtained by using the OXBASH code in its Michigan State University version (Brown *et al.* 1985, 1988; Brown and Wildenthal 1988), which includes different model spaces and different effective two-nucleon interactions.

In these calculations the Zuker–Buck–McGrory model space (Zuker *et al.* 1968) has been used. In the ZBM model the $1s_{\frac{1}{2}}$ and $1p_{\frac{3}{2}}$ are filled and the active (valence) particles are restricted to the $1p_{\frac{1}{2}}$, $2s_{\frac{1}{2}}$ and $1d_{\frac{5}{2}}$ orbits. The single particle energies were fitted as in the Reehal and Wildenthal (1973) paper, and the TBME were identified with G-matrix elements (Kuo 1967, 1974; Kuo and Brown 1966). The interaction ZBM-II was determined from Talmi fits for ^{16}O in the p and s shells (Zuker 1969), while the ZWM interaction was constructed using free nucleon–nucleon potentials with minimal corrections from the experimental energy levels in $A = 16$, 17 and 18 nuclei (Zuker 1969; Reehal and Wildenthal 1973). REWIL is entirely obtained by a fit of 134 binding and excitation energies of selected levels in $A = 13$–22 nuclei, considering the matrix elements of the Hamiltonian as free parameters (Reehal and Wildenthal 1973). In the ZBMO model the TBME are calculated by using a Hamada–Johnston G-matrix and the Oxford Avila–Aguirre–Brown (Brown *et al.* 1985, 1988; Brown and Wildenthal 1988) interactions.

In Table 4 we list the total PNC matrix element values within different weak and strong interactions models. The partial contribution of the π-exchange meson together with the $\rho(\omega)$-mesons parts are also shown in Table 4, while in Fig. 1 we plot the π-meson contributions only. Excluding the large DDH values and small Kaiser–Meissner values for the PNC matrix elements, we may conclude that a 'realistic' value for the PNC matrix element mentioned in this section is $\simeq 0.4$ eV.

Table 4. PNC matrix element values (in eV) calculated within different weak and strong interactions

The abbreviations are given in the text

Interactions	KM			DDH		
	V_π	$V_{\rho(\omega)}$	$V_{\text{tot}}^{\text{KM}}$	V_π	$V_{\rho(\omega)}$	$V_{\text{tot}}^{\text{DDH}}$
ZBM-I	−0.0064	−0.0125	−0.0189	−0.1685	−0.0121	−0.1806
ZBMO	−0.0312	−0.0328	−0.0640	−0.7484	−0.0301	−0.7785
ZWM	−0.0239	−0.0194	−0.0433	−0.5743	−0.0304	−0.6047
REWIL	−0.0119	−0.0069	−0.0188	−0.2851	−0.0059	−0.2910
ZBM-II	−0.0027	+0.0002	−0.0025	−0.0644	+0.0007	−0.0637
Interactions	**AH**			**DZ**		
	V_π	$V_{\rho(\omega)}$	$V_{\text{tot}}^{\text{AH}}$	V_π	$V_{\rho(\omega)}$	$V_{\text{tot}}^{\text{DZ}}$
ZBM-I	−0.0704	−0.0240	−0.0944	−0.0437	−0.0182	−0.0619
ZBMO	−0.3444	−0.0598	−0.4042	−0.2141	−0.0469	−0.2610
ZWM	−0.2643	−0.0341	−0.2984	−0.1643	−0.0270	−0.0193
REWIL	−0.1312	−0.0117	−0.1429	−0.0816	−0.0092	−0.0908
ZBM-II	−0.0296	+0.0011	−0.0285	−0.0184	+0.0003	−0.0181

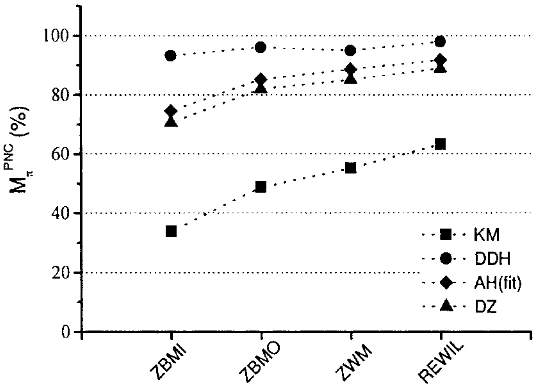

Fig. 1. The π-meson contributions (in per cent) to the total PNC matrix element M_{PNC} within different models of the weak and strong interactions. The abbreviations are discussed in the text.

4. Longitudinal and Irregular Transverse Analysing Powers for the ^{15}N$(\vec{p}, \alpha_0)^{12}$C Resonance Reaction

The explicit expressions for the analysing powers are (Dumitrescu *et al.* 1990; Dumitrescu 1991; Kniest *et al.* 1991):

$$A_L = 2\,Re\left[\sigma_0^{(1)}\left(\sigma_0^{(0)}\right)^{-1}\right], \tag{7}$$

$$A_b = -2\sqrt{2}\,Re\left[\sigma_1^{(1)}\left(\sigma_0^{(0)}\right)^{-1}\right], \tag{8}$$

$$A_n = -2\sqrt{2}\,Im\left[\sigma_1^{(1)}\left(\sigma_0^{(0)}\right)^{-1}\right]. \tag{9}$$

Here A_L is the PNC longitudinal, A_b the PNC transverse and A_n the PC transverse analysing powers, in which

$$\begin{aligned}\left(\sigma_k^{(v)}\right)_{nn} = k_i^{-2} &\sum_{Jlsl_1s_1J'l'sl_2s_2L} F^{(v,k)}_{Jlsl_1s_1,\,J'l'sl_2s_2}(L)\,P_{Lk}(\cos\theta_f)\\ &\times\, T^{J^\pi}_{\beta ls,\,\beta_1 l_1 s_1}\left(T^{J^\pi}_{\beta' l' s',\beta_2 l_2 s_2}\right)^*,\end{aligned} \tag{10}$$

where the $P_{Lk}(\cos\theta_f)$ are the associated Legendre polynomials and

$$\begin{aligned}F^{(v,k)}_{Jlsl_1s_1,\,J'l'sl_2s_2}(L) &= \left(4\hat{j}_i^2\hat{I}_i^2\right)^{-1}\left\langle j_i|O^{(v)}|j_i\right\rangle(-1)^{(I_i-j_i+v-k+J-s-l_2+s_2+2s_1)}\\ &\times\, \hat{l}_1\hat{l}_2\hat{s}_1\hat{s}_2\hat{l}\hat{l}'\hat{L}^2\hat{J}^2\hat{J}'^2\sqrt{\frac{(L-k)!}{(L+k)}}W(JlJ'l';\,sL)W\left(\tfrac{1}{2},\,\tfrac{1}{2},\,s_1,\,s_2;\,v,\,\tfrac{1}{2}\right)\\ &\times \begin{pmatrix} l & l' & L\\ 0 & 0 & 0\end{pmatrix}\sum_j(-1)^j\hat{j}^2\begin{pmatrix} L & v & j\\ k & -k & 0\end{pmatrix}\begin{pmatrix} l_1 & l_2 & j\\ 0 & 0 & 0\end{pmatrix}\begin{Bmatrix} l_1 & l_2 & j\\ s_1 & s_2 & v\\ J & J' & L\end{Bmatrix}\end{aligned} \tag{11}$$

are the corresponding geometrical coefficients (Dumitrescu *et al.* 1990), with

$$O^{(v)} = \begin{cases} 1 & v = 0\\ \vec{S} & v = 1\end{cases} \tag{12}$$

and

$$\langle j_i|1|j_i\rangle = 1,$$

$$\langle j_i|S^{(1)}|j_i\rangle = \frac{\sqrt{3}}{2}.$$

The next step is to find out as rigorously as possible the PC sector of the nuclear reaction mechanism. The general form of the PC resonance T-matrix elements is

$$T^{J^\pi}_{\beta ls,\beta_1 l_1 s_1} = \frac{i\exp(i\xi_{\beta ls})\sqrt{\Gamma^{J^\pi}_{\beta ls}}\sqrt{\Gamma^{J^\pi}_{\beta_1 l_1 s_1}}\exp(i\xi_{\beta_1 l_1 s_1})}{E - E^{J^\pi} + \frac{i}{2}\Gamma^{J^\pi}}, \tag{13}$$

while the PNC T-matrix elements have the following expression:

$$T^{J^{\pi,-\pi}}_{\beta ls,\beta_1 l_1 s_1} = \frac{i\exp(i\xi_{\beta ls,\beta_1 l_1 s_1})\sqrt{\Gamma^{J^{-\pi}}_{\beta ls}}\langle J^{-\pi}|H_{PNC}|J^\pi\rangle\sqrt{\Gamma^{J^\pi}_{\beta_1 l_1 s_1}}\exp(i\xi_{\beta_1 l_1 s_1})}{(E - E^{J^{-\pi}} + \frac{i}{2}\Gamma^{J^{-\pi}})(E - E^{J^\pi} + \frac{i}{2}\Gamma^{J^\pi})}. \tag{14}$$

Here $\xi_{\beta ls}$, E^{J^π} and Γ^{J^π} stand for the channel phases, resonance energies and total resonance widths respectively. The quantities $\sqrt{\Gamma^{J^\pi}_{\beta ls}}$ are the amplitudes of the channel widths which also contain signs.

The largest energy anomaly of the A_L (A_b) analysing power is around the energy of the small width level of the PMD, i.e. around the $J^\pi\, T = 1^+1$, $E_p = 4.0814$ MeV resonance. In the vicinity of this resonance $A_{L(b)}$ has the following simple expression:

$$A_{L(b)} = D_{L(b)}\frac{1}{2}\Gamma^{1^+}\left(E - E^{1^+} + \frac{i}{2}\Gamma^{1^+}\right)^{-1} e^{\left(i\Phi^{L(b)}_{PC} + \Phi_{PNC}\right)}, \tag{15}$$

where

$$D_{L(b)} = \frac{|M_{PNC}|}{|(E - E^{1^-} + \frac{i}{2}\Gamma^{1^-})|}\sqrt{\frac{\Gamma^{1^-}}{\Gamma^{1^+}}}|C_{L(b)}|. \tag{16}$$

In equation (16)

$$\begin{aligned} C_{L(b)} &= |C_{L(b)}|e^{i\Phi^{L(b)}_{PC}} \\ &= 2\,\frac{\left|\left(E - E^{1^-} + \frac{i}{2}\Gamma^{1^-}\right)\right|\sum_l P^{(k)}_l(\cos\theta)\sum_{mn} b^l_{mn}(L(b))\left(\tilde{t}_m\, t^*_n + \tilde{t}^*_m\, t_n\right)}{\sqrt{\Gamma^{1^-}\Gamma^{1^+}}\sum_l P_l(\cos\theta)\sum_{mn} a^l_{mn}\, t_m\, t^*_n} \end{aligned} \tag{17}$$

is a function of the PC transition matrix elements only [for L: $k = 0$, for b: $k = 1$, $\tilde{t}_n = T^{1^-}_{pls,pl_1s_1}\exp[i(\xi_{pls} - \xi_{pl's'})]$]. The coefficients $a^{(l)}_{mn}(L(b))$ and $b^{(l)}_{mn}(L(b))$ are simple specific values of the $F^{(v,k)}$ geometrical coefficients. In the factor $D_{L(b)}$ we separated the large enhancement factor F (Dumitrescu and Clausnitzer 1993) ($D_{L(b)} = 10^{-8}F|C_{L(b)}|$), which always estimates the magnitude of the PNC analysing powers, the quantity $C_{L(b)}$ being very close to unity in many cases when coherence effects arise. In the case of random phases in the numerator of $C_{L(b)}$, this factor acts destructively and in any case it should not be omitted.

5. Discussion of the Results

To calculate the $C_{L(b)}$ factor is the most complicated part of the PNC calculations. In Table 5 we reproduce the resonance parameters for the PC T-matrices used. The spectroscopic amplitude is defined in terms of some geometrical coefficients and the spectroscopic amplitudes given by the OXBASH code:

$$\theta^{J^\pi}_{pls} = \sum_{nj} \hat{j}\,\hat{s}(-1)^{(l+s-J)} W\big(\tfrac{1}{2}\,\tfrac{1}{2}\,Jl;\ sj\big)\theta^{(\mathrm{OXBASH})}_{nlj}(J^\pi\,T;\,E(\mathrm{MeV})). \tag{18}$$

In Table 6 we reproduce the scattering phase shifts for the α channel calculated with a double folded M3Y potential in the Michigan State University version (Grigorescu *et al.* 1993). The scattering phase shifts for the proton channel are taken to be equal to the Coulomb phase shifts. The PC T-matrices used are the following:

$$\begin{gathered} t_1 = T^{0^+}_{\alpha 00,p11}, \qquad t_2 = T^{1^-}_{\alpha 10,p01}, \qquad t_3 = T^{1^-}_{\alpha 10,p21}, \qquad t_4 = T^{2^+}_{\alpha 20,p11}, \\ t_5 = T^{2^+}_{\alpha 20,p31}, \qquad t_6 = T^{3^-}_{\alpha 30,p21}, \qquad t_7 = T^{3^-}_{\alpha 30,p41} \end{gathered} \tag{19}$$

Table 5. Resonance parameters used in the calculation of the PNC analysing powers

$I^\pi T$	E_p (MeV)	$E^*_{^{16}\mathrm{O}}$ (MeV ± keV)	Γ (keV)	Γ_p (keV)	Γ_α (keV)	$(\theta^p_{ls})^2/(\theta_p)^2$	Open channels
1^+1	4.0814	16.209 ± 2	19 ± 3	7 ± 3		1.00; 0.00	γ, n, p
1^-0	4.0724	16.20 ± 90	580 ± 60	210 ± 38	370	0.40; 0.60	γ, α, p
3^-0	3.2804	15.408 ± 2	132 ± 7	15 ± 5	103	0.50; 0.47	α, p
2^+0	3.1324	15.26 ± 50	300 ± 100	15	12	0.67; 0.33	α, p
0^+	2.9694	15.097 ± 5	166 ± 30	12	152	1.00	α, p
2^+	2.7984	14.926 ± 2	54 ± 5	20 ± 3	1.5	0.62; 0.18	α, p
1^-1	0.9624	13.090 ± 8	130 ± 5	100	40	0.00; 1.00	γ, α, p
2^+0	0.8924	13.020 ± 8	150 ± 10	3.4	146.6	0.002; 0.37	γ, α, p
1^-0	0.3124	12.440 ± 2	91 ± 6	0.9 ± 0.1	102 ± 4	0.25; 0.74	γ, α, p

Table 6. The α-phase shifts used in the calculation of the PNC analysing powers

These quantities are calculated as $\tan^{-1} F_l/G_l$, F_l and G_l, being the regular and irregular scattering solutions produced by the M3Y double-folded potential

I^π	$E^*_{^{16}\mathrm{O}}$ (MeV)	E^{lab}_p	$\xi_{l=I,0}$
0^+	15.097	3.1674	0.00
1^-	12.440	0.3323	−1.5492
1^-	13.009	1.0266	−1.4939
1^-	16.200	4.3535	−1.5463
2^+	13.02	0.9519	−0.0107
2^+	14.926	2.9849	−0.0108
2^+	15.26	3.3492	−1.563

and the two PNC reaction matrix elements, which participate in the reaction process are

$$T_1 = T^{1^-,+}_{\alpha 10, p10}, \qquad T_2 = T^{1^-,+}_{\alpha 10, p11}. \tag{20}$$

The resonance parameters are taken from the Ajzenberg-Selove (1986) compilation. In Figs 2 and 3 we show on an expanded horizontal scale the predicted size of the quantities relevant for an experiment designed to determine the PNC matrix elements by measurement

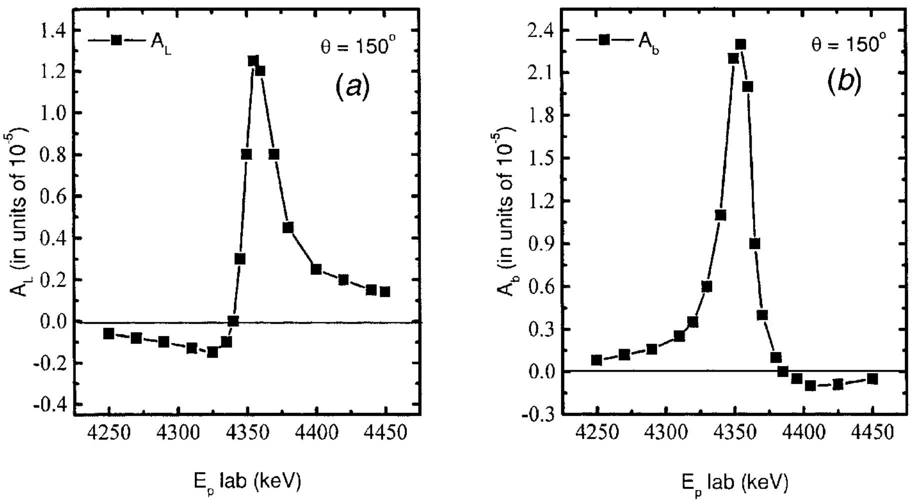

Fig. 2. (*a*) Longitudinal analysing power A_L and (*b*) transverse analysing power A_b of the reaction $^{15}N(\vec{p}, \alpha)^{12}C$ versus proton energy, for $\theta = 150°$, around the proton energy $E_p^{lab} \approx 4.35$ MeV ($M_{PNC} = 0.4$ eV).

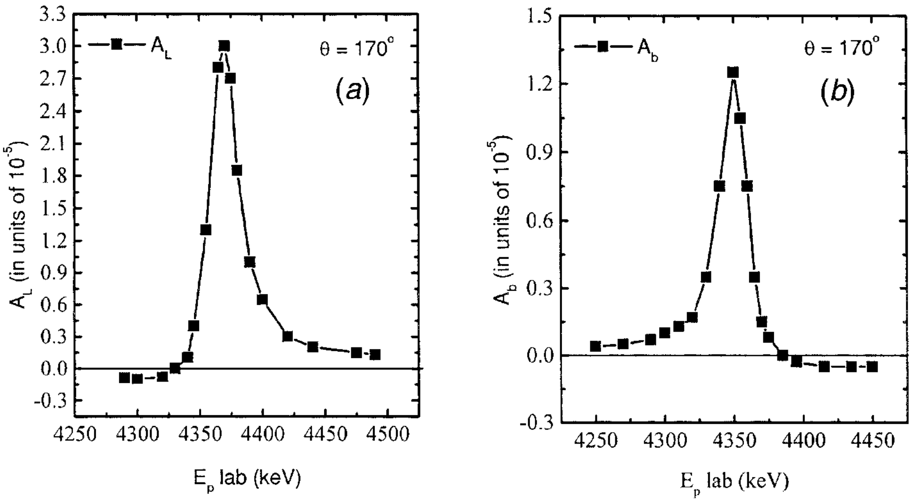

Fig. 3. (*a*) Longitudinal analysing power A_L and (*b*) transverse analysing power A_b of the reaction $^{15}N(\vec{p}, \alpha)^{12}C$ versus proton energy, for $\theta = 170°$, around the proton energy $E_p^{lab} \approx 4.35$ MeV ($M_{PNC} = 0.4$ eV).

of A_L and/or A_b around the narrow 1^+1 resonance. Figs 2a and 2b represent the analysing powers (A_L and A_b respectively) for $\theta = 150°$, while Figs 3a and 3b represent the same observables calculated for $\theta = 170°$ around the proton energy $E_p^{lab} \approx 4.35$ MeV. In all these calculations the shell model PNC matrix element has been taken to be equal to 0.4 eV. Results for all the models given in Table 4 can be obtained by a straightforward multiplication. If we define $\Delta A_{L(b)}$ as the distance between the minimum and the maximum of the PNC analysing powers in the excitation function, we find that this quantity is equal to the quantity $D_{L(b)}$ defined in equation (16) and it does not depend on the PNC matrix element phase Φ_{PNC} or PC quantity phase $\Phi_{L(b)}$. The main result of the present paper can be condensed in the following formula:

$$D_{L(b)} = D^0_{L(b)} \text{ (in eV}^{-1}) \sum_{s=\pi,\rho,\omega,\Delta T} V_s^{PNC}(\Delta T) \text{ (in eV)}, \tag{21}$$

where $V_s^{PNC}(\Delta T)$ are different meson contributions to the total PNC shell model matrix element:

$$M_{PNC} = \sum_{s=\pi,\rho,\omega,\Delta T} V_s^{PNC}(\Delta T) \text{ (in eV)} = \sum_{k,\, s=\pi,\rho,\omega} F_{k,s} M_{k,s} \text{ (in MeV)}. \tag{22}$$

The $M_{k,s}$ nuclear structure matrix elements in units of MeV calculated within the OXBASH code are given in Table 3 for several reasonable effective strong interactions. For $\theta_{cm} = 150°$, $D^0_L = 1.28 \times 10^{-5}$ eV^{-1} and $D^0_b = 2.24 \times 10^{-5}$ eV^{-1}, while for $\theta_{cm} = 170°$, $D^0_L = 3.24 \times 10^{-5}$ eV^{-1} and $D^0_b = 1.26 \times 10^{-5}$ eV^{-1}.

The comparison with the predictions of the PNC single particle model (see the column ‘valence particle’ in Table 3) shows that the core contribution is suppressed by a factor of 3 to 10. For some part, this factor arises from the fact that the $\frac{1}{2}^+$ states and $\frac{1}{2}^-$ states are not described by a pure configuration with a neutron in $2s_{\frac{1}{2}}$ and $1p_{\frac{1}{2}}$ orbits respectively. For the other part, it represents a pairing effect which, for the type of operator considered here, is usually accounted for by a factor, $u_i u_f - v_i v_f$. Indeed, the dominant PNC contribution, due to the transition $2s_{\frac{1}{2}} \longleftrightarrow 1p_{\frac{1}{2}}$ is cancelled for $\simeq 20\%$ to 60% by the similar, but time reversed, transition $1\bar{p}_{\frac{1}{2}} \longleftrightarrow 2\bar{s}_{\frac{1}{2}}$.

The examination of the contribution of the valence nucleons ($1p_{\frac{1}{2}}$, $1d_{\frac{5}{2}}$, $2s_{\frac{1}{2}}$) is also instructive. As all core nucleons generally contribute coherently to the single particle PNC interaction, one might *a priori* expect that they would increase the core contribution. Looking at Table 3 shows that it is true in many cases, for the transition $^3S_1{-}^3P_1$, as well as for the transition $^3S_1{-}^1P_1$ (after appropriately separating in this case the contributions arising from the transitions $^3S_1{-}^1P_1$ and $^1S_0{-}^3P_0$ which are assumed to dominate). This is not so however for the isovector $^1S_0{-}^3P_0$ transition, whose contribution is small (ZBM-II) or even destructive (ZBM-I). Clearly, the results are very sensitive to strong interactions in $^1S_0$ and $^3S_1$ states, whose relative strength in nuclei is not well determined (Desplanques *et al.* 1991; Bernabeu *et al.* 1990). The well-known pairing correlations between like particles tend to support the dominance of the first one, whereas the existence of the deuteron as a bound state in the $^3S_1$ channel indicates that the corresponding force should have the most important role. As for the core contribution, the dependence of the behaviour of the results on the transition can be traced back to specific ‘pairing’ effects and to a more or less destructive interference of the contributions of the single particle transitions $2s_{\frac{1}{2}} \longleftrightarrow 1p_{\frac{1}{2}}$ and the time reversed one $1\bar{p}_{\frac{1}{2}} \longleftrightarrow 2\bar{s}_{\frac{1}{2}}$.

6. Conclusions

In the excitation spectrum (Ajzenberg-Selove 1986) of the ^{16}O nucleus there is a new isovector PMD lying at 16.2 MeV excitation energy ($J^{\pi}\,T = 1^{-}\,0,\ 16.200\,\mathrm{MeV};\ \Gamma^{1^{-}0} = 580\,\mathrm{keV}$ with $J^{\pi}\,T = 1^{+}1,\ 16.209\,\mathrm{MeV};\ \Gamma^{1^{+}1} = 19\,\mathrm{keV}$) for which the enhancement factor (Adelberger and Haxton 1985) $\sqrt{\Gamma^{1^{-}0}/\Gamma^{1^{+}1}}$ is 5.53. Within the shell model code (OXBASH) with ZBM model space and different interactions (see Table 4) we calculated the PNC matrix element and PNC analysing powers (A_L and A_b). The average value for the PNC matrix element is 0.4 eV. The maximum in the energy anomaly of the PNC analysing powers (A_L and A_b) we got to be several units above the 10^{-5} value considered to be in agreement with the last measurements (Elsener *et al.* 1982, 1984; Zeps 1989; Zeps *et al.* 1989; Swanson *et al.* 1986).

The parity mixing between members of the above-mentioned doublet is of particular interest because:

(1) The mixing is sensitive to the $\Delta T = 1$ components of H_{PNC} and especially to the part describing weak pion exchange (see Table 4 and Fig. 1), if working in the quark model picture. In this case we may have quantitative information about neutral current contributions to H_{PNC}. There are few experiments which are sensitive only to the $\Delta T = 1$ components of the PNC-NN weak interaction and which can be studied with polarised protons. In the ^{20}Ne experiment (Kniest *et al.* 1990), for example, the PNC longitudinal analysing power value of $(1.5 \pm 0.76) \times 10^{-3}$ is, in our opinion, too large. However, the interpretation of this experimental result is clouded by nuclear structure uncertainties, because of the high degree of center-of-mass spurious state contributions to the ^{20}Ne excited states with $J = 1$ and it is not also a case of simple two-level mixing. A large α-cluster state structure contribution should diminish the PNC matrix element in this case.

(2) The observable provides a highly precise way to measure the PNC matrix elements. The energy anomaly in the PNC analysing powers (A_L and A_b) is magnified by nuclear structure effects also, in addition to the 9 keV energy difference between the levels involved in the doublet mentioned. The magnification arises because of the coherent contribution of proton and α channels. The quantity $C_{L(b)}$ is essentially a ratio between the PNC-matrix contribution to the PNC analysing powers and the cross section for the (p, α) reaction induced by an unpolarised proton beam. The value of this ratio in the resonance region is about 0.1, a value which speaks about the coherence effect mentioned. The width of the $1^{+}1$ resonance level is quite small (19 keV) and acts as an enhancement factor. The ratio $\Gamma_p^{1^-} / \Gamma_p^{1^+} = 210/7$ plays also the role of an enhancement factor as elsewhere (Adelberger and Haxton 1985).

(3) The cross section is smaller at back angles compared with the elastic scattering cross section, but larger at forward angles; however, the α channel can select more cleanly the transition. The normal PC analysing power is negligibly small in this energy region for large angles. Thus, the experiment can be considered free of measurement errors.

(4) The PNC α_0 transition can be studied via the $^{15}\mathrm{N}(\vec{p}, \alpha_0)^{12}\mathrm{C}$ resonance reaction with two different observables independently, namely the PNC longitudinal A_L and PNC transverse A_b analysing powers, which sometimes show a different energy anomaly as a function of scattering angle.

(5) The theoretical models included in the OXBASH code are reasonably good, at least for the levels which are members of the doublet mentioned. In any case, ^{16}O being an even–even nucleus is much better described by such realistic models than odd–mass or odd–odd nuclei (Kniest *et al.* 1991; Dumitrescu 1991).

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References

Adelberger, E. G., and Haxton, W. C. (1985). *Ann. Rev. Nucl. Part. Sci.* **35**, 501.
Adelberger, E. G., Hindi, M. M., Hoyle, C. D., Swanson, H. E., Von Lintig, R. D., and Haxton, W. C. (1983). *Phys. Rev.* C **27**, 2833.
Afrens, G., Harfst, W., Kass, J. R., Mason, E. V., Schober, H., Stefens, G., and Waeffler, H. (1982). *Nucl. Phys.* A **390**, 486.
Ajzenberg-Selove, F. (1986). *Nucl. Phys.* A **460**, 1.
Arnison, G., *et al.* (1983). UA-1 Collaboration, *Phys. Lett.* B **122**, 103.
Auerbach, N., and Brown, B. A. (1999). *Phys. Rev.* C **60**, 025501.
Banner, M., *et al.* (1983). UA-2 Collaboration, *Phys. Lett.* B **122**, 476.
Barnes, C. A., Lowry, M. M., Davidson, J. H., Mars, R. E., Morinigo, F. B., Chang, B., Adelberger, E. G., and Swanson, H. E. (1979). *Phys. Rev. Lett.* **40**, 840.
Bernabeu, J., *et al.* (1990). *Z. Phys.* C **46**, 323.
Bini, M., Bizzeti, P. G., and Sona, P. (1981). *Phys. Rev.* C **23**, 1265.
Bini, M., Bizzeti, P. G., and Sona, P. (1984). *Lett. Nuovo Cimento* **41**, 191.
Bini, M., Fazzini, T. F., Poggi, G., and Taccetti, N. (1985). *Phys. Rev. Lett.* **55**, 795.
Bini, M., Fazzini, T. F., Poggi, G., and Taccetti, N. (1988). *Phys. Rev.* C **38**, 1195.
Bizzeti, P. G., Fazzini, T. F., Maurenzig, P. R., Perego, A., Poggi, G., Sona, P., and Taccetti, N. (1980). *Lett. Nuovo Cimento* **29**, 167.
Bludman, S. A. (1958). *Nuovo Cimento* G, 433.
Brandenburg, R. A., *et al.* (1978). *Phys. Rev. Lett.* **41**, 618.
Brown, B. A., and Wildenthal, B. H. (1988). *Annu. Rev. Nucl. Part. Sci.* **38**, 29.
Brown, B. A., Richter, W. A., and Godwin, N. S. (1980). *Phys. Rev. Lett.* **45**, 1681.
Brown, B. A., Etchegoyen, A., and Rae, W. D. M. (1985). MSU-NSCL Report No. 524.
Brown, B. A., Ormand, W. E., Winfield, J. S., Zhao, L., Etchegoyen, A., Rae, W. M., Godwin, N. S., Richter, W. A., and Zimmerman, C. D. (1988). MSU-NSLL Report, Michigan State University, version of the OXBASH code 524.
Desplanques, B. (1975). *Nucl. Phys.* A **242**, 423.
Desplanques, B. (1983). Proc. 8th Int. Workshop on Weak Interactions and Neutrinos (Ed. A. Morales), p. 515 (World Scientific: Singapore).
Desplanques, B. (1984). *J. Phys. (Paris)* **45**, C3–55.
Desplanques, B., and Dumitrescu, O. (1993). *Nucl. Phys.* A **565**, 306.
Desplanques, B., and Missimer, J. (1978). *Nucl. Phys.* A **300**, 286.
Desplanques, B., Donoghue, J. F., and Holstein, B. R. (1980). *Ann. Phys. (New York)* **124**, 449.
Desplanques, B., *et al.* (1991). *Z. Phys.* C **51**, 499.
Dubovik, V. M., and Zenkin, S. V. (1986). *Ann. Phys. (New York)* **172**, 100.
Dubovik, V. M., Zenkin, S. V., Obluchovskii, I. T., and Tosunyan, A. (1987*a*). *Fiz. Elem. Chastitz At. Yadra* **18**, 575.
Dubovik, V. M., Zenkin, S. V., Obluchovskii, I. T., and Tosunyan, A. (1987*b*). *Sov. J. Part. Nucl.* **18**, 244.
Dumitrescu, O. (1991). *Nucl. Phys.* A **535**, 94.
Dumitrescu, O., and Clausnitzer, G. (1993). *Nucl. Phys.* A **552**, 306.
Dumitrescu, O., Gari, M., Kuemmel, H., and Zabolitzky, J. G. (1971). *Phys. Lett.* B **35**, 19.
Dumitrescu, O., Gari, M., Kuemmel, H., and Zabolitzky, J. G. (1972). *Z. Naturforsch.* A **27**, 733.
Dumitrescu, O., Horoi, M., Carstoiu, F., and Stratan, G. (1990). *Phys. Rev.* C **41**, 1462.
Elsener, K., Gruebler, W., Koenig, V., Schweitzer, C., Schmeltzbach, P. A., Ulbricht, J., Sperisen, F., and Merdzan, M. (1982). *Phys. Lett.* B **117**, 167.

Elsener, K., Gruebler, W., Koenig, V., Schweitzer, C., Schmeltzbach, P. A., Ulbricht, J., Sperisen, F., and Merdzan, M. (1984). *Phys. Rev. Lett.* **52**, 1476.
Englert, E., and Brout, R. (1964). *Phys. Rev. Lett.* **13**, 321.
Flambaum, V. V., and Murray, D. W. (1997). *Phys. Rev.* C **56**, 1641.
Flambaum, V. V., and Vorov, O. K. (1993). *Phys. Rev. Lett.* **70**, 4051.
Flambaum, V. V., Murray D. W., and Orton, S. R. (1997). *Phys. Rev.* C **56**, 2820.
Gari, M. (1973). *Phys. Rep.* C **6**, 317.
Glashow, S. L. (1961). *Nucl. Phys.* **22**, 579.
Glashow, S. L., Iliopoulos, H., and Maiani, L. (1970). *Phys. Rev.* D **2**, 1284.
Grigorescu, M., Brown, B. A., and Dumitrescu, O. (1993). *Phys. Rev.* C **47**, 2666.
Hasert, F. J., *et al.* (1973). *Phys. Rev. Lett.* B **46**, 138.
Haxton, W. C., Gibson, B. F., and Henley, E. M. (1980). *Phys. Rev. Lett.* **45**, 1677.
Higgs, P. W. (1964). *Phys. Rev. Lett.* **13**, 508.
Kaiser, N., and Meissner, U. G. (1988). *Nucl. Phys.* A **489**, 671.
Kaiser, N., and Meissner, U. G. (1989). *Nucl. Phys.* A **499**, 699.
Kaiser, N., and Meissner, U. G. (1990*a*). *Nucl. Phys.* A **510**, 759.
Kaiser, N., and Meissner, U. G. (1990*b*). *Mod. Phys. Lett.* A **5**, 1703.
Kniest, N., Huettel, E., Pfaff, E., Reiter, G., Clausnitzer, G., Bizzeti, P. G., Maurenzig, P., and Taccetti, N. (1983). *Phys. Rev.* C **27**, 906.
Kniest, N., Huettel, E., Pfaff, E., Reiter, G., and Clausnitzer, G. (1990). *Phys. Rev.* C **41**, 1337.
Kniest, N., Horoi, M., Dumitrescu, O., and Clausnitzer, G. (1991). *Phys. Rev.* C **44**, 491.
Kobayashi, M., and Maskawa, T. (1973). *Prog. Theor. Phys.* **49**, 652.
Kuo, T. T. S. (1967). *Nucl. Phys.* A **103**, 71.
Kuo, T. T. S. (1974). *Annu. Rev. Nucl. Part. Sci.* **24**, 101.
Kuo, T. T. S., and Brown, G. E. (1966). *Nucl. Phys.* **85**, 40.
Lacomb, M., *et al.* (1980). *Phys. Rev.* C **21**, 861.
Machleidt, R. (1989). *Adv. Nucl. Phys.* **19**, 189.
Machleidt, R., Holinde, K., and Elster, Ch. (1987). *Phys. Rep.* **149**, 1.
Mak, H. B., Evans, H. C., Ewan, G. T., Leslie, J. R., MacArthur, J. D., McLachtie, W., Robertson, B. C., Skensved, P., Mann, S. A., McDonald A. B., and Barnes, C. A. (1981). Report on Research in Nuclear Physics at Queens University. Kingston, Ontario, p. 19.
Maurenzig, P. R., Bini, M., Bizzeti, P. G., Fazzini, T. F., Perego, A., Poggi, G., Sona, P., and Taccetti, N. (1979). Proc. Int. Conf. on Neutrinos, Weak Interactions and Cosmology, Vol. 2 (Eds A. Haatuft and C. Jarlskog), p. 97.
Miller, G. A., and Spencer, J. E. (1976). *Ann. Phys. (New York)* **100**, 562.
Mitchell, G. E., Bowman, J. D., and Weidenmueller, H. A. (1999). *Rev. Mod. Phys.* **71**, 445.
Ohlert, J., Traudt, O., and Waeffler, H. (1981). *Phys. Rev. Lett.* **47**, 475.
Reehal, B. S., and Wildenthal, B. H. (1973). *Part. Nucl.* **6**, 137.
Salam, A., and Ward, J. C. (1964). *Phys. Lett.* **13**, 168.
Swanson, H. E., Zeps, V. J., Adelberger, E. G., Gossett, C. A., Sromicki, J., Haeberli, W., and Quin, P. (1986). Proc. Conf. on Weak and Electromagnetic Interactions in Nuclei (Eds H. V. Klapdoor and J. Metzinger), pp. 277, 648.
Weinberg, S. (1967). *Phys. Rev. Lett.* **19**, 1264.
Zeps, V. J. (1989). PhD Thesis, University of Washington.
Zeps, V. J., Adelberger, E. G., Garcia, A., Gossett, C. A., Swanson, H. E., Haeberli, W., Quin, V., and Sromicki, J. (1989). Proc. AIP Conf., Vol. 176, p. 1098.
Zuker, A. P. (1969). *Phys. Rev. Lett.* **23**, 983.
Zuker, A. P., Buck, B., and McGrory, J. B. (1968). *Phys. Rev. Lett.* **21**, 39.

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