Exotic nuclei with isospin $T > A/2$ and the radiative capture of pions

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The hypothetic properties of exotic nuclei with $T > A/2$ are treated. Complete decay of such nuclei to A nucleons is possible by electromagnetic or weak interactions ($\Delta T \geq 1$). Evidence for such nuclei may be found by looking at highly excited states of ordinary nuclei with energies slightly below the rest mass of pion and for specific products of nuclear interactions of heavy ions.

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The capture of π^- mesons by protons is known to result either in charge exchange ($\pi^- + p \rightarrow \pi^0 + n$) or in emission of a γ quantum that carries away the whole rest mass of the pion m_π. Bound states of a pion-nucleon system with a mass less than the sum of rest masses of two particles are unknown, and the first excited state of the nucleon with isospin T larger than $A/2 = 1/2$ is the well-known nucleon isobar $\Delta(T = 3/2$, spin $S = 3/2)$, with rest mass 1236 MeV, strongly decaying ($\tau \approx 10^{-23}$ sec.) to a pion and a nucleon.

The binding of a pion in a two-nucleon system is unlikely; this is indicated, e.g., by the fact that the shift of the π^--level in a ($D\pi$) atom[1] coincides with calculations[2–4] in which no pole was obtained (because of the low value of the πN-scattering length, ca. 10^{-14} cm for slow pions).

Qualitatively the same picture seems to be valid also for three-nucleon systems. However, one cannot exclude *a priori* the possibility of binding of pions in systems with a relatively small number of nucleons ($A \sim 10 - 100$), for which the Migdal methods[5,6] of the calculation of exotic nuclear states with very large mass numbers A are still not valid.

It is more likely that only experiments can answer the question whether the possible occurrence of bound pion states can exist in nuclei with masses exceeding the mass of the ground state of the initial (many-nucleon) system by less than m_π. Therefore we call attention to the extremely interesting consequences that follow from the assumption that binding of pions in systems with comparatively small number of nucleons is possible.

It is clear that a positive binding energy of a pion in the nucleus corresponds to the possibility of pion radiative capture:

$$\pi^- + A^z \rightarrow A^{z-1} + \gamma,$$

with formation of a system with an isospin differing by two units from its initial value: $T = T_0 + 2$.

Although the bound state of a pion in a two-nucleon system, as stated above certainly does not occur, the possible consequences of a change of isospin of a nucleus by two units following the radiative capture of a pion can be treated in a simple way just with such an example. It is obvious, e.g., that radiative capture of the type

$$\pi^- + D \rightarrow (n^2)^* + \gamma$$

could correspond to the formation of an "exotic" excited nucleus with isospin $T > A/2$. The decay of such an exotic nucleus A^*_{exot} to all A nucleons can proceed only with violation of isospin conservation, and therefore the lifetime of A^*_{exot} would be no less than about $10^{-19} - 10^{-18}$ sec. Correspondingly the probability of pion radiative capture (if its binding energy is positive), compared to the trivial case of "star" formation, would be about $10^{-4} - 10^{-5}$.

The exotic nucleus A^*_{exot} with mass A and isospin $T = A/2 + 1$ would be one of the $2(A/2+1)+1 = A+3$ components of an exotic multiplet. In the case of $A = 2$ this multiplet would involve five nuclei: Li^2 (with its charge $Z > A$!) He^{2*}_{exot}, H^{2*}_{exot}, n^{2*}_{exot}, and $(-H)^2$ (with negative electric charge—an atom with such a nucleus and with a positron shell is possible!). (Two of these nuclei could decompose only by β-decay*): $Li^2 \xrightarrow{\beta^+} (He^{2*}_{\text{exot}}) \rightarrow 2p$ and $(-H)^2 \xrightarrow{\beta^-} (n^{2*}_{\text{exot}}) \rightarrow 2n$, and the three others—by electromagnetic decay to two nucleons ($\Delta T = 1$).

The search for these interesting possibilities can be performed along two directions:

a) Attempts of finding highly excited states of ordinary nuclei, located only slightly below m_π (which correspond to radiative capture of pions). Such states of ordinary nuclei would be very broad because of the possibility of their strong decay to several nucleons and/or lighter nuclei. Their existence can be established by detailed studies of the excitation functions for the inelastic scattering of various particles and by the emission of γ rays with energies close to m_π in a rare radiative channel of decay of such states formed either by inelastic scattering or by radiative capture of pions.

$$\pi^- + N^{14} \rightarrow \gamma + C^{14\ 1)}$$

$$T = 1 \quad T = 0 \quad T = 1 \quad T = 2$$

In this approach, however, one cannot expect the formation of nuclei with $T > A/2$, because the initial stable target has a low T-value, and the decay of any exotic products of the above mentioned interactions to lighter exotic nuclei is energetically impossible.

b) Detailed analysis of the products of nuclear interactions of heavy ions, when the total energy in the center-of-mass system is close to m_π. In this case virtual pions can be formed which can be captured by a group of nucleons with increase in their isospin, for instance:

$$\begin{array}{ccccccc} Li^7 & + & Li^7 & \rightarrow & C^{6*}_{exot} & + & 8n \\ T=\frac{1}{2} & & T=\frac{1}{2} & & T=4 & & T=4 \end{array}$$

or:

$$\begin{array}{ccccccccc} Li^7 & + & Li^7 & \rightarrow & n^{6*}_{exot} & + & H^3 & + & 5p \\ T=\frac{1}{2} & & T=\frac{1}{2} & & T=4 & & T=\frac{1}{2} & & T=\frac{5}{2} \end{array} .$$

The excitation energy of the exotic nucleus C^{6*}_{exot} could show up in the spectrum of the decay protons: C^{6*}_{exot} could show up in the spectrum of the protons: $C^{6*}_{exot} \rightarrow 6p(\Delta T=1)$, and the excited hexaneutron with isospin $T=4$ and lifetime of about $10^{-19}-10^{-18}$ sec. would represent a narrow peak in the missing-mass spectrum of products in the second case. The prototype of a particularly interesting reaction takes the form

$$\begin{array}{ccccccccc} Li^7 & + & Li^7 & \rightarrow & (-H)^6 & + & He^3 & + & 5p \\ T=\frac{1}{2} & & T=\frac{1}{2} & & T=4 & & T=\frac{1}{2} & & T=\frac{5}{2} \end{array} .$$

All seven reaction products here are electrically charged (the sum of their absolute charges is eight), including a negatively charged, β^--active nucleus $(-H)^6$ that decays into six neutrons.

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[1)] β-decay of such nuclei can be preceeded by γ-emission with $\Delta T=-1$.

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