1.E.7

Nuclear Physics **A123** (1969) 357—364; © *North-Holland Publishing Co., Amsterdam*

SHELL-MODEL CALCULATIONS OF M1 TRANSITION PROBABILITIES FROM ISOBARIC ANALOGUE STATES

S. MARIPUU †

Fysisch Laboratorium der Rijksuniversiteit, Utrecht, Netherlands

Received 1 November 1968

Abstract: Shell-model calculations of M1 transition probabilities within isobaric-spin doublets have been performed for cases without configuration mixing. The Schmidt values and effective values of gyromagnetic ratios have been used. A strong enhancement of M1 transition rates for the "parallel" case $J = j = l+\frac{1}{2}$ as compared to the "anti-parallel" case $J = j = l-\frac{1}{2}$ is obtained. It is also shown that the M1 transition probability in a certain single particle orbit is decreasing with increasing isobaric spin. The results are compared with recent experimental data. The positions of $\frac{7}{2}^-$ states in ^{31}P have been calculated with the modified surface delta interaction for simple three-particle configurations. The wave functions thus obtained have been used to calculate M1 transition probabilities between the $\frac{7}{2}^-$ states in ^{31}P.

1. Introduction

It has been pointed out that isobaric analogue states stand out as strong resonances in (p, γ) reactions [1]). The γ-decay is simple and very often predominantly proceeds with a strong M1 transition to one particular lower state.

The single-particle states of a nucleus, obtained by coupling a nucleon with isobaric spin t to a core with isobaric spin $T_0 \neq 0$ are split up due to isobaric-spin alignment [2]). The two components of the doublet with $T_> = T_0+\frac{1}{2}$ and $T_< = T_0-\frac{1}{2}$ are heavily split up in energy due to the $(\boldsymbol{T}_0 \cdot \boldsymbol{t})$ interaction. The splittings observed so far are in agreement with the relation

$$E_{T_>} - E_{T_<} = (T_0+\tfrac{1}{2})V_1/A, \tag{1}$$

where V_1 is independent of the mass number A; for several nuclei the constant $V_1(\mathrm{f}_{\frac{7}{2}})$ has been computed [3,4]).

If the coupling is not weak, the core state may change when a particle is added [2]). The single-particle states which, with a $J_0 = 0$ core, would form a doublet in the weak-coupling case, then become fragmented. It has indeed been reported from ^{48}Ca(^{3}He, d)^{49}Sc measurements that the strengths of $T = T_<$ single-particle states are fragmented [5,6]). Theoretical calculations on such core-polarization effects have been performed [7]).

The shell-model calculations of the strengths of M1 transitions between $T_>$ and $T_<$ states presented in this paper show that:

† On leave from Dept. of Physics, Chalmers University of Technology, Göteborg, Sweden.

(i) The $T_> \rightarrow T_<$ M1 transitions between $J = l+\frac{1}{2}$ states are fast, whereas those between $J = l-\frac{1}{2}$ states are slow.

(ii) These transitions are more complicated than has been assumed previously. The mixing of only two configurations in the ^{31}P calculations e.g., already makes it understandable that only one $\frac{7}{2}^- \rightarrow \frac{7}{2}^-$ transition is observed instead of the two expected.

The calculations on ^{31}P, presented in sect. 5, include only two configurations and therefore are only provisional. It is felt, however, that more involved calculations, e.g. along the lines of Halbert *et al.*[19]), not only would take quite some time to come forth, but also would tend to cloud the simple results, from the present simple calculation. Of course one expects that more elaborate calculations will result in better values for the absolute transition probabilities.

2. Calculations

Generally, the reduced transition probability (with the matrix elements reduced with respect to orbital space and spin space but *not* with respect to isospin space) can be written [8]) as

$$B(\text{M1}) = \frac{1}{2J_\text{i}+1} \langle J_\text{f}\, T_\text{f}\, M_T || \Omega(\text{M1}) || J_\text{i}\, T_\text{i}\, M_T \rangle \,. \tag{2}$$

The indices i and f refer to initial and final states, respectively; the third component of the isospin is given by $M_T \equiv (N-Z)/2$; $B(\text{M1})$, the reduced transition probability has the dimensions of [nuclear magnetons]^2. The magnetic dipole transition operator $\Omega(\text{M1})$ is a sum of single-particle operators. When the transition proceeds within configurations in the same subshell, the operator can be separated into two parts

$$\Omega(\text{M1}) = \Omega_0(\text{M1}) + \Omega_1(\text{M1}), \tag{3}$$

with

$$\Omega_0(\text{M1}) = \sqrt{\frac{3}{4\pi}} \sum_k \frac{g_{\text{p}k}+g_{\text{n}k}}{2} \boldsymbol{j}(k) \frac{e\hbar}{2mc},$$

and

$$\Omega_1(\text{M1}) = -\sqrt{\frac{3}{4\pi}} \sum_k \frac{g_{\text{p}k}-g_{\text{n}k}}{2} \boldsymbol{j}(k)\tau(k) \frac{e\hbar}{2mc},$$

where $\Omega_0(\text{M1})$ is a scalar and $\Omega(\text{M1})$ a vector in isospin space; $g_{\text{p}k}$ and $g_{\text{n}k}$ are the Schmidt (or effective) values of the proton and neutron gyromagnetic ratios, respectively, in the orbit of the kth particle.

A reduction in isospin space then yields

$$B(\text{M1}) = \frac{1}{2J_\text{i}+1} \left[\frac{\langle T_\text{i} M_T 00 | T_\text{f} M_T \rangle}{\sqrt{2T_\text{f}+1}} \langle J_\text{f}\, T_\text{f} || \Omega_0(\text{M1}) || J_\text{i}\, T_\text{i} \rangle + \frac{\langle T_\text{i} M_T 10 | T_\text{f} M_T \rangle}{\sqrt{2T_\text{f}+1}} \langle J_\text{f}\, T_\text{f} || \Omega_1(\text{M1}) || J_\text{i}\, T_\text{i} \rangle \right]^2 . \tag{4}$$

For $T_i \neq T_f$ the Clebsch-Gordan coefficient $\langle T_i M_T 00 | T_f M_T \rangle$ vanishes. When considering the $T_> \rightarrow T_<$ transition one is thus left with only the second term in the expression (4). With only one nucleon outside the core the following arguments can be applied. The extra nucleon will contribute to the M1 transition only if the configuration of the core particles remains intact. With the aid of some elementary tensor algebra, the extra-nucleon contribution to the transition probability can be derived from expression (4)

$$B(\mathrm{M1}) = \frac{9}{8\pi}(2J_f+1)(2T_i+1)\langle T_i M_T 10 | T_f M_T \rangle^2 j(j+1)(2j+1) \times \begin{Bmatrix} j & j & 1 \\ J_f & J_i & J_0 \end{Bmatrix}^2 \begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & 1 \\ T_f & T_i & T_0 \end{Bmatrix}^2 (g_p - g_n)^2, \quad (5)$$

where j is the total angular momentum of the single particle, and the two curly brackets denote $6j$ symbols. Expression (5) can be used to calculate reduced transition probabilities from single-particle analogue states to $T = T_<$ states, under the assumption that the core particles do not contribute to the transition probability. Furthermore, if the core particles are coupled to spin zero ($J_0 = 0$) the expression (5) reduces to

$$B(\mathrm{M1}) = \frac{9}{8\pi}(2T_i+1)\langle T_i M_T 10 | T_f M_T \rangle^2 j(j+1) \begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & 1 \\ T_f & T_i & T_0 \end{Bmatrix}^2 (g_p - g_n)^2. \quad (6)$$

The expression (6) gives the complete transition probability, since for $J_0 = 0$ the core does not contribute.

3. Results of calculations for pure states

The strengths of $T_> \rightarrow T_<$ transitions in odd-A nuclei, calculated with expression (6), are given in table 1. It is seen that the transition rates between states with $J = j = l+\frac{1}{2}$ are larger by a factor of 20 to 200 than between those with $J = j = l-\frac{1}{2}$. This difference is mainly due to the factor $(g_p - g_n)^2$. In the "parallel" case the orbital and spin-projected magnetic moments of a single proton and the spin-projected magnetic moment of a single neutron all add up to give a maximum of $|g_p - g_n|$, whereas in the "anti-parallel" case this quantity has a minimum. Consequently, M1 transitions between members of isobaric-spin doublets with $J = j = l-\frac{1}{2}$ will be rather difficult to observe. The factor $(g_p - g_n)^2$ for different single-nucleon orbits is included in table 1.

It can also be noted that the transition probabilities for a certain orbit decrease with increasing isobaric spin. The ratio between the transition rate within a $T = T_0 - 1$ doublet and the $T = T_0$ doublet can be obtained from expression (5) as

$$\frac{T_0}{T_0 - 1} \left\{ \frac{2T_0 - 1}{2T_0 + 1} \right\}^2 .$$

The addition of two neutrons to the core will thus reduce the resulting magnetic dipole moment and correspondingly also the M1 transition probability.

It should be remarked that shell-model transitions from the $T = T_>$ state to $T = T_<$ states with $J_0 \neq 0$ are somewhat different. In that case only the core particles contribute (due to rearrangement of the core the single-nucleon contribution vanishes). In sect. 5 transition rates within some simple many-particle configurations will be discussed.

TABLE 1

Strengths of M1 single-nucleon transitions within isobaric-spin doublets (in Weisskopf units [9])

$T_>$	$T_<$	$s_{\frac{1}{2}}$	$p_{\frac{3}{2}}$	$p_{\frac{1}{2}}$	$d_{\frac{5}{2}}$	$d_{\frac{3}{2}}$	$f_{\frac{7}{2}}$	$f_{\frac{5}{2}}$
$\frac{3}{2}$	$\frac{1}{2}$	1.95	1.59	0.071	1.85	0.051	2.24	0.0105
$\frac{5}{2}$	$\frac{3}{2}$	1.40	1.15	0.052	1.36	0.037	1.62	0.0076
$\frac{7}{2}$	$\frac{5}{2}$	1.07	0.88	0.039	1.02	0.028	1.24	0.0058
$\frac{9}{2}$	$\frac{7}{2}$	0.87	0.71	0.032	0.82	0.023	1.00	0.0047
$\frac{11}{2}$	$\frac{9}{2}$	0.72	0.59	0.027	0.69	0.019	0.84	0.0039
$(g_p - g_n)^2$		88.5	14.5	3.25	7.20	0.465	4.86	0.0408

TABLE 2

Experimental M1 transition strengths (in Weisskopf units) and corresponding theoretical strengths for single-nucleon transitions calculated with Schmidt g-factors (table 1) and with effective g-factors (see text)

Orbit	$f_{\frac{7}{2}} \to f_{\frac{7}{2}}$			$p_{\frac{3}{2}} \to p_{\frac{3}{2}}$	
Nucleus	$^{31}_{15}P_{16}$	$^{35}_{17}Cl_{18}$	$^{37}_{17}Cl_{30}$	$^{35}_{17}Cl_{18}$	$^{49}_{21}Sc_{28}$
Initial and final states (MeV) and branching (%)	9.40 → 4.43 88	7.55 → 3.16 97	10.24 → 3.11 ≧ 80	7.84 → 4.17 29	11.56 → 3.08 < 1
Experimental (W.u.)	0.5±0.1	≧ 1.4±0.2	≧ 1.7±0.3	1.0	$< 6 \times 10^{-4}$
Theoretical: Schmidt g-factors (W.u.)	2.24	2.24	1.62	1.59	0.71
Theoretical: Effective g-factors (W.u.)	1.60	1.60	1.16	—	—

4. Comparison with experiment

So far, only a restricted number of experimental M1 transition rates from isobaric analogue states have been reported. In table 2, data from refs. [1,10,11]) are given together with calculated values from table 1.

In refs. [12,13]) it is shown that in restricted areas of the periodic table magnetic moments and M1 transition probabilities are well reproduced when effective magnetic moments (or effective g factors) are assigned to protons and neutrons in a given single-particle orbit. The improvement in the agreement with experimental data with such an approach is not surprising since the real magnetic moments of nuclei are known to be "quenched" inside the Schmidt lines.

Effective g-factors for $s_{\frac{1}{2}}$ and $d_{\frac{3}{2}}$ orbits in good agreement with experimental data are given in ref. [12]). From refs. [13,14]) effective g-factors for the $f_{\frac{7}{2}}$ orbit can be found. In table 2, transition rates calculated with effective g-factors from the above mentioned references are included for the $f_{\frac{7}{2}}$ orbit. The factor $(g_p^{eff}-g_n^{eff})^2$ for the $f_{\frac{7}{2}}$ orbit is found to be 3.46. The $p_{\frac{3}{2}}$ orbit has been omitted from such a calculation as there are no effective g-factors available for that orbit.

From table 2 it is seen that a rough agreement with experimental values for the calculated single-nucleon transition rates is obtained in all cases except for ^{49}Sc. In order to obtain an idea about how the lower member of the isobaric-spin doublet in ^{31}P is mixed with a possible polarized-core state, a three-particle calculation for the $\frac{7}{2}^-$ states in ^{31}P is performed in sect. 5.

5. Extended calculations and discussion

If one considers ^{28}Si as an inert core, one can expect the following configurations for possible $\frac{7}{2}^-$ states in ^{31}P (spins and isospins of different particle groups are given as sub-indices) $[(s_{\frac{1}{2}}^2)_{01}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$, $[(s_{\frac{1}{2}}^2)_{01}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$ and $[(s_{\frac{1}{2}}^2)_{10}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$. The first two configurations are the two members of the isobaric-spin doublet with an expected energy difference of about 5 MeV as estimated from expression (1). The third configuration gives a polarized core state which is expected to mix with the $T = \frac{1}{2}$ member of the doublet.

In order to be able to calculate the matrix elements for M1 transitions from the $T = \frac{3}{2}$ state to the two $T = \frac{1}{2}$ states one has to know the amount of mixing of the lower two states. To obtain an idea about mixing and also about the theoretical positions of states, a calculation with two-body matrix elements from the modified surface delta interaction (MSDI)†[15]) has been employed. Slightly different values for the matrix elements of the residual interaction as compared to ref. [15]) has been used. The matrix elements, obtained from a fit to 33 levels in the $A = 29$–34 mass region, and the single-particle binding energies used in this calculation, are the following (all in MeV)

$$\langle sf|V|sf\rangle_{30} = -2.24, \qquad \langle s^2|V|s^2\rangle_{01} = -0.59,$$

$$\langle sf|V|sf\rangle_{40} = -2.77, \qquad \langle s^2|V|s^2\rangle_{10} = -2.31,$$

$$\langle sf|V|sf\rangle_{31} = -0.76, \qquad E(2s_{\frac{1}{2}}) = -8.75,$$

$$\langle sf|V|sf\rangle_{41} = 0.59, \qquad E(1f_{\frac{7}{2}}) = -5.13.$$

† The MSDI differs from the normal surface delta interaction (SDI) in that a T-dependent term has been added.

The $f_{\frac{7}{2}}$ single-particle energy has been taken from the position of the first $\frac{7}{2}^-$ state in ^{29}Si (E_x = 3.623 MeV). After diagonalizing the two-body matrix of the residual interactions between the lower two states, the wave functions for these states were obtained. The wave functions were then used to calculate the M1 transition rates. The results of energy level and transition rate calculations are summarized in fig. 1, presented together with hitherto known experimental information [16].

From fig. 1 it is concluded that the MSDI quite well predicts the positions of the members of the isobaric-spin doublet. The position of the polarized core state

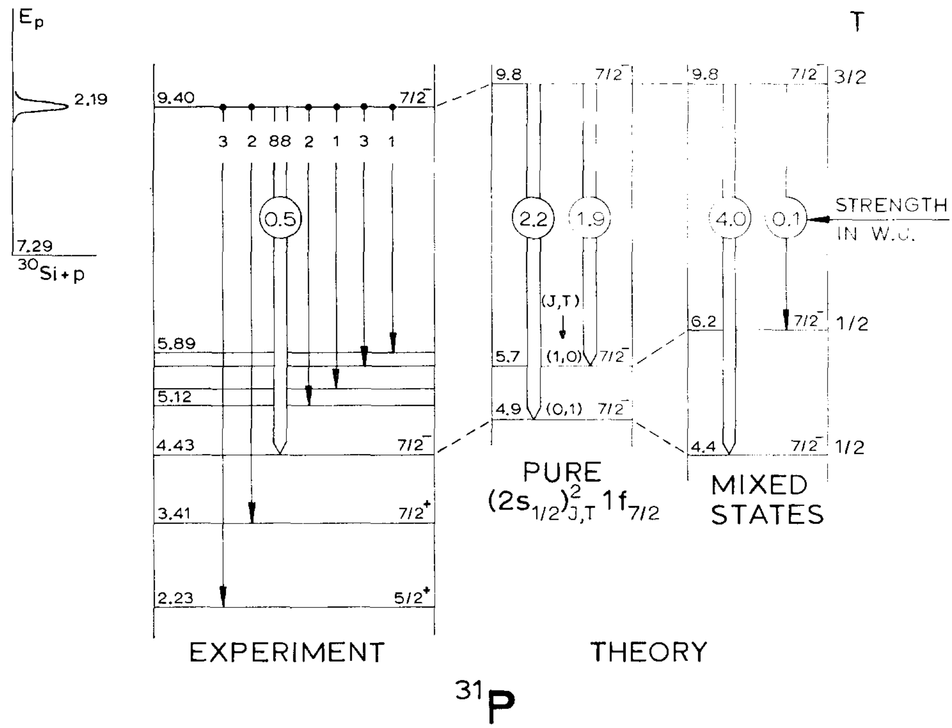

Fig. 1. Experimental results of the decay of the 9.40 MeV level and theoretical results of the $\frac{7}{2}^-$ level positions and M1 transition strengths between these states in ^{31}P. The wave functions obtained from MSDI calculations are $\sqrt{0.72}\,[s^2_{01}f]-\sqrt{0.28}\,[s^2_{10}f]$ and $\sqrt{0.28}\,[s^2_{01}f]+\sqrt{0.72}\,[s^2_{10}f]$ for the 4.4 and 6.2 MeV levels, respectively.

predicted at E_x = 6.16 MeV is unknown experimentally. The γ-decay from the 9.40 MeV level has a branching of 88 % to the 4.43 MeV level [17]). Weak transitions are observed to some other lower levels. Apparently, it is impossible at present to decide which state should be identified with the $\frac{7}{2}^-$ level calculated to be at 6.16 MeV (see fig. 1). From ^{30}Si(^{3}He, d)^{31}P measurements [18]) the only l_p = 3 group observed is the one to the 4.43 MeV level, although according to the predictions made in this article 28 % of the single-particle strength should go into the predicted 6.16 MeV level.

It is seen that the M1 transition rate between the assumed isobaric-spin doublet becomes enhanced over the transition to the state which is expected to be mainly core-polarized. The theoretical intensity ratio is 87. When effective g-factors are used (for the $s_{\frac{1}{2}}$ orbit the factor $(g_p^{eff}-g_n^{eff})^2$ is [12]) 14.4) the transition rates become 1.88 and 0.30 W.u., respectively, corresponding to a theoretical intensity ratio of 20. In these calculations a possible excitation of the $s_{\frac{1}{2}}$ particles to the $d_{\frac{3}{2}}$ orbit has not been taken into account. As the factor $(g_p-g_n)^2$ is comparatively small in the $d_{\frac{3}{2}}$ orbit, such a configuration mixing would reduce the transition rates. The estimate for the stronger transition would thus come closer to the experimental value.

Elaborate shell-model calculations with matrices up to order 265, taking into account up to two holes in the $d_{\frac{5}{2}}$ sub-shell, have recently been performed on even-parity states in $A = 30$–33 nuclei [19]). The $A = 30$ states thus obtained, with a $1f_{\frac{7}{2}}$ particle coupled to them, would form an ideal starting point for more nearly realistic calculations of M1 transition probabilities in ^{31}P. Such calculations are being considered at present.

Possible configurations for $\frac{7}{2}^-$ states in ^{35}Cl are the following (an inert core of ^{32}S is assumed) $[(d_{\frac{3}{2}}^2)_{01}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$, $[(d_{\frac{3}{2}}^2)_{21}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$, $[(d_{\frac{3}{2}}^2)_{01}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$, $[(d_{\frac{3}{2}}^2)_{21}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$, $[(d_{\frac{3}{2}}^2)_{10}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$ and $[(d_{\frac{3}{2}}^2)_{30}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{1}{2}}$. The first and the third configuration are the members of the isobaric-spin doublet with inert core. The second configuration might mix with the $T = \frac{3}{2}$ member of the doublet and the remaining three configurations are expected to mix with the $T = \frac{1}{2}$ members. Experimentally, a dominating M1 transition, with a branching of 97 % from the $E_x = 7.55$ MeV state to the $E_x = 3.11$ MeV state, has been observed such that it is reasonable to assume that these states mainly have the configurations of the isobaric-spin doublet. From the configuration $[d_{01}^2f]_{T=\frac{3}{2}}$ M1 transitions are possible to the $[d_{01}^2f]_{T=\frac{1}{2}}$ and $[d_{10}^2f]_{T=\frac{1}{2}}$ configurations. Transitions to the remaining two $T = \frac{1}{2}$ configurations are spin-forbidden. The transition $[d_{01}^2f]_{T=\frac{3}{2}} \rightarrow [d_{01}^2f]_{T=\frac{1}{2}}$ is a f nucleon transition; the non-vanishing contribution is only due to the part of the M1 operator that operates on the f nucleon since the d particles are coupled to spin zero. The transition $[d_{01}^2f]_{T=\frac{3}{2}} \rightarrow [d_{10}^2f]_{T=\frac{1}{2}}$ is only due to the d particles; due to rearrangement of the d^2 group the f nucleons do not contribute. As the factor $(g_p-g_n)^2$ is comparatively small in the $d_{\frac{3}{2}}$ orbit the first of the above mentioned transitions will be much stronger. A configuration mixing will thus not affect the f-nucleon transition strength as in the case of ^{31}P. The observed dominating transition, in good agreement with the single-nucleon strength, might then indicate rather pure configurations for the members of the isobaric-spin doublet.

Similarly, possible $\frac{7}{2}^-$ states in ^{37}Cl arise from the following configurations: $[(d_{\frac{3}{2}}^4)_{02}f_{\frac{7}{2}})_{\frac{7}{2}\frac{5}{2}}$, $[(d_{\frac{3}{2}}^4)_{02}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$, $[(d_{\frac{3}{2}}^4)_{11}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{5}{2}}$, $[(d_{\frac{3}{2}}^4)_{21}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$ and $[(d_{\frac{3}{2}}^4)_{31}f_{\frac{7}{2}}]_{\frac{7}{2}\frac{3}{2}}$. A strong $f_{\frac{7}{2}}$ nucleon transition might be expected between $[d_{02}^4f]_{T=\frac{5}{2}}$ and $[d_{02}^4f]_{T=\frac{3}{2}}$ configurations from similar arguments as used for ^{35}Cl. Energy calculations of the above mentioned configurations in ^{37}Cl, with effective two-body interactions deduced from the ^{34}Cl and ^{35}Cl spectra, are reported in ref. [7]).

MSDI calculations, with possible mixing between the members of the isobaric-spin doublet and the polarized core states taken into account, might reveal whether the good agreement for transition strengths in ^{35}Cl and ^{37}Cl is accidental or not.

The transition strength in ^{49}Sc given in table 2 is for the transition from the strongest component of the fragmented analogue state around $E_x \approx 11.5$ MeV to the $E_x = 3.08$ MeV state [11]. The 3.08 MeV state has the strongest $l_p = 1$ single-particle strength in ^{49}Sc, but smaller fractions go to several higher levels [5,6]. The strong inhibition of the $p_{\frac{3}{2}} \rightarrow p_{\frac{1}{2}}$ transition is difficult to understand.

It is concluded that a comparison of single-nucleon M1 transition rates, as presented in table 1, with measured M1 transition rates can give some idea of single-particle purity of the states involved. The identification of isobaric-spin doublets provides information on the effective nucleon-nucleon interaction.

The author is indebted to Prof. P. M. Endt, Dr. P. J. Brussaard, and Dr. P. W. M. Glaudemans for valuable discussions, and for critical reading of the manuscript. Dr. Glaudemans has kindly provided the author with empirical data for MSDI calculations, which is gratefully acknowledged.

This investigation was partly supported by "Statens Råd för Atomforskning" and partly by the joint program of the "Stichting voor Fundamenteel Onderzoek der Materie" and the "Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek".

References

1) P. M. Endt, Nuclear structure (North-Holland Publ. Comp., Amsterdam, 1967)
2) J. B. French, Proc. Conf. on nuclear spectroscopy with direct reactions, Argonne National Lab. Rept. ANL-6848 (1964)
3) R. Sherr, B. F. Bayman, E. Rost, M. E. Rickey and C. G. Hoot, Phys. Rev. **139** (1965) B1272
4) A. K. Hyder Jr. and G. I. Harris, Phys. Lett. **24B** (1967) 273
5) J. R. Erskine, A. Marinov and J. P. Schiffer, Phys. Rev. **142** (1966) 633
6) D. D. Armstrong and A. G. Blair, Phys. Rev. **140** (1965) B1226
7) R. K. Bansal, Phys. Rev. **153** (1967) 1084
8) I. Talmi and I. Unna, Ann. Rev. of Nucl. Sci. **10** (1960) 382
9) D. H. Wilkinson, Nuclear Spectroscopy, Part B, ed. F. Ajzenberg-Selove (Academic Press, New York, 1960)
10) D. D. Watson, J. R. Manthuruthil and F. D. Lee, Phys. Rev. **164** (1967) 1399
11) G. B. Vingiani, G. Chilosi and W. Bruynesteyn, Phys. Lett. **26B** (1968) 285
12) G. Wiechers and P. J. Brussaard, Nucl. Phys. **73** (1965) 604
13) A. de-Shalit, Nucl. Phys. **22** (1961) 677
14) J. Vervier, Nucl. Phys. **78** (1966) 497
15) P. W. M. Glaudemans, P. J. Brussaard and B. H. Wildenthal, Nucl. Phys. **A102** (1967) 593
16) P. M. Endt and C. van der Leun, Nucl. Phys. **A105** (1967) 1
17) A. C. Wolff, M. A. Meyer and P. M. Endt, Nucl. Phys. **A107** (1968) 332
18) M. Betigeri, R. Bock, H. H. Duhm, S. Martin and R. Stock, Z. Naturf. **21a** (1966) 980
19) E. C. Halbert *et al.*, Oak Ridge National Laboratory and Utrecht University, private communication