PHYSICAL REVIEW C VOLUME 43, NUMBER 3 MARCH 1991

Ordinary and radiative muon capture on ^{14}N

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(Received 26 March 1990; revised manuscript received 15 October 1990)

Detailed shell-model analysis of the $A=14$ isovector $^{14}N_{g.s.} \rightarrow {}^{14}C^*$ response has been performed. It allows us to suggest the ^{14}N nucleus as a prospective target for the inclusive radiative muon capture experiment. Capture rates and photon spectra for several values of the induced pseudoscalar coupling constant g_P are given.

I. INTRODUCTION

Both ordinary muon capture (OMC) and radiative muon capture (RMC) involve a sizable momentum transfer and thus appear as appropriate for studying the magnitude of the induced pseudoscalar coupling in the weak hadronic currents. The OMC data are by now available for the majority of possible targets.[1] The observation of RMC, on the contrary, has been very limited: Until recently, we have only had data for ^{40}Ca and ^{16}O and low-statistic observation for a few heavier nuclei.[2] The use of the time-projection chamber at TRIUMF made possible the observation of RMC for a series of nuclei.[3]

As for the theoretical aspects of the RMC studies, one should realize that the nuclear structure part of the calculation represents a serious challenge. The extraction of the weak coupling constants from the data requires that the photon yield and spectra are theoretically evaluated on the basis of some nuclear response model. As we discuss below, such calculations are possible, but should be interpreted with a great care. Actually, two possibilities can be exploited.

First, the nuclear partial transitions provide definitely a safer ground for a theoretician and have been repeatedly advocated[2,4] for the RMC studies. Experimentally, however, they are rather difficult: The estimate performed in Ref. 2 has shown that, e.g., for a very strong partial transition in the reaction $\mu^- + {}^{10}B(3^+0) \rightarrow {}^{10}Be(2_2^+1, 5.96\text{ MeV}) + \nu_\mu + \gamma$, event rate for the coincidence of only one per hour can be expected. Thus the experiment should be feasible, but the event rates are of the same order of magnitude as estimated, e.g., for RMC on hydrogen or ^{3}He. In addition, only very few examples exist of strong enough partial transitions appropriate for this purpose; the heavier nuclei are fully excluded since there one does not find appropriately separated nuclear levels. Thus the A systematics cannot be studied. Nevertheless, even observation and analysis of a few RMC partial transitions remains a rewarding task for the future.

The second possibility for the RMC study, which we exploit here, is based on the observation of the inclusive photon spectra and the muon-spin photon angular correlations. The experimental possibilities are now broadly extended with the use of the TRIUMF time-projection chamber[3] for this purpose and allow observation both for the light and heavy nuclear targets. The theoretical description of the inclusive spectra is indeed a responsible task, and detailed investigations of the nuclear response is needed. This is, however, possible, and the reliability of the results obtained within the assumption of the so-called resonance domination[2,5] is for the low-momentum-transfer processes well under control.

In the present paper we intend to give predictions for the inclusive photon spectra due to the RMC reaction on ^{14}N. We suggest it as one of the prospective targets to be used in the coming experiments since it provides a new possibility to investigate RMC for an open-shell nucleus with $J_{g.s.} \neq 0$. It may support (or disprove) the tendency for renormalization of the weak coupling constant g_p observed[6–8] in the analyses of RMC data for the ^{12}C and ^{16}O targets. Our present treatment of the RMC mechanism closely follows the earlier works[6,7] for the $A=12$, 16, and 40 nuclei.

Two circumstances should be mentioned which lead us to believe that the inclusive RMC spectra can be meaningfully interpreted in the above-mentioned cases. Namely, the calculated transition strength is mainly connected with the configuration space chosen, and the possible small and even moderate redistribution of the strength among the individual levels of the final nucleus does not influence appreciably the integral photon yield.[9] Indeed, the inclusive photon spectrum may receive contributions from transitions to the levels of complicated structure (e.g., the 2^+ levels in ^{14}C discussed below).

These cases are easily identifiable from the analysis of the analogous reactions (radiative pion capture, OMC, inelastic electron and pion scattering, etc.). Such a transition, if even individually strong, contributes at most 10–20 % to the integral photon yield and always can be approximately estimated in such a way that the corresponding inclusive observable is calculated accurately enough. This is indeed connected with the fact that we consider the ratio of the radiative to ordinary muon capture. The analysis performed below fully supports our expectation that such a relative quantity is almost insensitive to the details of the nuclear structure input.

After this discussion it should be clear that a meaningful calculation of the inclusive RMC rates and spectra should be performed within the context of simultaneous analysis of several low-momentum-transfer reactions, which pertain to the same nuclear initial and final states and provide the check of the nuclear structure input. In Sec. II we perform such an analysis. Then in Secs. III and IV we describe the method of our RMC calculations and define the observables which can be compared with the theoretical evaluation. The results are shown in Sec. V, and finally, Sec. VI is devoted to some conclusions.

II. SHELL-MODEL STATES

Our hypothesis about the so-called resonance domination of the low-momentum-transfer nuclear processes allows us to formulate the model of the nuclear response. Namely, we expect that similarly to the OMC, radiative pion capture (RPC), etc., the nucleus (^{14}C) is after RMC, left in one of the isovector collective nuclear states with $J=0^-, 1^-, 2^-, 3^-, 0^+, 1^+$, and 2^+, the other contributions being fully negligible.

The spin and isospin reduced matrix element of any single-particle operator $\hat{O}$ can be written in the form[10]

$$(E_fJ_fT_f|||\hat{O}_{JT}|||E_iJ_iT_i)=\sum_{a'a}\Psi^{fi}_{JT}(a',a)(a'|||\hat{O}_{JT}|||a)\ , \tag{1}$$

where $\Psi^{fi}_{JT}(a',a)$ are reduced density matrix elements. To describe the nuclear initial and final states, we have used the shell-model (SM) wave functions calculated by diagonalization of the nuclear residual force within the complete space of $l\hbar\omega$ ($0\hbar\omega$) harmonic-oscillator basis states for the negative- (positive-) parity levels of $A=14$ nuclei. For the states of normal parity, we employed Cohen-Kurath (8-16)2BME interaction[11] (in the following CK); for the states of non-normal parity, the modified Gillet COP interaction[12] has been adopted. The relevance of this type of effective N-N interaction to the various reactions of interest has been proved and discussed elsewhere.[9]

Here we mention only that the spurious contamination has been removed completely from the physical states. The stability of our results against variation of effective N-N interaction has been checked by using also the empirical matrix elements fitted by van Hees and Glaudemans.[13] We have found that the total transition rates are fairly independent of the SM option for the N-N interaction.

The low-lying states of non-normal parity in $A=14$ nuclei are all accounted for and quite well reproduced within the frame of the $1\hbar\omega$ model space (see also Ref. 13). Less satisfactory is the description obtained within the $0\hbar\omega$ space for the natural parity levels. In the remaining part of this section, we discuss the related problems.

A. $0\hbar\omega$ model space and $A=14$ nuclei

The SM $0\hbar\omega$ basis for mass number $A=14$, isospin $T=1$, provides only two $J=0^+$ and two $J=2^+$ states. So it is clear that the $0\hbar\omega$ basis is too poor to describe all the experimentally known low-lying normal parity states in ^{14}C. Because of the well-pronounced configurational splitting between Young tableaus [442] and [433], the upper and lower $J=0^+$ and 2^+ $0\hbar\omega$ states are separated by as much as 8–10 MeV for both interactions used by us. As a consequence, the experimentally known ^{14}C states $0^+_{2'}$, $0^+_{3'}$, $2^+_{2'}$, and 2^+_3 have to be interpreted as intruder states in $0\hbar\omega$. The two lowest 2^+ states (at 7.01 and 8.32 MeV) lie so close to each other that probably they both contain a strong mixture of $0\hbar\omega$ and $2\hbar\omega$ configurations. Actually, Lie,[14] restricting the $2\hbar\omega$ space to the $2sd$ active particles, revealed a sizable admixture of $p^{-2}(2sd)^2$ configurations in some low-lying $A=14$ states, and, namely, as large as about 50% in both $2^+_1 1$ and $2^+_2 1$ states. On the other hand, the ground states of ^{14}N and ^{14}C contain only a negligible $(2sd)^2$ admixture in this model space. Lie succeeded to reduce twice the electromagnetic $M1$ transition strength to the $2^+_1 1$ state (in ^{14}N), overestimated by the factor of 4 in $0\hbar\omega$ calculations. The summed transition strength to the $2^+_1 1$ and $2^+_2 1$ states remains, however, almost the same as the one calculated in $0\hbar\omega$ space for the $2^+_1 1$ state. The transition strength is only redistributed or spread to the $0\hbar\omega$ components of Lie's $2^+_1 1$ and $2^+_2 1$ states. In other words, a portion of the transition strength to the $2^+_2 1$ state is already contained in the transition to the $2^+_1 1$ state, if calculated in $0\hbar\omega$ space. It should be stressed, however, that this summed transition strength is still too high by a factor of 2 when compared with experimental data.[15] Similar overestimation by a factor of 2 of the summed transition strength, we discuss, is observed in *RPC*.[16–18] This puzzle cannot be solved by adding $p^{-2}(2sd)^2$ configurations to the $0\hbar\omega$ space only. The ^{13}C(d,p) reaction[19] exhibits rather dissimilar structure of these two states, and the recent measurement of angular distributions in ^{14}N$(\gamma,\pi^+)^{14}$C* (Ref. 20) even shows that the restriction on $p^{-2}(2sd)^2$ excitations results in still further disagreement between theory and experiment.

It has been argued long ago[21] that the large $p^{-1}(3pf)$ admixtures as low as 11 MeV in ^{14}N might play an important role. Recently, the Utrecht group[22] has found 20% of $p^{-1}(3pf)$ and 10% of $p^{-2}(2sd)^2$ configurations even in the ground states of $A=14$ and 15 nuclei, using the full $0\hbar\omega+2\hbar\omega$ model space. Although in the experiment[23] on ^{15}N$(\vec{d},t)^{14}$N no significant $l=2$ and/or $l=3$ pickup could be identified, it was not possible to disentangle the $1p$ and $3p$ contributions to the $l=1$ transitions. Because some discrepancies between $T=1$ CK matrix elements and those estimated from experiment have been found, it could be a result of just the $3p$ configurations interplay. Such admixtures would change the one-particle transition strength calculated, and, namely, in the 2_1^+1 and 2_2^+1 states.[24] Clearly, the description of these states and even of the $A=14$ ground states remains an open and interesting problem in nuclear structure, whose proper investigation was beyond our present computational possibilities. Even large (but not complete) $0+2\hbar\omega$ calculations of inelastic pion[25] scattering show that for the description of these 2^+1 excitations the delicate shell-dependent corrections (effective charges) should be introduced. Thus we keep in mind for OMC and RMC calculations that the only 2_1^+1 state in $0\hbar\omega$ space represents in fact two states with components also in $2\hbar\omega$ space. However, the $0\hbar\omega$ transition strength is not simply redistributed between these two states, but should be further reduced by a factor of 2.

At the end of this section, we would like to mention a selection rule that governs $M1$ transitions in $0\hbar\omega$ space and explains why the 2^+1 states exhaust a good deal of $M1$ strength in $A=14$ nuclei.

In the limit of LS classification of nuclear states, for the matrix element of the transition operator $\hat{O}$, one has

$$([f_f]L_fS_fJ_f|||\hat{O}_{LSJ}|||[f_1]L_iS_iJ_i) = \begin{bmatrix} L_i & S_i & J_i \\ L & S & J \\ L_f & S_f & J_f \end{bmatrix} C([f_f][f_i]) , \quad (2)$$

where the expression C involves the product of coefficients of fractional parentage and the single-particle matrix elements. The Young tableaus $[f]$ classify the spatial symmetry of nuclear wave functions. The $9j$ symbol expresses selection rules for angular momenta. It can be proved that due to the relative simplicity of the $0\hbar\omega$ space, one obtains

$$C([f_f],[f_i]) \sim \delta_{[f_f][f_i]} \quad \text{if } L=0 . \quad (3)$$

In the wave function of the ^{14}N ground state, there is a strongly dominating component $[442]^{13}D_{1'}$, with a weight of $\alpha^2 \sim 0.9$, fairly independent of the effective N-N interaction used. In the ground-state wave function of ^{14}C, there is neither the D component nor the symmetry [442] dominates. Therefore, the ground-state $L=0$, $M1$ transitions are hindered, related exclusive reactions are very difficult to measure, and the strength is distributed in other excited states. The 2_1^+1 level of ^{14}C ($E_x=7.01$ MeV) contains a large $[442]^{31}D_2$ component. And, namely, this component, even though spread if the model space is enlarged, does contribute to the $M1$ sum rules. This enhancement of the $M1$ transition to the low-lying 2^+1 states (7.01 and 8.32 MeV or ^{14}N analogs) was observed in RPC,[16,18] electron scattering,[24] and photoproduction of pions[20] as well as in OMC.[26]

III. MUON CAPTURE

In the case of the RMC reaction, the transition operator $\hat{O}$ has the form[7]

$$\hat{O}_{LSJ} = \begin{bmatrix} l & l' & L \\ 0 & 0 & 0 \end{bmatrix} j_l(kr)j_{l'}(nr)[Y_L(\hat{r})\times\sigma_s]_J\tau^{(-)} . \quad (4)$$

Here σ_s for $S=0$ ($S=1$) is the unit (Pauli) matrix, $\tau^{(-)}$ is the isospin lowering operator, k and n are photon and neutrino energies, respectively. The spherical Bessel function $j_{l'}(nr)$ stems from the partial-wave decomposition of the outgoing neutrino and $j_l(kr)$ from the decomposition of the photon plane waves. The necessity to expand outgoing neutrino and photon waves separately is a technical consequence of the modified impulse approximation[7] (MIA) based essentially on the continuity equation for nuclear electromagnetic current. This technique helps to include partly the meson-exchange-current corrections.[2] The relation between impulse approximation and MIA can be found in Refs. 2 and 17.

The transition operator for OMC can be obtained from Eq. (4) in the limit of $k\rightarrow 0$, $l=0$. In this case the operator $\hat{O}$ in Eq. (4) contains only one spherical Bessel function, of the argument qr, where $q=n$ is the transferred momentum limited by the muon mass as $q \leq 0.5\text{fm}^{-1}$. The higher partial waves L in Eq. (4) are effectively suppressed in radial integrals, because they are evaluated within the nuclear volume ($qR<2$). In RMC, because of the richer structure of the transition operator $\hat{O}$ in Eq. (4) (two spherical Bessel functions), the $L=2$ partial wave is less suppressed as compared to OMC. This influences $M1$ transitions through the operator $[Y_2\times\sigma]_{1^+}$.

Because of the computer limitations, we have omitted velocity-dependent operators like $[Y_L\times\nabla]_J$ in both the OMC and RMC calculations. It was numerically demonstrated[27] for the ^{16}O and ^{40}Ca targets that omitting these velocity-dependent operators in the calculation, one finds the ratio of RMC to OMC rates only negligibly changed though both rates individually are diminished by about 10%. We expect, however, that such an approximation would not be valid for the further muon-spin photon correlations calculations.

The OMC transition rate is most sensitive to the variation of the axial-vector coupling g_A and is insensitive to the other couplings.[28] The effective range of g_A obtained from the OMC measurements in nuclei comes close to the values drawn from neutron β decay and muon capture in hydrogen.[28] We have chosen the value $g_A^{\text{eff}}(0)=-1.24$ as fixed, to follow the earlier work[7] on this subject. At present, however, the value $g_A \sim -1.26$ seems to be more realistic. RMC by nuclei is known to be particularly sensitive to the pseudoscalar coupling constant g_p. We use related observables for determination of it, keeping remaining couplings fixed as well founded via other experiments.[28]

IV. OBSERVED QUANTITIES

Starting with the effective RMC Hamiltonian, one derives the full RMC amplitude $M(\rho)$ (see Ref. 7). Summing over photon polarization and integrating over all directions of the outgoing neutrino momentum, the exclusive photon spectrum corresponding to the transition from the state $|E_iJ_iM_i\rangle$ to the state $|E_fJ_fM_f\rangle$ is given as

$$N^{fi}(k)=\frac{2(\alpha Z)^3}{(2\pi)^4\hbar}\alpha(G\cos\vartheta_C)^2 m_\mu C(Z)k(k_{\max}-k)^2 \times\frac{1}{(2J_i+1)}\sum_{\rho M_f M_i}|M(\rho)|^2 . \quad (5)$$

Here α and G are the electromagnetic and weak-interaction constants, ϑ_C is the Cabbibo angle and $C(Z)$ stems from the muon atomic wave function; ρ is the polarization index of the outgoing photon and $k_{\max}$ is the maximum photon energy. Performing the integration over the photon energy k, we obtain the partial RMC rate

$$\Lambda_{\mathrm{RMC}}^{fi}=\int N^{fi}(k)dk . \quad (6)$$

The inclusive energy photon spectrum is obtained from Eq. (5) by summing over all final nuclear states:

$$N(k)=\sum_f N^{fi}(k) . \quad (7)$$

The total RMC rate is the integral of $N(k)$ over the photon energy:

$$\Lambda_{\mathrm{RMC}}=\int N(k)dk . \quad (8)$$

The OMC amplitude M can be derived from that of RMC using the limit $k\to 0$. The OMC rate is then given as

$$\Lambda_{\mathrm{OMC}}=\frac{2}{\pi\hbar}(nG\cos\vartheta_C)^2(m_\mu\alpha Z)^3 C(Z) \times\frac{1}{2(2J_i+1)}\sum_{M_f M_i}|M|^2 . \quad (9)$$

The quantities most frequently quoted for RMC are the relative photon spectrum

$$R(k)=\frac{N(k)}{\Lambda_{\mathrm{OMC}}} , \quad (10)$$

and the branching ratio

$$R=\frac{\Lambda_{\mathrm{RMC}}}{\Lambda_{\mathrm{OMC}}} . \quad (11)$$

V. RESULTS

A. Ordinary muon capture

In Table I we show the dependence of the OMC rate on the induced pseudoscalar coupling constant g_P/g_A, and the contributions of positive- and negative-parity states separately. The OMC rate depends moderately on g_P; it varies by about 17% for the values of g_P/g_A between 4.5 and 20. The canonical value of g_P derived as a partially conserving axial-vector current (PCAC) prediction is $g_P/g_A=6.78$ (see, e.g., Ref. 2). There are indications from the recoil polarization measurements[29] on ^{12}C that g_P may be somewhat larger than the canonical value; $g_P/g_A\sim 10-12$ is determined also from exclusive μ-capture and β-decay rates[30,31] on $A=16$ targets. In the SM calculations of the Λ_{OMC} on the ^{12}C,[6,32] it is tempting to use an enhanced pseudoscalar coupling constant g_P/g_A in order to reproduce the data. The experimental value[1] for the OMC rate on ^{14}N, $\Lambda_{\mathrm{OMC}}^{\mathrm{expt}}=(69\,300\mp 800)$ s^{-1}, is lower in comparison with that we have calculated. As discussed in Sec. II, the pure $0\hbar\omega$ configurations are insufficient to ensure a realistic description of the absolute capture rates to the normal parity states.

In Table II we have selected some partial transitions, giving main contributions ($\Lambda_{\mathrm{OMC}}^{fi}>2000$ s^{-1}) to the total rate. The dominance of selected states is not significantly influenced by the value g_P used for calculations, and so we have chosen as a representative one the value $g_P/g_A=16$. As concerns the experiment, there was measured[26] the partial transition rate to the 2_1^+1 state at $E_x=7.01$ MeV, with the result $\Lambda_{\mathrm{OMC}}(2^+)=4640\mp 700$ s^{-1}. This experimental value is by about a factor of 4 lower than our calculation. However, we have obtained result comparable to other calculations.[33,34] This discrepancy was discussed in Sec. II, where it was argued that this calculated transition in the $0\hbar\omega$ space represents actually summed transition rate for the 2_1^+1 and 2_2^+1 state with components also in the $2\hbar\omega$ space, and that it should be still reduced by a factor of 2 in order to obtain the reasonable estimate. So let us reduce our calculated total OMC rate by $\Delta\Lambda_{\mathrm{OMC}}\sim 1200$ s^{-1} in order to inspect further whether this procedure influences relative inclusive observables ($R=\Lambda_{\mathrm{RMC}}/\Lambda_{\mathrm{OMC}}$) or not. Thus the corrected total OMC rate is $\bar{\Lambda}_{\mathrm{OMC}}(g_P/g_A=16)\sim 74\,000$ s^{-1}. One should realize, however, that this result will be increased by about 10% if the nucleon-velocity-dependent terms omitted here (cf. Sec. III) are included into the calculation.

Among other major contributions to the total OMC rate, we have obtained the strong excitation of the 1_1^+1 state at $E_x=11.3$ MeV. Analogous strength was seen in RPC (Refs. 16 and 18) at 10–13 MeV and in inelastic scattering on ^{14}C at 11.3 MeV.[24] We predict also a strong excitation of the 3^-1 state at $E_x=6.7$ MeV. This state is strongly excited in the ^{13}C(d,p) reaction[19] and has been seen in electron scattering.[24] The giant dipole resonance

TABLE I. OMC rates in s^{-1} summed over the positive- (Λ_{OMC}^+) and negative- (Λ_{OMC}^-) parity states in ^{14}C and total OMC rates in dependence on g_P.

g_P/g_A	4.5	7.5	10	12	14	16	20
Λ_{OMC}^+	29 450	27 870	26 810	26 130	25 600	25 220	24 910
Λ_{OMC}^-	71 870	68 060	65 430	63 660	62 200	61 050	59 670
Λ_{OMC}	101 320	95 930	92 240	89 790	87 800	86 270	84 580

TABLE II. OMC rates for several dominant partial transitions to the ^{14}C excited states, calculated with $g_P/g_A=16$.

E_x (MeV)	$J_f^\pi T$	$\Lambda_{\mathrm{OMC}}^{fi}$ (s^{-1})	Dominant multipolarity
7.0	2^+1	22 750	$M1,E2$
11.3	1^+1	2010	$E2,M1$
6.7	3^-1	3060	$M2,E3$
14.9	3^-1	3380	$M2$
15.7	3^-1	2540	$M2$
14.6	2^-1	2530	$M2$
17.8	2^-1	2240	$M2$
18.4	2^-1	5830	$E1$

(GDR) region built on the ^{14}N has been studied through photoexcitation and radiative proton capture. The ^{13}C$(p,\gamma)^{14}$N* excitation function[35] shows a broad structure in the region $18 \le E_x \le 24$ MeV with prominent peaks at $E_x=22.5$ and 23.0 MeV. The analogs in ^{14}C are expected at $E_x \sim 20$ MeV. Much of this strength is associated with 2^-1 states. Our calculations provide a strong $E1$ transition to the 2^-1 state, placed by Gillet COP force by 2 MeV low. The $M2$ transitions to the states 2^-1 and 3^-1 predicted just below the main peak in the GDR region could be probably connected to the broad structure in photon spectrum which has been observed in RPC (Ref. 18) near $E_x \sim 15$ MeV. These transitions constitute the spin-isospin dipole vibrations.

B. Radiative muon capture

In Table III we present the partial RMC rates summed over all nuclear final states with the definite spin and parity $\Lambda_{\mathrm{RMC}}(J^\pi)$, the total RMC rate Λ_{RMC}, and the branching ratio R. In the energy integration only the interval $k \ge 57$ MeV is taken into account; below this energy the RMC photons cannot be observed due to the μ-decay bremsstrahlung background. We have also calculated the relative photon spectra $R(k)$ as a function of g_P/g_A; they are presented in Table IV.

There are always only a few nuclear states which provide major contributions to the total reaction probability, and these states are the same for both OMC and RMC. The only exception is the transition $^{14}N_{\mathrm{g.s.}} \to {}^{14}\mathrm{C}_{\mathrm{g.s.}}$, for which the $\Delta L=2$, $M1$ transition is not suppressed (as discussed in Sec. III). However, it is still too weak for exclusive measurement. It is therefore a reasonable approximation to take for the calculation of R a subset of the shell-model states most strongly excited in the OMC. Namely, we have limited the summation for both OMC and RMC by those states which show up $\Lambda_{\mathrm{OMC}}(\mathrm{partial}) \ge 100$ s^{-1}. They exhaust about 96% of the calculated total OMC rate.

As we have expected, the calculated partial rate to the 2_1^+1 state is very high. It represents again the summed transition rate analogous to the OMC case and should be further reduced by a factor of 2. Taking this into account, let us reduce the total RMC rate for $g_P/g_A=16$ by $\Delta\Lambda_{\mathrm{RMC}} \sim 0.290$ s^{-1}. Remembering the similar reduction in the OMC reaction ($\Delta\Lambda_{\mathrm{OMC}} \sim 12\,000$ s^{-1}), we can evaluate the corrected branching ratio $\bar{R}(g_P/g_A=16) = 1.91/74\,270 = 2.57\times10^{-5}$. This corrected value does not differ significantly from the uncorrected one, presented in the Table III. The same holds also for other pseudoscalar couplings. We believe, therefore, that the calculated branching ratios R are not significantly distorted by the unsufficient size of the $0\hbar\omega$ space discussed in Sec. II and can serve for the extraction of the pseudoscalar coupling constant g_P.

The earlier calculation of the RMC rates on the ^{12}C (Ref. 6) has shown good agreement with the data $[R=(2.3\mp0.2)\times10^{-5}]$ of Ref. 36 if an enhanced value of the pseudoscalar coupling, $g_P/g_A \sim 16$, has been used.

The RMC calculation[8] based on the sum-rule technique and therefore independent of the shell-model diagonalization leads for RMC on ^{12}C to the value of $g_P/g_A \sim 12$, if the calculated results are extrapolated so as to cover the above quoted experimental value of R. Unfortunately, the authors of Ref. 8 have used a much smaller preliminary and by now obsolete experimental value of R and reached the conclusion of lesser renormalization for g_P/g_A.

For ^{16}O two groups of data are available. The measurements by Döbeli *et al.* [37] $[R=(2.44\pm0.47)\times10^{-5}]$ and Armstrong *et al.*[38] $[R=(2.2\pm0.2)\times10^{-5}]$, if combined with the calculations of Ref. 7, also lead to a preference of the enhanced value of $g_P/g_A \ge 14$. The

TABLE III. RMC rates (in s^{-1}) summed over the nuclear final states of a given spin and parity J^π, total RMC rates, and the branching ratio R (in 10^{-5}) in dependence on g_P.

g_P/g_A	7.5	10	12	14	16	20
$\Lambda_{\mathrm{RMC}}(0^+)$	0.041	0.048	0.055	0.065	0.076	0.103
$\Lambda_{\mathrm{RMC}}(1^+)$	0.051	0.050	0.049	0.049	0.049	0.052
$\Lambda_{\mathrm{RMC}}(2^+)$	0.708	0.658	0.627	0.603	0.589	0.578
$\Lambda_{\mathrm{RMC}}(0^-)$	0.048	0.057	0.066	0.074	0.086	0.112
$\Lambda_{\mathrm{RMC}}(1^-)$	0.231	0.251	0.272	0.299	0.329	0.402
$\Lambda_{\mathrm{RMC}}(2^-)$	0.430	0.485	0.538	0.560	0.669	0.833
$\Lambda_{\mathrm{RMC}}(3^-)$	0.328	0.339	0.354	0.374	0.400	0.468
Λ_{RMC}	1.825	1.888	1.963	2.064	2.199	2.550
R	1.90	2.05	2.19	2.39	2.55	3.01

TABLE IV. Relative photon spectrum $R(k)=N(k)/\Lambda_{\rm OMC}$ (in 10^{-6} MeV^{-1}) as a function of the photon energy.

k (MeV) \ g_P/g_A	7.5	10	12	14	16	20
57	1.28	1.34	1.39	1.46	1.55	1.75
64	0.98	1.05	1.11	1.19	1.28	1.50
71	0.64	0.70	0.75	0.82	0.89	1.08
78	0.32	0.35	0.38	0.42	0.46	0.56
85	0.11	0.12	0.13	0.14	0.16	0.20

measurement by Frischknecht *et al.*[39] on ^{16}O [$R=(3.8\pm0.4)\times10^{-5}$] indicates an even much larger value of g_P, $g_P/g_A>20$. The sum-rule calculation of Ref. 8 shows roughly 30–35 % upward renormalization for g_P/g_A. It is therefore highly interesting to have data for other targets, for the ^{14}N considered here in particular.

VI. CONCLUSIONS

Both OMC and RMC reactions selectively excite the analogs of giant $M1$ states of the target. The $0\hbar\omega$ shell-model space does not suffice for the proper description of all experimentally known normal parity levels of $A=14$ nuclei. This concerns, particularly, strongly excited states 2^+1 at the ^{14}C excitation energy of 7.01 and 8.32 MeV. For the correct description of these levels, it is not enough to include only $p^{-2}(2sd)^2$ configurations, but the full $0+2\hbar\omega$ calculation is needed. Especially, the influence of $p^{-1}(3pf)$ configurations for the nuclei near the upper end of the p shell should be investigated carefully. The inability of $0\hbar\omega$ calculation to treat properly all positive-parity states in ^{14}N and ^{14}C does not influence significantly the value of branching ratio R for RMC. The negative-parity states of $A=14$ nuclei are, in general, well described in the frame of $1\hbar\omega$ space. The calculations give evidence for excitations of spin-isospin dipole vibrations in the GDR region. The predominant contributions are from 2^- and 3^- states. The RMC branching ratio R is a sensitive function of induced pseudoscalar coupling constant g_P. The measurement of RMC on the ^{14}N target is desirable.

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