*HADRONIC ATOMS**

V. M. KOLYBASOV

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In addition to pionic atoms, the properties of which are considered in detail in the review by Backenstoss, there can exist also other hadronic atoms. Owing to the Coulomb attraction, a positively charged nucleus is capable of holding such particles as K^-, p^-, Σ^-, Ξ^-, Ω^-, and even more complicated systems such as $\overline{D}$, $\overline{T}$, or $\overline{He}^3$. K^--mesic, antiproton, and Σ^--hyperonic atoms have already been observed.[1–6] So far, in view of the scanty statistics, the accuracies with which the x-ray transitions in these atoms have been measured are low and suffice, as a rule, only for the identification of the lines. In the future, however, investigations of hadronic atoms will yield information on the interactions of K^-, $\bar{p}$, and Σ^- with nuclei, just as the widths and energy shifts of the lines in pionic atoms presently yield information on the interactions between pions and nuclei. On the other hand, it becomes possible to measure more accurately the masses of the hadrons, the magnetic moments of the Σ^- hyperon and antiproton (from the fine structure of the lines) and perhaps also the polarizability of hadrons in strong electric fields.[6,7]

Experimental studies were made of the K-mesic atoms of a large number of elements from Z = 3 to Z = 92.[1b] Transitions from 3d → 2p (in elements with Z = 3–5) to 12n → 11m (Z = 81 and 92) were observed. These measurement yielded the value k m_{K^-} = 493.7 ± 0.22 MeV. (We recall that usually one 439.82 ± 0.11 MeV). Initially, from the ratio of the intensities of different transitions, it was concluded that a neutron halo exists in heavy nuclei[1a] The experiments have shown clearly that the line intensity of a definite series decreases with increasing Z, and this series practically vanishes at a certain Z. The series n = 4 → 3 terminates at Z = 17, the series 5 → 4 at Z = 28, the series 6–5 at 42 ≤ Z ≤ 53, and the series 7 → 6 at Z = 64 or 65. If we calculate the probability of the nuclear capture of a K^- meson by perturbation theory, then such values of Z can be obtained only by assuming that the radius of the neutron distribution exceeds the radius of the proton, distribution and the periphery of the nucleus consists in the main of neutrons. More correct calculations,[8] however, with account taken of the distortion of the Coulomb wave function of the K-mesic atoms at small distance as a result of the strong interaction, have shown that such a conclusion is premature, and the existing data do not contradict the assumption that the radii of the proton and neutron distributions are equal. Of course, a more thorough study of the yields, widths, and level shifts will yield new information on the nuclear surface.

To describe the interaction of slow K^--mesons with nuclei it was proposed[8] to use a simple optical potential constructed in analogy with the pion-nuclear potential (see formula (15) of the Backenstoss article):

$$2\overline{m}_K V = -4\pi\,[1 + (m_K/m_N)][A_1\rho_n(\mathbf{r}) + 0.5\,(A_0 + A_1)\,\rho_p(\mathbf{r})]; \qquad (1)$$

here $\overline{m}_K$ is the reduced mass of the K meson and the nucleus, m_N is the nucleon mass, ρ_n and ρ_p are the densities of the neutrons and protons, and A_1 and A_0 are the KN-scattering lengths in states with isospins 1 and 0. According to [9]

$$A_0 = (-1.674 + i\cdot 0.722)\,\mathrm{F},\quad A_1 = (-0.003 + i\cdot 0.688)\,\mathrm{F}.$$

When the pion-nucleus potential is written for nuclei with isospin 0, then its local s-wave part contains the sum of the π^-p and π^-n scattering lengths, i.e., double the isosinglet pion-nucleon scattering length, which is very small. As a result, the contributions from the neutrons and protons cancel each other to a considerable degree, the local part of the potential becomes small, and the share of the gradient (p-wave) terms increases. Since there is no such cancellation in the s-wave terms for the K-meson potential, the gradient terms will play a negligible role in the potential. The approximation based on the introduction of the indicated optical potential is in essence a low-density approximation. It can be counted upon only if the length for scattering by the nucleon is much shorter than the average correlation distance between the nucleons. This condition is satisfied for pion scattering, and is not satisfied for the interaction between K mesons and nucleons at the center of the nucleus. The situation improves, however, if it is recognized that a strong KN interaction should be considered only on the periphery of the nucleus, where the density is lower by one order of magnitude than at the center. The point is that owing to the strong aboorption (unlike π^- mesons, K^- mesons can be absorbed also by individual nucleons in accordance with the scheme $K^-N \to \Sigma\pi$ or $K^-N \to \Lambda\pi$) the probability of observing the K^- meson close to the center of the nucleus is very low.

In analogy with the pionic case, allowance for the deviation of the local field acting on the nucleon from the mean field leads to a renormalization of the scattering lengths (cf. formula (16) in the Backenstoss review):

$$A_{\text{eff}} = A\,(1 + \langle e^{-\kappa r}/r\rangle_{\text{corr}}\,A)^{-1}.$$

The additional factor $e^{-\kappa r}$ is due to allowance for the vir virtual excitations of the nucleus, $\kappa = (2m_K\epsilon)^{1/2}$, and ϵ is the characteristic excitation energy and is of the order 10–20 MeV. The nature of the factor $e^{-\kappa r}$ can be easily understood by recalling that the kinetic energy of a slow meson that has excited the nucleus in one of the collisions with the nucleons becomes negative (this is not a real but a virtual process). Therefore the quantity e^{ikr} contained in the meson propagation function goes over into $e^{-\kappa r}$. Strictly speaking, such a factor should be written also for pionic scattering, but in the latter case it is not so important, since the small pion mass causes the numerical value of κ to be less. The symbol $\langle\ldots\rangle_{\text{corr}}$ denotes averaging with the nucleon-nucleon correlation function. On the periphery of the nucleus we have

$$\langle e^{-\kappa r}/r\rangle_{\text{corr}} = 0.1\text{–}0.2\ \mathrm{F}^{-1},$$

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and the corresponding correction turns out to be small.

Recent experimental data[5] on several transitions in K-mesic atoms admit of a detailed comparison with theory. It turns out that the level shifts correspond to a repulsion interaction and are smaller in value than the widths. Calculations based on the use of the potential (1) describe the level shifts well, but yield widths that are smaller by a factor 2–3 than those observed in experiment. Two possibilities have been proposed to explain this discrepancy:

1. It is necessary to take into account not only the single-nucleon K^--meson capture, but also multinucleon capture. Emulsion studies have shown that approximately 20% of all cases in K^--meson absorption pertain to multinucleon capture. Allowance for this circumstance increases the level widths appreciably.[6]

2. It is necessary to take into account the strong dependence of the KN-interaction amplitudes on the mass of the kaon + nucleon system. This dependence is caused by the presence of a strange resonance Y_0^* with a mass that is only 27 MeV less than the sum of the K^- and proton masses. This can lead to a noticeably difference between the interactions of K^- with the free nucleons and those bound in the nucleus, and then we can no longer use the threshold values of the amplitudes A_0 and A_1 in for formula (1). In[10] it was proposed to use the K^-p and K^-n scattering amplitudes averaged in a definite manner with account taken of the binding energy of the nucleon and its motion inside the nucleus. The averaged amplitudes differ substantially from the threshold ones (for example, their real parts even reverse sign), and the corresponding calculations give much larger level widths that agree fairly well with experiment. The table lists the calculated shifts of the energies ϵ and the widths Γ^{10} for a number of levels, and also the corresponding experimental data. Two sets of $\bar{K}N$ interaction parameters were used in the calculations, from[9,11] and from[12]. For comparison, the values in the parentheses were calculated using the threshold values of the KN scattering amplitudes. All the transitions are between circular orbits with $l = n-1$.

The question of allowance for the role of the resonance Y_0^* is at present of principal significance in the k theory of kaonic atoms. In addition to influencing the KN-interaction parameters, this resonance can come into play also directly, being produced in the process $K^- + p_n \to Y_0^*$ after which it interacts with the other nucleons. Further investigations of kaonic atoms can show the extent to which such processes are important.

Although earlier studies of kaonic atoms revealed individual lines, which were ascribed to Σ^- atoms (see e.g.,[1b]), a reliable observation of Σ^- atoms took place only relatively recently.[4] This was done at CERN. They used a beam of slow K^- mesons, containing ~ 1000 particles per accelerator cycle. The Σ^- were obtained in interactions with nucleons ($K^- + p \to \Sigma^- + \pi^+$, $K^- + n \to \Sigma^- + \pi^0$. $K^- + p + n \to \Sigma^- + p$) and were captured on high atomic orbits. This was followed first by Auger transitions and then by x-ray transitions to lower states. Σ^- atoms of sulfur, chlorine, and zinc were investigated. The observed transitions were 6 → 5 (E = 96.7 ± 0.3 keV) in ${}^{15}_{16}S$, 7 → 6 and 6 → 5 in ${}_{17}Cl$, and 11 → 10, 9 → 8, and 8 → 7 in ${}_{30}Zn$.

At approximately the same time, antiproton atoms of several elements from phosphorus to thallium were also discovered at CERN.[3] Theoretical estimates have shown that owing to strong absorption, the cascades in the $\bar{p}$-atoms should terminate in the transition $n = 4 \to n = 3$ in light elements of the O^{16} region (transition energy ~ 70 keV) and the transition $n = 9 \to n = 8$ for elements in the lead region (transition energy ~ 550 keV). An experiment using a separated slow-antiproton beam (~ 300 antiprotons per accelerator cycle) revealed transitions from 15 → 14 to 10 → 9 in the $\bar{p}$-atom ${}_{81}Tl$. The energies of these transitions yielded the value $m_{\bar{p}} = m_p \pm 0.5$ MeV. The 10 → 9 line is broadened, apparently as a result of the fine structure due to the magnetic moment of the antiproton.

In conclusion, let us stop discuss the interesting possibility of determining the electromagnetic dimensions of hadrons and their polarizabilities with the aid of hadronic atoms. The fact that the hadron has an electric form factor leads, generally speaking, to a shift of the energy level of the corresponding atom. This effect comes into play most strongly for the 1s levels, but, as shown by estimates,[7] does not exceed several per cent of the level shift due to strong interactions. It is therefore hardly observable.

If the hadron is on an atomic orbit, then it is acted upon by a strong electric field. In nuclei with large Z, the field at a distance ~20 F can reach a value 2×10^{18} V/cm, i.e., the potential drop over the Compton wavelength amounts to δV ~ 300 keV. This makes it possible to study the polarizability of the hadron, in which an induced dipole moment $\mathbf{d} = \kappa \mathbf{E}$ can appear, leading to an energy-level shift[7] $\Delta E_{nl} = -\kappa (Z\alpha)^2 (Z^4/a^4) \beta_{nl}$, where α is the fine-structure constant, a is the Bohr radius of the hadronic atom, and

K-mesic atom transition	RMS radius, F	Calculation with K_N parameters				Experiment	
		from [9,11]		from [12]			
		ε, keV	Γ, keV	ε, keV	Γ, keV	ε, keV	Γ, keV
B^{10} (3 → 2)	2.45	−0.30 (−0.23)	0.65 (0.24)	−0.25 (−0.22)	0.72 (0.25)	−0.208±0,035	0.81±0,10
B^{11} (3 → 2)	2.42	−0.30 (−0.23)	0.64 (0.24)	−0.26 (−0.23)	0.70 (0.26)	−0.167±0,035	0.70±0,08
C^{12} (3 → 2)	2.42	−0.80 (−0.59)	1.44 (0.55)	−0.67 (−0.58)	1.58 (0.58)	−0.59±0,08	1.73±0,15
P^{31} (4 → 3)	3.188	−0.52 (−0.49)	1.65 (0.58)	−0.36 (−0.48)	1.68 (0.60)	−0.33±0,08	1.44±0,12
S^{32} (4 → 3)	3.244	−0.88 (−0.82)	2.73 (0.94)	−0.61 (−0.80)	2.78 (0.98)	−0.55±0,06	2.33±0,06
Cl^{35} (4 → 3)	3.335	−1.44 (−1.29)	4.06 (1.45)	−1.05 −1.27	4.28 1.51	−0.77±0,40	3.8±1,0

$$\beta_{nl} = 0.5\,[3n^2 - l(l+1)]/n^5\,(l+3/2)\,(l+1)\,(l+1/2)\,l\,(l-1/2).$$

Quark-model estimates[7] yield $\kappa = \alpha \times 9m_\pi a_\pi^4/2$, where $a_\pi = 1-1.4$ F. For the transitions 5g → 4f in atoms with Z = 60–90, the energy shift due to the pion polarizability is 10–50% of the shift due to the strong interaction. An estimate of the polarizability by Ericson and Hufner (see [6]) using the dipole sum rule (the characteristic dipole frequency of the elementary particle was assumed to be ~ 1 GeV) yielded a value of κ smaller by an approximate factor 60 than in[7]. Terent'ev's calculations[13] based on the PCAC hypothesis[14] lead to a value $\kappa = 0.1\alpha/m_\pi^3$, where m_π is the pion mass. One can see in any case that the hadron-polarization effects are already at the borderline of the capabilities of modern experiments. One must not forget, to be sure, that the nucleus is also in the strong electric field of the hadron and is itself polarized. The resultant level shift is several times larger than the hadron-polarization effect. Therefore, in order to determine reliably the hadron nuclear polarizability, and also to take into account the effects of strong interaction and the change of the Coulomb field of the nucleus resulting from the screening by the electrons, and to have a more accurate value of the pion mass.

We note that if an atom has on the Coulomb orbit a complex particle such as, e.g., $\overline{D}$, such a particle will disintegrate as a result of polarization before it experiences a strong interaction.[6] This makes it very difficult to investigate the interactions of $\overline{D}$, $\overline{T}$, etc. with nuclei at zero energy by means of the mesic-atom procedure.

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