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CAN POLARIZABILITIES OF NUCLEI AND ELEMENTARY PARTICLES
BE DETERMINED FROM EXOTIC ATOMS?

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A B S T R A C T

The nuclear and hadronic response to the electromagnetic fields in exotic atoms causes an energy shift proportional to a sum of nuclear and hadron polarizabilities. The shifts are shown to be within present experimental precision.

The behaviour of any system, macroscopic or microscopic, in a static and not too strong external field is completely determined by a few global structure constants. Corresponding to the leading order of the applied field these are the total charge and magnetic moment. To second order in the field the additional structure constants are the electric and magnetic polarizabilities.

The electric polarizability α implies that a constant electric field E induces a dipole moment d in the system

$$d = \alpha E \quad (1)$$

(Here, α is a scalar quantity only for isotropic systems.) The interaction of this induced dipole with the electric field leads to a total energy change

$$\Delta E = -\frac{1}{2} \alpha E^2. \quad (2)$$

The energy is lowered as the system adjusts to the external field, since $\alpha > 0$ for static fields.

Consider now the case when the electric field arises from a particle of charge e located at a distance r from the system. The electric field has then the strength

$$E = \frac{e}{r^2}. \quad (3)$$

The response of the system to the presence of this charge changes the energy by

$$\Delta E = -\frac{\alpha}{2} \frac{e^2}{r^4}. \quad (4)$$

This equation remains valid as long as the position r of the particle is constant in time or varies so slowly that the system adjusts completely to the momentary direction and strength of the electric field. Then the time average of the polarization energy is given by

$$\Delta E = -\frac{\alpha}{2} e^2 \langle r^{-4} \rangle. \quad (5)$$

A measurement of this energy shift is therefore equivalent to a determination of the structure constant α .

The situation we have just described is in practice well realized in K^- , $\bar{p}$, Σ^- , etc., atoms. A hadron captured in a Bohr orbit revolves around the nucleus and X-rays are emitted in the transitions between the orbits. Since the hadron is absorbed extremely rapidly inside nuclear matter, only those atomic states are in practice observable for which the probability to find the hadron inside the nucleus is extremely small. These are orbits with high centrifugal barriers and high principal quantum numbers. For these states it is a good approximation to consider the hadron the source of an external electric field. This field is further nearly static since the atomic frequencies are low compared to nuclear frequencies (a few hundred keV as compared to many MeV, typically). Therefore, Eq. (5) describes the polarization shift in an exotic atom with the expectation value of r^{-4} taken for the Bohr orbit characterized by the quantum numbers n_0, l_0 .

The previous argument must be slightly generalized because the hadron has an internal structure and is exposed to the electric field from the nucleus (Z times stronger than before)¹⁾. The situation is completely symmetric. The hadron (with charge $-e$) polarizes the nucleus and the nucleus (with charge Ze) polarizes the hadron. The total polarization shift of the orbit n_0, l_0 is the sum of both effects

$$\Delta E_{n_0 l_0} = - \frac{e^2}{2} (\alpha_N + Z^2 \alpha_H) \langle r^{-4} \rangle_{n_0 l_0} \quad (6)$$

with α_H and α_N the static polarizabilities of the hadron and of the nucleus. Although α_H is expected to be much smaller than α_N , both contributions in (6) are in practice of similar size because of the enhancement factor Z^2 .

Since the structure constants α_N and α_H completely give the polarization shifts, the possibility of exploiting these shifts for a determination of the α 's depends on their quantitative values.

A rather good estimate for the nuclear polarizability α_N is obtained by taking the nucleus to consist of neutrons and protons without exchange forces, and with the entire dipole strength concentrated in the giant dipole resonance. This gives

$$\alpha_N = \frac{NZ}{A} \frac{e^2}{m\omega_D^2} \simeq 2.5 \cdot 10^{-3} \left(\frac{4NZ}{A} \right) A^{5/3} \text{ fm}^3 \quad (7)$$

using the giant dipole frequency $\omega_D \simeq 80 A^{-1/3} \text{ MeV}$.

A dimensional estimate for the hadron polarizability is the expression ²⁾

$$\alpha_H = 2 \sum_g \frac{|\langle 0 | d_z | g \rangle|^2}{(\omega_g - \omega_0)} = \frac{2}{3} \frac{\langle d^2 \rangle}{\bar{\omega}} \approx \frac{2}{3} \frac{e^2 \langle r^2 \rangle}{\bar{\omega}}. \quad (8)$$

Here $\langle r^2 \rangle^{\frac{1}{2}}$ is the hadron root mean square charge radius and $\bar{\omega}$ is the average dipole excitation energy. The lowest possible value for $\bar{\omega}$ is the pion mass, while the first resonance of right quantum numbers typically has $\bar{\omega} \lesssim 1$ GeV. Important contributions come from the one and few pion continuum, so that $\bar{\omega} = 0.5$ GeV is a reasonable compromise, i.e., a proton polarizability of $\approx 10^{-3} \text{ fm}^3$. While this provides the scale of α_H , it is a very interesting question whether some of the hadrons are "softer", i.e., more easily polarizable than others. Deviations by a factor 2-3 from the dimensional estimate seem quite possible. On the basis of a simple quark model, Iachello and Lande ¹⁾ and Schröder ³⁾ predict polarizabilities for the π^- and K^- which are larger than the above estimates by a factor 10-100. Terentyev ⁴⁾ uses dispersion relations and PCAC and finds for the π^- values of a factor 2 to 4 larger than the estimate (8).

Apart from the hadronic atoms, the structure constants α_N and α_H could in principle be measured in any experiment which subjects the system to low frequency electromagnetic fields. An example is low frequency Compton scattering, in which the photons act as a quasistatic external electromagnetic field. The ω^2 term (the Rayleigh term) for elastic scattering depends on the polarizability α . In this way the proton polarizability has been measured directly, using 70 MeV photons ⁵⁾:

$$\alpha_p = (9 \pm 2) 10^{-4} \text{ fm}^3. \quad (9)$$

We know of no corresponding direct measurement of the nuclear polarizability ^{*)}.

Another way of obtaining information on the polarizability with photons is by dispersion relations. In the long wave-length limit α_N satisfies the following special case of a more general dispersion relation:

*) Indirect measurements exist, however, in a few cases. The nuclear polarizability modifies the Coulomb excitation cross-sections as a small perturbation and it is possible to extract a value for α_N in special cases ⁶⁾.

$$\alpha_N = \frac{1}{2\pi^2} \int_0^\infty \frac{\sigma_{E1}(\omega)}{\omega^2} d\omega \quad (10)$$

where σ_{E1} is the total E1 photo-nuclear cross-section to order e^2 . This integral can be evaluated using the experimental total photo-nuclear cross-sections. These are dominated by their low energy part, including the E1 giant resonance, but they also contain minor contributions from other multipoles. In this way one obtains an approximate average value ⁷⁾

$$\alpha_N \approx 3.2 \cdot 10^{-3} A^{5/3} \text{ fm}^3 \quad (11)$$

The value is about 25% higher than the estimate (7). For individual nuclei heavier than Argon, it is accurate to about 20%.

The relative size of the hadronic and nuclear polarization shifts in atoms follows directly from these considerations. We use the proton polarizability as typical of that of a hadron, in general. We have then, from Eqs. (9) and (11)

$$\frac{\Delta\epsilon_{\bar{p}}}{\Delta\epsilon_N} = \frac{Z^2 \alpha_p}{\alpha_N} \approx \frac{1}{3} \frac{Z^2}{A^{5/3}}$$

This ratio is, in practice, nearly independent of Z and A , and it is of order 0.3. The antiproton polarization shift is therefore nearly as large as the nuclear shift. Provided the polarization shift is so large as to be observable, it may thus be possible to extract both hadron polarizabilities and nuclear polarizabilities by an appropriate analysis.

The possibility of observation is determined by the magnitude of the polarization shift. Using the dispersion estimate (11) for α_N the nuclear shifts are given in Fig. 1 for the relevant orbits of antiprotonic atoms. The effect is typically of order 10^{-4} of the transition energies. In the "critical orbit", i.e., the orbit from which the antiproton is removed by strong interactions, the shifts are characteristically between 20 and 50 eV. The strong interaction shift is proportional to the probability of finding the hadron inside the nucleus and it vanishes very rapidly for higher states. In the "critical orbit" the strong interaction shift is still comparable to that of the polarization shift, but already in the next higher orbit its influence is negligible. It should be noted that the polarization shift is the dominant nuclear effect in high orbits.

The main other contribution to the energy shifts in these orbits (apart from pure quantum electrodynamic corrections) is due to electron screening. This effect increases in importance as the atomic orbits become larger and is typically of order 50 eV in the critical orbit. The uncertainty in this term has two sources : a) the uncertainty in the population of the electron states which have been perturbed by the X-ray cascade of hadron, which at present leads to an uncertainty of 10-20% in the screening shift. b) the contribution to the screening shift due to the polarization of the electron cloud by the hadronic Bohr atom [about 2% of the total screening shift ⁷⁾]. The screening corrections have as yet not been carefully investigated experimentally in the higher orbits, where they give rise to much larger shifts. The uncertainties from this source will very likely be significantly reduced in the future.

We therefore conclude that the polarization shift occurs on the level of experimental precision currently used for precise mass measurements and quantum electrodynamic tests in exotic atoms, so that its experimental study is within reach. Corrections from other sources are understood and controllable.

At this point it is appropriate to question the accuracy of the simple formula (6) for the polarization shift, which is the basis of our discussion. We show rigorously in a forthcoming paper ⁷⁾ that for circular orbits of $n \gtrsim 5$, this expression is accurate to a few per cent or better. In particular, the quasistatic limit becomes very accurate for high orbits. Further, higher multipole polarizabilities (E2, E3, M1, etc.) give small contributions but for accidental degeneracies. There is thus excellent reason to believe that polarizabilities can be correctly extracted from observed shifts. The situation is thus quite different from the polarization shifts in low-lying orbits of muonic atoms ⁸⁾.

The direct determination of α_N and α_H would be very interesting. In the nuclear case the dispersion relation (10) has never been tested to our knowledge. Apart from the case of the proton nothing is known about the polarizabilities of the hadrons. For example, it is unknown whether the kaon or pion is "softer" than the nucleon, as suggested in several recent papers ¹⁾⁻⁴⁾. Exotic atoms provide a unique way to determine their polarizability.

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FIGURE CAPTION

Nuclear polarization shifts for antiprotonic atoms, as a function of Z . The dashed end of each curves indicates the region where strong absorption from this orbit is the dominant process.