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RADIATIVE π^- CAPTURE IN NUCLEI

J. Delorme

Institut de Physique Nucléaire
Université de Lyon, Lyon

and

T.E.O. Ericson

CERN - Geneva

ABSTRACT

An effective Hamiltonian for the process $\pi^- + N(A, Z) \rightarrow N^*(A, Z-1) + \gamma$ is derived from pion photoproduction in the impulse approximation. Good agreement with total experimental yields is found using techniques from the theory of μ^- capture in nuclei.

The branching ratio of the radiative capture of stopped pions : $\pi^- + N(A, Z) \rightarrow \gamma + N^*(A, Z-1)$ to all pion absorption process has recently been observed to be of the order of a few percent in several complex nuclei ^{1), 2)} (N^* stands for all bound or unbound accessible nuclear states). The associated γ spectra are typically peaked between 100 and 120 MeV ²⁾, indicating quasi-free capture on individual protons. The present note has two purposes :

- 1) to show that the observed yields can be well understood from inverse photoproduction on bound nucleons, using the impulse approximation and closure over final nuclear states;
- 2) to emphasize not only that the radiative π^- capture in nuclei is kinematically quasi-identical to muon capture but also that the effective Hamiltonians for the two processes are very similar ^{*)}.

Consequently, the entire theory of nuclear muon capture can be transferred bodily to radiative π^- capture but for minor changes with the experimental advantage that the neutrino has become an easily observable high energy γ ray. This last statement implies that a whole nuclear spectroscopy dominated by transitions to members of the giant dipole supermultiplet ⁴⁾ is experimentally within reach ^{**)} .

The basic capture process is assumed to be the reaction $\pi^- + p \rightarrow n + \gamma$ analogous to $\mu^- + p \rightarrow n + \nu_\mu$ in weak interactions. An effective Hamiltonian for nuclear radiative capture is deduced in the impulse approximation from the non-relativistic limit of the amplitude for the inverse process of pion photoproduction ⁵⁾. Neglecting the isoscalar part and keeping only the electric and magnetic dipole terms of the isovector part, we obtain

*) This has been previously realized and applied to ^3He to obtain nuclear matrix elements for use in the determination of μ capture coupling constants ³⁾.

**) A pair spectrometer would permit energy resolutions of the order of 200-300 keV out of 100 MeV.

2.

$$\mathcal{H}_{\text{eff}} = 4\pi i \sum_{j=1}^A \tau_j^- \left\{ A(\underline{\sigma}_j \cdot \underline{\hat{E}}) + B(\underline{\sigma}_j \cdot \underline{\hat{E}})(\underline{r}_j \cdot \underline{k}) \right. \\ \left. + C(\underline{\sigma}_j \cdot \underline{k})(\underline{q} \cdot \underline{\hat{E}}) + iD[\underline{q} \cdot (\underline{k} \times \underline{\hat{E}})] \right\} \delta(E - E_j) \quad (1)$$

Here, $\underline{\sigma}_j$ and τ_j^- are the ordinary spin and isospin matrices of the j th nucleon and $\underline{r}_j$ is its co-ordinate. The photon polarization and propagation vectors are denoted by $\underline{\hat{E}}$ and $\underline{k}$, the pion momentum by $\underline{q}$ and the pion and photon co-ordinates by $\underline{r}$. The effective coupling constants A, B, C, D, are related to the pion zero energy limit of the various multiple amplitudes in photoproduction with nuclear recoil corrections included. The dominant term is the electric dipole $A \simeq (-3.4 \pm 0.3) \cdot 10^{-2} m_\pi^{-2}$ ⁶⁾ (in units of $\hbar = c = 1$) which acts as an effective axial vector coupling constant in weak interaction language. The magnetic dipole transitions giving rise to p wave pions are usually perturbations for capture from bound Bohr orbits. The associated effective coupling constants are ⁶⁾ : $B \simeq 0.7 \cdot 10^{-2} m_\pi^{-4}$, $C \simeq -0.5 \cdot 10^{-2} m_\pi^{-4}$, $D = -2.8 \cdot 10^{-2} m_\pi^{-4}$. Replacing $\underline{q}$ by $-i \underline{\nabla}_\pi$, we have found them to represent typically about 1% of radiative captures in 1s orbits, 5% in 2p orbits and 12% in 3d orbits on the basis of the nuclear model discussed below.

While Eq. (1) could be used for a detailed discussion of radiative pion capture, the existing yield measurements with the associated rough information on the residual excitation energies indicate that for the moment it is more useful to demonstrate that radiative π capture can be understood in the present approach. Summing over the nuclear and photon final states, we obtain the total capture rate λ_γ :

$$\lambda_\gamma = \frac{1}{(2\pi)^2} \sum_{f, \epsilon} k_f^2 \int d\Omega_{k_f} \left| \langle f; \epsilon | e^{-i(\underline{k}_f \cdot \underline{r})} | \mathcal{H}_{\text{eff}} | \phi(\underline{r}); i \rangle \right|^2 \quad (2)$$

The summation index $\underline{f}$ represents the final nuclear states and the index $\underline{\epsilon}$ the two polarization directions of the photon. The final photon momentum in transitions to $\underline{f}$ is denoted by k_f and $\phi_{nl}(\underline{r})$ is the normalized pion wave function in the n, l orbit (distorted by the strong pion-nuclear interaction).

To obtain explicit predictions, Eq. (2) has been evaluated for the Fermi gas model after closure approximation. We have replaced k_f by an average photon momentum $\bar{k}$. This step can be made more readily than in μ^- capture since the rough photon spectrum is known, which is of importance because λ_γ depends on $\bar{k}^3 - \bar{k}^4$ ⁷⁾. For the 1s Bohr orbit, the approximation of a Fermi gas is known to work excellently for μ^- capture (Primakoff plot), though its success appears to go beyond expectations, particularly in light elements ⁸⁾. We have thus used such a model with $p_F = 268 \text{ MeV/c}$ (corresponding to $r_0 = 1.12F$). Terms of order A^{-1} have been neglected in the evaluation.

The expression (2) gives the capture rate in nuclei while the measured quantity is a branching ratio of radiative capture to all pion absorption processes. The total absorption rates for 2p and 3d states have been taken from an analysis in terms of pion optical model of the competition between absorptive processes and K_{α} and L_{α} electromagnetic transitions by M. Ericson ⁹⁾. The total 1s absorption rate is presently known rather poorly in the absence of width measurements of π^- mesic atoms. An evaluation may be performed on the basis of the pion optical model. Correction terms of order A^{-1} have been neglected, though they are important in light elements. We give in Table 1 the yields from circular orbits ($n = l + 1$) obtained for the five nuclei investigated by the Liverpool group ²⁾ (the experimental yields are given in the column R_{exp}). The numbers labelled R_{th} are averages of the results of columns 1, 2, 3 according to the experimental relative absorption rates from the different orbits.

	o r b i t s			R_{th} %	R_{exp} %
	1s	2p	3d		
${}^6\text{Li}$	5.3			5.3	3.3 ± 0.2
${}^7\text{Li}$	2.6			2.6	1.9 ± 0.2
${}^{12}\text{C}$	4.6	1.8		2.0	1.6 ± 0.1
${}^{32}\text{S}$		1.8	1.1	1.7	1.8 ± 0.1
${}^{63}\text{Cu}$		1.8	1.2	1.5	1.5 ± 0.1

T A B L E 1

(no A^{-1} corrections)

Theoretical and experimental yields of radiative capture from the 1s, 2p and 3d orbits in various nuclei

Corrections of order A^{-1} in non-radiative absorption channels bring the yields in ${}^6\text{Li}$ and ${}^7\text{Li}$ down by about 25-30%.

This excellent agreement may in part be accidental in its details as may be the case for μ capture ⁸⁾. It is, however, quite obvious that the relatively large yields of high energy γ rays are very well understood on the basis of the picture given here. The uncertainties in this description are more likely to be in the closure approximation and in the Fermi gas model than in the effective Hamiltonian. Among applications of this technique to specific problems in capture to individual nuclear states, we re-emphasize the importance of the spin dependent giant dipole collective states which are expected to play a central role both in radiative π^- capture and in μ^- capture ⁴⁾. In particular, this technique should be of very great interest for elucidating the negative parity states in ${}^4\text{H}$ (and ${}^4\text{He}$) ¹⁰⁾. Further, the same effective Hamiltonian technique can as well be applied to pion photoproduction from complex nuclei.

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