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NEUTRON-PROTON MASS DIFFERENCE IN NUCLEI IN A RELATIVISTIC HARMONIC QUARK MODEL

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SUMMARY:

The nuclear dependence of the neutron-proton mass difference is examined in a relativistic harmonic quark model with the assumption of a swelling of the individual nucleon originated by a decrease of the spring constant inside the nuclear medium. A decrease of the neutron-proton mass difference is obtained which is reasonably small and in the right direction to cope with the Nollen-Schiffer anomaly in mirror nuclei.

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This note is concerned with the neutron-proton (n-p) mass difference in the nuclear medium and is motivated by a recent discussion[1] of the problem in the framework of several models for the nucleon which incorporate relativistic kinematics. The aim of Ref. [1] was to investigate the relevance of those models for a possible explanation of the Nollen-Schiffer (NS)[2,3] anomaly which, as is well-known, is a persistent discrepancy between the experimental and theoretical values of the binding energies of mirror nuclei i.e isobaric pairs (Z,N) and (N,Z) with $Z = \frac{(A+1)}{2}$ and $N = \frac{(A-1)}{2}$. In fact, it turns out that the observed mass differences are systematically larger than the theoretically

calculated ones. The discrepancy (i.e the NS anomaly) increases with the mass number A and amounts to about[3] 0.700 MeV for ^{208}Pb.

On the other hand, in a previous work[4], Palladino and the present author presented a detailed analysis of the mass difference of light hadron isomultiplets based on a relativistic independent, harmonic quark model[5], implemented by center-of-mass, one-gluon exchange, electromagnetic and pion-cloud corrections. In particular, they showed that the n-p mass difference arises almost completely, due to several cancellations (such as $\Delta W_\pi(p) \simeq \Delta W_\pi(n)$ for the pion-cloud effect) from the difference of the Dirac energies W_i of the quarks involved, with $m_d > m_u$ and $R_d < R_u$, where m denotes the quark mass and R, the *"Gaussian"* radius of the light quark (u,d) which parametrizes the single-quark wave function in the present harmonic model.

In this context, each quark in the nucleon obeys a Dirac equation[5] ($\hbar = c = 1$)

$$\left[\alpha\, p + \beta\, m_i + \frac{1}{2}\left(1 + \beta\right)\left(V_0 + \frac{1}{2} K r^2\right)\right]\psi_i\left(\underset{\sim}{r}\right) = W_i \psi_i\left(\underset{\sim}{r}\right) \qquad (1)$$

where $\underline{i}$ is the quark-flavour index ($\underline{i}$ = u.d).

For the S-wave ground state, Eq. (1) is exactly solvable. The corresponding energy eigenvalue is given by

$$W_i = \frac{1}{2}\left\{V_0 + \left[\left(2m_i + V_0\right)^2 + \frac{12}{R_i^2}\right]^{1/2}\right\}. \qquad (2)$$

In the Eq. (2), the Gaussian radii R_i are related to the spring-constant K by

$$R_i = \left[\frac{2}{(W_i + m_i)K}\right]^{1/4}. \qquad (3)$$

On the other hand, by the Feynman-Hellmann theorem[6], one gets from Eq. (1)

$$\frac{\partial W_i}{\partial K} = \langle \psi_i | \frac{\partial H}{\partial K} | \psi_i \rangle = \frac{3}{2} R_i^2 N_i^2 > 0 \qquad (4)$$

where N_i is the normalization constant of the ground-state solution. Eq. (4) shows that W_i is a monotonic increasing function of K. Hence, from Eq. (3), it is clear that R_i is a monotonic decreasing function of K. This result will give us the dynamical reason for the swelling of the individual nucleon inside the nucleus, assumed in this note.

We note that the idea of swelling of the nucleon inside the nucleus has been put forward in the literature in connection either with the EMC effect[7] or the NS anomaly[8-10].

The n-p mass difference in free space, $\delta_{np} = M_n - M_p$, in the above described approximation[4] is given by $\delta_{np} = M_n(ddu) - M_p(uud) = W_d - W_u$.

In the nuclear medium, on the other hand, we assume that a <u>swelling</u> of the individual nucleon takes place, described by a small increase of the Gaussian radii $\delta R_i = R_i + \delta R$ ($\underline{i}$ = u,d). Defining Δ_{np} as

$$\Delta_{np} = W_d\left[m_d,\ R_d + \delta R\right] - W_u\left[m_u,\ R_u + \delta R\right]$$

and developing it to first order in δR, one gets, using Eq. (2)

$$\Delta_{np} = \delta_{np} - 12\left[\frac{1}{(W_d R_d)}\frac{1}{R_d^2} - \left[d \rightarrow u\right]\right]\delta R + \ldots \qquad (5)$$

In Eq. (5), Δ_{np} clearly represents the n-p mass difference inside the nucleon. Setting $p = \frac{\delta R}{R_0}$, where R_0 is the Gaussian radius of the quark-core[10] in the model, we get

$$\delta_{np} - \Delta_{np} \simeq 7.016\ p\ (\mathrm{MeV}). \qquad (6)$$

In obtaining Eq. (6), the values of Ref. [4] (with V_0 = 71 MeV,

R_0 = 0.58 fm, K = 42.31 × 10^8 MeV^3) were used, namely m_u = 5.3 MeV, R_u = 0.5805 fm and m_d = 8.7 MeV, R_d = 0.5785 fm. Making use of the data for ^{208}Pb given in Ref. [3], we get from Eq. (5), for the NS anomaly a_{NS}

$$a_{NS} \equiv \delta_{np} - \Delta_{np} \lesssim 0.7\ \mathrm{MeV} \qquad (7)$$

which implies $p \leq 0.1$, corresponding to reasonably small values for the swelling fraction p. Furthermore, if we assume for p a linear dependence in $A^{-1/3}$, we get with the help of Table XI of Ref. [3] for the mirror pairs C-N and Ca-Sc, the result

$$a_{NS} = 1.494 - 3.017\ A^{-1/3}, \qquad (8)$$

showing an increase with the mass number.

In conclusion, we note that in the present model the n-p mass difference decreases in the nuclear medium, a result which is in the right direction at least to reduce the NS anomaly. Finally, it should be emphasized that in the present work, the isospin is broken not only through $m_d > m_u$ but <u>also</u> through $R_d < R_u$, in constrast to what occurs, for instance, in Ref. [8] where the isospin breaking is due to the difference $m_d - m_u$ only.

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