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ELECTROMAGNETIC INTERACTIONS OF NUCLEI SEEN IN EXOTIC ATOMS

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The level structure of exotic atoms is determined largely by the electromagnetic interaction between the positively charged nucleus and the negatively charged orbiting particle. This is rigorously correct for muonic atoms whereas for hadronic atoms also the strong interaction must be considered. However, due to the very different ranges of the strong and the electromagnetic interactions it is possible to study the latter also in hadronic atoms in atomic states beyond the reach of the strong interaction. But also valuable information can be obtained from atomic states affected by the strong interaction by comparison with purely electromagnetic measurements. I will discuss four different aspects which seem to me related to the problems relevant to this Conference even if only partly experimental results have been obtained.

1) Polarizabilities of Nuclei and Hadrons

Due to the larger mass the orbits of hadronic atoms are correspondingly smaller than those of ordinary atoms and hence the hadron experiences a much stronger nuclear electric field. It amounts in heavy nuclei to several 10^{19} V/cm at a distance for outside the strong forces. Similarly the nucleus moves within the electric field of the hadron. This leads to an attractive energy shift of the atomic level

$$\Delta E = -\tfrac{1}{2}\, e^2 \left[\alpha^N + Z^2\alpha^H\right] \langle r^{-4}\rangle_{n,\ell}$$

where α^N and α^H are the polarizabilities of nucleus and hadron respectively and the average of r^{-4} is taken over the corresponding atomic orbit n,ℓ. The possibility to determine α^H was pointed out first by Iachello and Landé [1] and discussed in some detail by Ericson and Hüfner [2] who also studied α^N. Experimentally a limit of α^H for kaons was given [3] to be $\alpha^K \leq 0.02\ \text{fm}^3$ where the effect caused by α^N is expected to be still about 10 times smaller [2]. With the improvement of the experimental technique as demonstrated below the effects under discussion should in future not be too far out from the experimental possibilities.

2) Nuclear distrubutions from hadronic atoms - Isotope effects.

The heavier the orbiting particle is the more the overlap $\int\rho\,|\psi|^2 d\tau$ is peaked at the surface of the nuclear density ρ where ψ is the wave function of the orbiting particle. For K-meson, antiprotons and Σ hyperons this means that the overlap becomes significant outside the regions where the nuclear density has dropped roughly to 20%, 10% and 5% respectively of its value at the center. The strong interaction effects consist of shifts of the energy levels and of broadenings of the levels and intensity attenuations due to the absorptive interaction. They are described in the simplest way by an optical potential $V(r) \propto |A_p\rho_p(r) + A_n\rho_n(r)|$ where A_p and A_n are effective complex scattering lengths and ρ_p and ρ_n the distributions of protons and neutrons respectively. In perturbation theory shifts and widths are then proportional to the overlap integral times the real or imaginary part of a scattering length $\bar{A}$ properly averaged over A_p and A_n

$$\Delta E_{n,\ell} \propto \mathrm{Re}\bar{A}\int\rho(r)\psi_{n,\ell}(r)d\tau$$
$$\Gamma_{n,\ell} \propto \mathrm{Im}\bar{A}\int\rho(r)\psi_{n,\ell}(r)d\tau$$

These quantities depend on the nuclear distribution as well as on the hadron nucleus interaction described by $\bar{A}$ and one can hope to disentangle them by a number of different experiments. For different hadrons A_p and A_n are different (e.g. Im A_n = 0 for Σ^-) and ρ_p and ρ_n may differ in particular nuclei. As a suitable experiment to clarify these problems measurements on $\bar{p}^{16}O$ and $\bar{p}^{18}O$ have been performed by our group. The results are consistent with the assumption that the $\bar{p}p$ and $\bar{p}n$ interaction is the same and the $\rho_n(r)$ extends beyond $\rho_p(r)$ as predicted from measurements of the charge distributions and model calculations [4].

3) Precise Muonic X-rays and the Vacuum Polarization

Previously measurements of X-ray energies in muonic atoms have been reported [5,6] which suggest discrepancies of 2-3 standard deviations with respect to theoretically calculated transition energies. Since the transitions are chosen such that other sources of uncertainties such as finite size effect, nuclear polarization and electron screening are minimized, possible deviations are thought to be connected with quantum electrodynamical corrections, predominantly vacuum polarization.

Hence, additional information is desirable which we obtained by measuring the energy difference between the 4→3 transitions in μ-Ba and the 5→4 transitions in μ-Pb which are doubletts interleaving each other. The components are, however, sufficiently separated that the energy difference can be determined with a high precision. Any effect depending independently on Z and the muonic state $(n, \ell j)$ should be detectable sensitively in this way.

We measured the X-rays from a composite Ba-Pb target simultaneously with two Ge(Li) detectors and obtained for the energy difference

perfect agreement with theory within the experimental errors of 13 eV and 16 eV for the transitions between the $\ell+\frac{1}{2}$ - and the $\ell-\frac{1}{2}$ states respectively.

The absolute energies can be determined with the help of a built in calibration line from the excited state of ^{137}Cs at 455 keV produced by $\mu^- + {}^{138}Ba \rightarrow {}^{137}Cs^* + n$ which is only 14 keV above the Ba X-rays. A recent determination of this γ line [7] seems to indicate that there are no significant discrepancies for the muonic Ba and Pb transitions.

4) Parity Violations in Muonic Atoms

The existence of neutral currents in weak interactions as evidenced by neutrino experiments has stimulated the interest in theories aiming at a unified description of weak and electromagnetic interactions. The questions arise now to which extent are neutral currents parity violating and to which extent can parity violation be observed in processes dominated by electromagnetic interaction.

The muonic atom is a system very suitable to study these questions since it is a bound system where the muonic wave function overlaps the nucleus much more than in electronic atoms. It has been suggested [8,9] to investigate the MI(EI) mixing in light or medium muonic atoms. A detailed examination of the experimental possibilities lead us to the conclusion that the necessary measurements of the interference term in the form of circular polarization of the X-rays or an asymmetry of them with respect to the muon spin are very hard. However a measurement of the E2(EI) mixing [10] though difficult, seems to be more promising. The advantages of this method are discussed in some details and it is believed that the measurements based on the MI(EI) mixing need measuring times longer by orders of magnitude.

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