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ELECTROPRODUCTION OF PIONS ON NUCLEI IN BOUND STATES

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It is known that study of π-mesic atoms is one of the most sensitive methods of investigating the structure of the nucleus [1]. However, the usual method of formation of π-mesic atoms by capture of stopped (stopping) pions has one fundamental shortcoming. The point is that the probability of the capture of the pion by the nucleus increases with Z more rapidly than the probability of the radiative transition, and therefore, starting with a certain Z, transitions to states with lower orbital angular momentum cannot be seen. Thus, for example, the 2p - 1s transition is indiscernible already starting with Z = 12, and the transition 3d - 2p starting with Z = 27 [1]. Yet greatest interest attaches to just the levels with small ℓ and n, since their parameters are most sensitive to the interaction of the pion with the nucleus. It is therefore meaningful to consider an experiment on the production of a pion immediately in the bound state of the mesic atom. This experiment supplements all the available experiments and makes it possible to obtain data on the s-levels of mesic atoms with large Z.

The photoproduction of the π-mesic atom was considered in [2]. However, to register the production of the mesic atom it is more convenient to use the electroproduction process, because in this case the levels of the mesic atom correspond to the peaks in the energy distribution of the scattered electrons. The widths of these peaks amount to several dozen keV, and therefore for such an experiment it is necessary to have a beam of electrons with high monochromaticity. The most realistic, apparently, is the performance of the experiment with storage rings with internal gas target [3].

The cross section of this process is given by

$$\frac{d^2\sigma}{d\nu d\Omega} = \frac{2\alpha^2 f^2}{\mu^3 |q^2|}\frac{E'}{E}\left[|\mathfrak{m}_\perp|^2\left(\frac{E'E\cos^2\frac{\theta}{2}}{q^2} + \frac{1}{2}\right)\right.$$
$$\left. + |\mathfrak{m}_\parallel|^2\frac{|q^2|}{\nu^2}\frac{2E'E\cos^2\frac{\theta}{2}}{q^2}\right]\frac{\Gamma_n}{\left(\nu + W_n - \mu - \frac{q^2}{2M^*}\right)^2 + \frac{\Gamma_n^2}{4}}, \qquad (1)$$

where E and E' are the initial and final energies of the electron, μ the pion mass, ν and q the transferred energy and momentum, M^* the mass of the mesic atom, W_n and Γ_n its binding energy and width, θ the angle of inclination of the electron in the lab, $f^2 = (g^2/4\pi)(\mu/2M_N)^2 \approx 0.08$, $q^2 = \nu^2 - q^2$, and $\mathcal{M}_\perp$ and $\mathcal{M}_\parallel$ are the transverse and longitudinal parts of the amplitude for the production of the meson by the nucleus. In the impulse approximation they are given by

$$\mathcal{M}_{\perp,\parallel} = \sum_{\nu\nu'} <\nu'|\phi_n^*(r)M_{\perp,\parallel}\, e^{iqr}|\nu><f|a_{\nu'}^+ a_\nu|i> \tag{2}$$

$M_{\perp,\parallel}$ is the amplitude of the production on one nucleon, and $\phi_n(r)$ is the wave function of the pion.

For the estimate, we confine ourselves to the s-levels of the mesic atom. Then

$$\mathcal{M}_{\perp,\parallel} \approx \phi_n^*(0) \sum_{\nu,\nu'} <\nu'|\tilde{M}_{\perp,\parallel}\, e^{iqr}|\nu><f|a_{\nu'}^+ a_\nu)i> \tag{3}$$

$\tilde{M}_{\perp,\parallel}$ are the amplitudes of the production of the pion at the threshold. As the final state we must choose the ground state of the neighboring nucleus, in view of the fact that the excited nuclear states have widths greatly exceeding the level widths of the mesic atom$^{1)}$. In this case the matrix element reduces to the following:

$$\mathcal{M}_{\perp,\parallel} \approx \phi_n^*(0) <k\ell' j' m'|\tilde{M}_{\perp,\parallel}\, e^{iqr}|k\ell j m> u_{k\ell' j'} v_{k\ell j}. \tag{4}$$

Here $|k\ell jm>$ is the single-particle shell state of the upper unfilled shell, u_ν and v_ν are the occupation factors,

$$v_\nu^2 = n_\nu. \quad u_\nu^2 + n_\nu^2 = 1.$$

The results of the subsequent calculations depend already on the chosen potential, but for an estimate we can choose any potential, since all give the same order of magnitude of the matrix element. A rougher estimate is obtained if $\exp(i\vec{q}\cdot\vec{r})$ is replaced by unity. This can be done because $|\vec{q}|R \sim 1$. The order of magnitude of the matrix element remains unchanged in this case. Assuming this estimate, we obtain for the cross section at the width of the peak when $|q^2| \ll \nu^2$

$$\frac{d\sigma}{d\Omega} \approx \frac{\alpha^4 Z_f^3}{\sin^2\frac{\theta}{2}} \left(\frac{\nu}{k}\frac{d\sigma}{d\Omega}\right)_{Photo} \tag{5}$$

Z_f is the charge of the final nucleus, $[(\nu/k)(d\sigma/d\Omega)]_{Photo}$ is the cross section for the photoproduction of the pion on a free nucleon at threshold

$$\left(\frac{\nu}{k}\frac{d\sigma}{d\Omega}\right)_{Photo} \approx 2\cdot 10^{-29}\,\text{cm}^2.$$

$^{1)}$For heavy nuclei, in principle, it is possible to study the excitation of the analog states whose width is comparable with the width of the mesic-atom levels.

For concrete nuclei we obtain at $\theta = 20°$ the following values:

$$\frac{d\sigma}{d\Omega} \approx 5\cdot 10^{-34}\ \mathrm{cm}^2/\mathrm{sr} \qquad \text{for } C^{12},$$

$$\frac{d\sigma}{d\Omega} \approx 10^{-33}\ \mathrm{cm}^2/\mathrm{sr} \qquad \text{for } Ne^{20},$$

$$\frac{d\sigma}{d\Omega} \approx 10^{-32}\ \mathrm{cm}^2/\mathrm{sr} \qquad \text{for } Cl^{35}.$$

Allowance for the change of $|\phi_n(0)|^2$ because of the s-wave repulsion [4] decreases these sections by a factor 3 - 4.

The experiment on the production of mesic atoms can be of interest also from another point of view. It is seen from (3) that the cross section of this process contains the matrix element for the production of the pion at the threshold. For such matrix elements there are predictions of current algebra [5], a verification of which can be carried out in this experiment with good accuracy.

The main background for this process is bremsstrahlung. For light nuclei its cross section greatly exceeds the cross section for the production of the π-mesic atoms. But this background is well known and, in principle, it is possible to get rid of it. Among the other processes that can serve as a background in the registration of scattered electrons only, notice should be taken of direct electrodisintegration of nuclei. The cross section of the electrodisintegration is comparable with the cross section for the production of free pions [6]

$$\sigma_{dis} \sim \sigma_\pi^{\text{free}}.$$

But the phase volume corresponding to the production of a pion in the bound state is much larger than the phase volume of the free pion with the same momenta

$$\sigma_\pi^{\text{free}} \approx \sigma_\pi^{\text{free}} \frac{W_n}{\Gamma_n}.$$

One should therefore expect the background of this process to be negligible.

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