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RADIATIVE CAPTURE OF POLARISED MUONS ON ^{16}O AND ^{40}Ca

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1. INTRODUCTION

Until recently the experimental attempts to investigate the radiative muon capture (RMC) reaction

$$\mu^- + A(N, Z) \longrightarrow \gamma + \nu_\mu + A(N+1, Z-1)$$

have mainly been limited to the observation of the photon spectra[1,2]. The importance of the muon spin photon angular correlations in RMC has indeed been recognized already in the early papers; nevertheless, the experimental information remained scarce and subject to very large errors due to the technical difficulties[2].

If the RMC experiments are performed with polarized muons, one can observe a correlation between the direction of the emitted photon $\vec{k}$ and the polarization vector $\vec{\xi}$. The directional distribution of photons depends on the asymmetry coefficient $\Gamma_\gamma(k)$ which is known[3] to be strongly sensitive to the value of induced pseudoscalar weak coupling constant g_P. Also, it has been shown [3,4] that $\Gamma_\gamma(k)$ is almost insensitive to the details of the nuclear structure model used in the calculations. Apparently, with this two-fold motivation a new generation of the RMC experiments, which are planned and partly performed[2,5] by now, includes a programme of the high precision measurement of the coefficient $\Gamma_\gamma(k)$ at least for RMC on ^{40}Ca.

It has recently[6] been shown that the standard impulse-approximation (IA) calculations of RMC overestimate the photon yield by a factor of two or more. Actually, an extension of IA is needed, which takes into account the constraints dictated by the electromagnetic-current continuity equation. The appropriate modification of the impulse approximation (MIA) scheme has been derived in ref.[6]. It provides realistic results for the RMC photon spectra; in particular, the numerical results obtained in ref.[6] for the RMC rate on ^{16}O and ^{40}Ca show that this microscopic approach and the phenomenological calculations[7,8] are in mutual agreement.

In view of the above-mentioned experimental efforts to measure with precision the correlational RMC characteristics, we have extended the MIA calculations of ref.[6] to the cases of photon polarization and muon spin photon asymmetry.

2. CALCULATIONS

According to the general invariance principles, one can write all the RMC observables in terms of two functions $P_{fi}^{(\lambda)}(k)$ and $R_{fi}^{(\lambda)}(k)$. They enter the matrix element squared of the RMC transition from the state $|i>$ to the state $|f>$ in the form

$$|M_{fi}|^2 \propto \sum_\lambda \int d\Omega_{\vec{k}} (P_{fi}^{(\lambda)}(\vec{k}) + \vec{\xi}\cdot\hat{\vec{k}} R_{fi}^{(\lambda)}(\vec{k})), \tag{1}$$

where $\vec{k} = k\cdot\hat{\vec{k}}$ is the photon momentum, $\lambda = \pm 1$ is the circular polarization of the photon, and $\vec{\xi}$ is the muon spin vector, $\cos\theta_{\mu\gamma} = \hat{\vec{k}}\cdot\vec{\xi}$.

The inclusive photon spectrum is

$$N(k) = \sum_f \sum_\lambda N_{fi}^{(\lambda)}(k), \tag{2}$$

where

$$N_{fi}^{(\lambda)}(k) \propto \int d\Omega_{\vec{k}} P_{fi}^{(\lambda)}(\vec{k}). \tag{3}$$

The asymmetry coefficient $\Gamma_\gamma(k)$ controls the angular distribution $W(k, \theta_{\mu\gamma})$ of the photons with respect to $\vec{\xi}$,

$$W(k, \theta_{\mu\gamma}) \propto 1 + \Gamma_\gamma(k)\cos\theta_{\mu\gamma}. \tag{4}$$

In our notation Γ_γ is given by

$$\Gamma_\gamma(k) = \frac{\sum_f \sum_\lambda (k_{fi}^{max} - k)^2 R_{fi}^{(\lambda)}(k)}{\sum_f \sum_\lambda (k_{fi}^{max} - k)^2 P_{fi}^{(\lambda)}(k)}, \tag{5}$$

where k_{fi}^{max} is the maximum photon energy.

The circular polarization $P_\gamma(k)$ of the photons is obtained in the form

$$P_\gamma(k) = \frac{\sum_f (N_{fi}^{(+)}(k) - N_{fi}^{(-)}(k))}{\sum_f (N_{fi}^{(+)}(k) + N_{fi}^{(-)}(k))}. \tag{6}$$

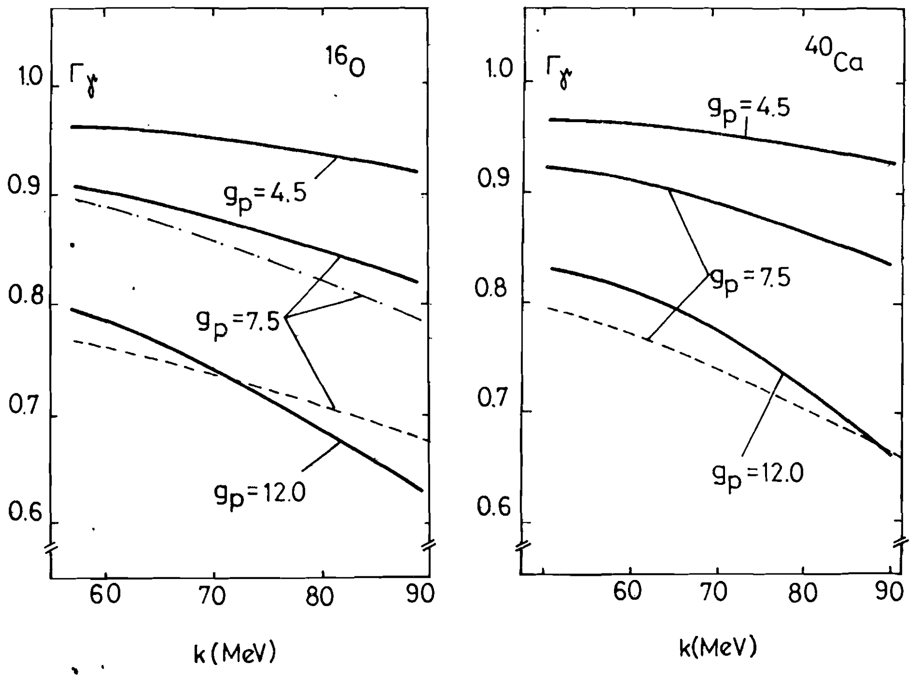
The calculation of the functions $P_{fi}^{(\lambda)}(k)$ and $R_{fi}^{(\lambda)}(k)$ though cumbersome, can indeed be done straightforwardly using the formulae of ref.[6]. In the present calculation, we follow all approximations which were introduced in that paper.

Our numerical results for $P_\gamma(k)$ and $\Gamma_\gamma(k)$ are shown in the table and the figure.

3. DISCUSSION

The most obvious observation is indeed that the results support the expected strong dependence of both $P_\gamma(k)$ and $\Gamma_\gamma(k)$ on the pseudoscalar coupling constant g_P. The full (dash-dotted) curves are all calculated in the MIA with the Eisenberg and Greiner [9] (Rose [10]) decomposition of the electromagnetic vector potential, for details see ref. [6]. The comparison of the two cases shows that the theoretical result is rather stable with respect to the details of imposing the continuity-equation constraint in the RMC calculations.

The dashed curves in the figure were calculated using the standard IA approach and $g_P = 7.5$. Comparing them with the full curves (corresponding to the MIA) calculated for $g_P = 7.5$, one can see the important effect on the calculated $\Gamma_\gamma(k)$ due to the continuity-equation constraint. As for our IA results, they indeed agree with those of ref. [4]. Several interference terms of the order $m_\mu/m_N \approx 1/10$ were left out in ref. [4] but included here. They change, however, only negligibly the inclusive RMC characteristics. Actually, it has been shown (see eq.(3.9) in ref. [3]) that such terms provide a zero contribution if the nuclear closure approximation is applied.



Asymmetry coefficients $\Gamma_\gamma(k)$ of photons from RMC on ^{16}O and ^{40}Ca. Full and dash-dotted lines were calculated using MIA (see the text); for the dashed lines we have applied the standard IA.

To elucidate the question of the sensitivity of our results to the nuclear structure model used, we have repeated the calculation of $P_\gamma(k)$ and $\Gamma_\gamma(k)$ for the $1\hbar\omega$ model of the nuclear final states of the ^{16}N nucleus (no correlations in the ^{16}O ground state) and compared them with the result presented in the table, which corresponds to the $1\hbar\omega + 3\hbar\omega$ model space of the ^{16}N final states ($0\hbar\omega + 2\hbar\omega$ correlated ground state of ^{16}O). The results are numerically almost identical, the difference being far less than one per cent in agreement with the results of refs. [3,4] mentioned in the introduction.

Table

Predictions of photon circular polarization $P_\gamma(k)$ and muon spin photon asymmetry coefficient $\Gamma_\gamma(k)$ for RMC on ^{16}O and ^{40}Ca as a function of photon energy.

k (MeV)	$P_\gamma(k)$			$\Gamma_\gamma(k)$		
	g_p=4.5	7.5	12.0	4.5	7.5	12.0
			$^{16}O(\mu^-, \gamma\nu)^{16}N$			
57	0.963	0.918	0.815	0.961	0.909	0.793
65	0.957	0.901	0.782	0.952	0.888	0.762
73	0.949	0.881	0.745	0.942	0.865	0.721
81	0.943	0.868	0.722	0.933	0.841	0.671
89	0.935	0.846	0.681	0.923	0.816	0.630
			$^{40}Ca(\mu^-, \gamma\nu)^{40}K$			
57	0.967	0.929	0.838	0.966	0.924	0.830
65	0.961	0.914	0.808	0.959	0.907	0.801
73	0.954	0.894	0.771	0.950	0.887	0.768
81	0.945	0.872	0.731	0.939	0.862	0.724
89	0.938	0.856	0.701	0.928	0.831	0.659

Before concluding, we wish to comment that the strong energy dependence of $\Gamma_\gamma(k)$ for $g_P \geq 10$ (see the figure) together with the very low statistics of the measurements in the high k region can probably lead to a substantial inaccuracy in extracting the value of g_P from the comparison of the measured energy-averaged Γ_γ with the calculated $\Gamma_\gamma(k)$.

The available experimental data for the energy-averaged correlation parameter Γ_γ are summarised in ref.[2]. The most recent result Γ_γ = 0.80±0.17 is due to Doebeli et al.[2]. Together with our calculation it leads to the value g_P = 11±8 not accurate enough to draw any conclusion at this moment.

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Радиационный захват поляризованных мюонов ядрами ^{16}O и ^{40}Ca

Рассчитаны коэффициент асимметрии углового распределения фотонов и циркулярная поляризация фотонов для процесса радиационного захвата поляризованных мюонов ядрами ^{16}O и ^{40}Ca. При построении оператора процесса было использовано уравнение непрерывности ядерного электромагнитного тока. Характеристики процесса радиационного захвата мюонов ядрами получены путем суммирования отдельных парциальных переходов. Ядерные состояния описываются в микроскопической оболочечной модели. Показана сильная чувствительность коэффициента асимметрии и циркулярной поляризации к величине константы индуцированного псевдоскалярного взаимодействия g_P и слабая зависимость этих характеристик к деталям структуры ядерных состояний. Проведено сравнение с экспериментом, которое дает для g_P величину g_P = 11±8. Большая погрешность в экспериментальных измерениях не позволяет делать конкретных выводов.

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Radiative Capture of Polarised Muons on ^{16}O and ^{40}Ca

The coefficient of asymmetry $\Gamma_\gamma(k)$ of the photon angular distribution (with respect to the muon spin) and photon circular polarization $P_\gamma(k)$ have been calculated for the radiative muon capture (RMC) on ^{16}O and ^{40}Ca and compared with the data. Nuclear states are treated in a microscopic model; the RMC characteristics are obtained by summing the contributions of individual partial transitions rather than by using the closure approximation.

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

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