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RARE ELECTROMAGNETIC DECAYS OF PIONIC ATOMS

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ABSTRACT

It is shown that the virtual decay $\pi^0 \rightarrow 2\gamma$ inside a nucleus, and the annihilation reactions $\pi^- + \pi^+ \rightarrow 2\gamma$ or e^+e^- on virtual pions in nuclei (the pionic analogies of positron annihilation in solids) have observable branching ratios. These processes should shed light on the microstructure of the pion optical potential and on the nuclear pionic field with its coupling and to nucleonic excitation modes. Additionally, the e^+e^- mode will allow one to measure axial nuclear form factors in contrast to the fixed points of radiative capture.

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Two major motivations for the interest in low-energy pion interactions in nuclei are:

- a) the pion propagation inside the nucleus and its relation to the pion-nucleon scattering amplitude; and
- b) the pionic degrees of freedom of the nucleus and their coupling to nuclear excitations.

It is therefore important to find probes sensitive to the detailed behaviour of real and virtual pions inside the nucleus. In analogy with positron annihilation on the electrons of a solid, we point out here that pion annihilation into (e^+e^-) and (2γ) on the virtual pions in the nucleus can be used for this purpose. In addition, inside the nucleus it is possible to convert a low-energy charged pion into a π^0 for a short time interval, even when this is energetically forbidden in the asymptotic state. During this interval an almost physical $\pi^0 \rightarrow 2\gamma$ decay is possible and observable. Consequently, we will discuss here the magnitudes of the rare electromagnetic (2γ) and (e^+e^-) decay branches of pionic atoms with the aim of using them as sources of information on points (a) and (b) above.

Consider first the very low-energy pion-nucleus optical potential. In the standard multiple scattering picture ¹⁾, the virtual charge exchange process $\pi^- \rightarrow \pi^0 \rightarrow \pi^-$, the second order fluctuation scattering, is supposed to play an extremely important role because of the near-cancellation at low energies of the leading term proportional to the isoscalar πN amplitude. If one accepts this point of view, it follows that inside the nucleus of a π^- atom the pion is roughly 50% of the time in the neutral state, with the nucleus in a corresponding excited state. While this appears plausible, the conclusion is based upon purely circumstantial evidence, the observed magnitude of the pionic energy shifts and the structure of the multiple scattering equations. Now apart from a few of the lightest pionic atoms (^1H , ^3He) for which the charge exchange of stopped π^- into π^0 is observed ²⁾, such real charge exchange is energetically forbidden in light nuclei and can only occur virtually. Since the phase space for the decay $\pi^0 \rightarrow 2\gamma$ is, to a good approximation, unchanged by a few MeV of nuclear binding, the lifetimes of these virtual π^0 's are close to that of the free π^0 . The summed photon energies will then reflect the momentary nuclear excitation energy E^* , while the momentum balance is a measure of the instantaneous pion momentum.

Qualitative estimates of the branching ratio $R_{2\gamma}$ through the virtual π^0 decay may be obtained as follows. From the absorption widths of the $1s$ levels in pionic atoms ³⁾, the effective imaginary part of the scattering

length per nucleon is of the order of $10^{-3} \text{ m}_{\pi}^{-1}$, corresponding to a characteristic absorption time in nuclear matter of $\tau_{\text{abs}} \sim 10^{-22} \text{ sec}$. With a probability P_{π^0} for neutral pions inside the nucleus, the branching ratio is hence

$$R_{2\gamma}^{\pi^0} \approx P_{\pi^0} \times \frac{10^{-16} \text{ sec}}{10^{-22} \text{ sec}} = P_{\pi^0} \times 10^{-6}.$$

The naive estimate of 50% for P_{π^0} neglects the influence of the nuclear excitation energy E^* which permits only a limited propagation of the π^0 . This would become the determining factor if it were less than the mean free path for charge exchange. Putting in numbers for the charge exchange potential, and also allowing for the π^- excitation of the analogue states, $P_{\pi^0} = 0.2$ is probably more realistic. This gives a branching ratio $R_{2\gamma}^{\pi^0} \approx 0.2 \times 10^{-6}$. One may argue that this figure should be enhanced in the nuclear periphery due to the reduced absorption. While this is correct, there will also be some decrease in the amount of charge exchange so that the gains should not be large.

A lower limit for the branching ratio is obtained by considering the virtual charge exchange on an isolated nucleon with subsequent π^0 decay. Consider first the physical process $\pi^- p \rightarrow \pi^0 n$ with an energy release $E_A \approx 3 \text{ MeV}$. Suppose now that because of nuclear binding the neutron energy is changed, and the energy release made negative $-E^*$. Although the π^0 is virtual, from the overlap of the tail of the π^0 Breit-Wigner shape with the kinematically accessible phase space for decay, we find, neglecting all small energy variations of the matrix elements,

$$\frac{R_{2\gamma}^{\text{Bound}}}{R_{2\gamma}^{\text{Free}}} = \frac{1}{4 \tau_{\pi^0} (E_A E^*)^{1/2}}.$$

With a typical value $E^* \sim 10 \text{ MeV}$, the above ratio is 3×10^{-7} . This can then be related to the ordinary radiative capture by the Panofsky ratio, which for hydrogen is about 1.5⁴⁾. The single photon process provides a convenient normalization also in nuclei, where it is usually less than 5% of the strong interaction mode⁵⁾. Hence, the predicted single nucleon contribution to the (2γ) decay mode via virtual charge exchange is about 3×10^{-8} , an order of magnitude less than our nuclear estimate. In conclusion, π^0 decay should become an observable process in nuclei at the level of $10^{-6} - 10^{-7}$ simply due to the charge fluctuations of the pion field when a π^- propagates in nuclear matter.

In addition to the process of virtual π^0 decay, the propagating π^- can also directly annihilate on one of the virtual pions, already present in the nucleus, by the processes $\pi^- + \pi^+ \rightarrow 2\gamma$. These are the pionic analogies of the well-known positron process in solids $e^+ + e^- \rightarrow 2\gamma$. The (2γ) annihilation in hydrogen has been considered by Joseph ⁶⁾ and various Soviet authors ⁷⁾. For a zero-energy pion, and neglecting terms of order m_π/M , the only Born term remaining in the Coulomb gauge is that of Fig. 1. This gives a branching ratio to the Kroll-Ruderman ⁸⁾ estimate for the 1γ process on the proton of

$$\frac{R_{2\gamma}^p}{R_{1\gamma}^p} \approx \frac{1.12\alpha}{15\pi} \approx 10^{-4}.$$

As before we deduce a branching ratio in nuclei using the observation that the 1γ branch there is typically 5%. This yields $R_{2\gamma} \approx 5 \times 10^{-6}$, which is an order of magnitude larger than our estimate based on the virtual π^0 decay. Unlike the π^0 estimate though, this is a single nucleon mechanism with no enhancement of the pion density assumed because the nucleons are in a nucleus. It should, however, be noted that the annihilation mechanism is sensitive only to the relatively soft π^+ components in the nucleus with $p_\pi \ll m_\pi$ in order that the two photons might materialize freely.

Experimentally ⁹⁾, an upper limit has been obtained for the (2γ) branch in ^{12}C of less than 4×10^{-5} . Even on the basis of our rough estimates this suggests that the pion content in ^{12}C is not anomalously high, as might be the case if a pion condensate had developed. Since the tests of a pion condensate proposed by the Migdal group ¹⁰⁾ are rather indirect, a more detailed test along the lines suggested here would seem much more appropriate and clear cut. We can expect this old limit ⁹⁾ should give a positive signal with only rather moderate improvements ^{*)}. We note in passing that π^0 decay and the annihilation processes are nearly incoherent. The reason is that the annihilation graph leads primarily to nuclear states excited by spin flip, whereas the charge exchange produces relatively little spin flip.

Apart from the isolated case of ^{208}Pb , true pion charge exchange becomes possible again for pionic atoms formed by nuclei heavier than about ^{40}Ca , and would be very interesting to measure for its own sake. Even in these cases the annihilation graphs might be competitive since only few nuclear levels are energetically accessible through charge exchange, and for these the nuclear overlap integrals tend to be rather small.

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*) An experiment with this aim is presently in progress ¹¹⁾.

While the (2γ) processes have many nice features on the theoretical level, they have a serious experimental drawback for any studies of the energy balance in the reaction. The reason is simply the difficulty in detecting and measuring two photons with high efficiency and good energy resolution. We would probably be left in the dark as to which levels were excited in the residual nucleus. An alternative approach might then be to study the annihilation into an electron-positron pair rather than two photons, as illustrated in the Born approximation of Fig. 2a. Now it was shown many years ago by Kroll and Wada¹²⁾ that due to the proximity of the photon propagator to the physical region, the majority of these internal pairs are dominated by quasi-real photons, and so carry little more information than radiative capture, except possibly concerning the photon polarization. To a good approximation $R_{e^+e^-}/R_{1\gamma} = 0.7\%$, essentially independent of the nucleus. Combining this with a 5% radiative capture probability in reasonable nuclei, we get

$$R_{e^+e^-} \approx 3 \times 10^{-4}$$

At this level the internal pairs could provide a competitive means of measuring the radiative capture itself. This depends somewhat on the experimental geometry, the quality of the pion beams, etc., but the γ ray has to be converted into an (e^+e^-) pair to be measured, and to preserve energy resolution this is typically only 3% efficient. The physics of the radiative capture has been well publicized¹³⁾. For example, it is sensitive to the axial-vector nuclear matrix elements measured in β decay or muon capture at different momentum transfers. Now by looking at the internal pairs, it is possible to vary this momentum transfer and so measure form factors rather than isolated points. Such experiments have been extensively suggested in the case of hydrogen with the hope of getting pion and nucleon form factors in the time-like region^{6),14)}. For pion capture in hydrogen, where the calculations are quite reliable because they can rest on a low-energy theorem^{8),12)}, approximately 3% of the pairs correspond to hard photons with $m_\gamma^2 > 2/3 m_\pi^2$. Unfortunately, it is only in this limit of wide-angle pairs that the longitudinal photons coming from the annihilation graph of Fig. 2a compete with the transverse photons radiated exclusively by the nucleon (Fig. 2b). (They would, of course, excite different nuclear states.) Consequently, as far as looking at the pion content of the nucleus is concerned, the branching ratio for interesting events is of the order of

$$R_{e^+e^-}(m_\gamma^2 > \frac{2}{3} m_\pi^2) \approx 10^{-5}$$

This is not dissimilar to the (2γ) estimate, and of course the charged particles are much easier to detect and measure. The price to be paid is in the resulting theoretical complication. Whereas in the (2γ) case the pion pole could be deemed dominant, even for the massive photon events, the longitudinal photons coming from the nucleon are the more important (assuming that gauge invariance allows us to make this separation).

In summary, we believe that looking at the (2γ) and (e^+e^-) decays of pionic atoms will give us further insight into the physics of the nucleus. At something between the 10^{-5} and 10^{-6} level, the two-photon decay probes the pion density in the nucleus, be it anomalous or not. If the experiments can be pushed down another order of magnitude, then through the decay of the virtual π^0 's we can "see" how the pion propagates through a nucleus. On the other hand, the (e^+e^-) pairs should already appear at the 10^{-4} level where they could provide a complementary means of performing radiative capture measurements. To study the momentum transfer variation of the radiative amplitudes by varying the photon mass, bring us down to the 10^{-5} rate, and it is at this level that we can expect effects from the pion cloud, although in not as clear a form as in the (2γ) case.

Detailed calculations on the basis of these mechanisms will be of varying difficulty; we have contented ourselves here simply with order-of-magnitude guesses for the rates. These seem to be comfortably within present experimental capabilities.

The relevance of the annihilation graph in the (2γ) case was noticed during discussions of one of us (T.E.) and the Louvain group, in particular P. Lipnik, J. Deutsch and C. Leroy. We should also like to thank D. Broadhurst, B. Read, N.W. Tanner and P. Truöl for helpful suggestions.

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FIGURE CAPTIONS

Fig. 1 : Dominant Born term in the Coulomb gauge for the reaction
 $\pi^- p \rightarrow \gamma \gamma n$ at low energies.

Fig. 2 : Born terms for $\pi^- p \rightarrow e^+ e^- n$ due to the charge coupling.

FIG.1

FIG.2