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Lambda-nucleus versus nucleon-nucleus potential

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Abstract. We are exploring a plausible mechanism why the Λ hyperon feels twice weaker mean field of a nucleus (∼ -27 MeV) compared to a nucleon (∼ -50 MeV).

1 Introduction

The depth of the potential which the Λ baryon is feeling in the nucleus is surprisingly independent of the nucleus in the whole region from the light to the heavy nuclei. Its value -27 MeV has been deduced from the $\pi^+ + A \rightarrow K^+ + {}_\Lambda A$ experiments. This number should be compared to the potential depth for the nucleon in the nucleus of about -50 MeV. The nuclear potential for the nucleons is less accurate than that for Λ because it cannot be measured for strongly bound nucleons. In fact, the Λ baryon in a nucleus is the best demonstration of the nuclear potential well.

2 Asumptions

1. The mean field of an isospin symmetric nucleus consists of an attractive σ-field and a repulsive ω-field. The former is a Lorentz scalar and the latter is a zero-component of a Lorentz four-vector.
2. We represent σ as a two-pion system and ω as a three-pion system.
3. Both fields are coupled to the probe (Λ or N) via pions.
4. Pions are coupled directly to quarks and not to an "elementary" baryon.
5. The strange quark has no pion cloud and no pion coupling.
6. We assume that the dominant "pion cloud" can be written as s one-pion and two-pion admixtures to bare quarks. The corresponding amplitude squared $a \approx 0.18$ has been determined from several nucleon observables in our previous papers [1–4] describing constituent quarks u and d as composites of bare quarks **u**, **d** and pions:

$$|u\rangle = \sqrt{(1 - \frac{3}{2}\,a - -\frac{3}{2}\,a^2)}\,|\mathbf{u}\rangle - \sqrt{a}|\mathbf{d}\pi^+\rangle + \sqrt{\frac{a}{2}}\,|\mathbf{u}\pi^0\rangle + a\,|\mathbf{u}(\pi^+\pi^- - \pi^0\pi^0/\sqrt{2})\rangle,$$

$$|d\rangle = \sqrt{(1 - \frac{3}{2}\,a - -\frac{3}{2}\,a^2)}\,|\mathbf{d}\rangle + \sqrt{a}\,|\mathbf{u}\pi^-\rangle - \sqrt{\frac{a}{2}}\,|\mathbf{d}\pi^0\rangle + a\,|\mathbf{d}(\pi^+\pi^- - \pi^0\pi^0/\sqrt{2})\rangle.$$

7. The coupling constant to the effective two pion fluctuation was assumed to be the square of the coupling constant for the single pion

3 The σ-field

The σ-field is proportional to the coupling of the two pions to quarks. Since we consider the ratio between the Λ-nucleus potential and the N-nucleus potential, rather than their absolute values, the proportionality constant cancels.

3.1 One-pion admixtures

The contribution comes from two different quarks. The probe (proton or neutron) feels the σ-part of the potential proportional to the amplitude

$$A^{N}_{\sigma,1} = \langle p\sigma|p\rangle = \langle p(\sqrt{\tfrac{2}{3}}\pi^{+}\pi^{-} - \sqrt{\tfrac{1}{3}}\pi^{0}\pi^{0})|p\rangle = -(\sqrt{\tfrac{2}{3}} - \tfrac{1}{2}\sqrt{\tfrac{1}{3}})\,(1 - \frac{3}{2}\,a - \frac{3}{2}\,a^{2})\,a = -0.064.$$

It is interesting that the probe Λ feels the same amplitude $A^{\Lambda}_{\sigma,1} = A^{N}_{\sigma,1}$! It is also interesting to note that this contribution, though small, is repulsive.

3.2 Two-pion admixtures

In this case, the contribution comes only from the same quark. Since the two-pion dressing of each quark is isoscalar, the u and d quarks contribute the same amplitude, and the s quark contributes nothing. Therefore Λ feels onli 2/3 of this contribution compared to the nucleon.

$$A^{N}_{\sigma,2} = 3 \times \sqrt{\tfrac{2}{3}}\sqrt{(1 - \frac{3}{2}\,a - \frac{3}{2}\,a^{2})}\,(a + \tfrac{1}{2}a) = 0.546\,,$$

$$A^{\Lambda}_{\sigma,2} = 2 \times \sqrt{\tfrac{2}{3}}\sqrt{(1 - \frac{3}{2}\,a - \frac{3}{2}\,a^{2})}\,(a + \tfrac{1}{2}a) = 0.364\,.$$

The total contribution is then

$$A^{N}_{\sigma} = A^{N}_{\sigma,1} + A^{N}_{\sigma,2} = 0.482\,, \qquad A^{\Lambda}_{\sigma} = A^{\Lambda}_{\sigma,1} + A^{\Lambda}_{\sigma,2} = 0.300\,.$$

4 Discussion

The nuclear binding is a fundamental question of the nuclear physics and requires a proper explanation.

In the early days of the hypernuclear spectroscopy Dalitz and von Hippel [5] suggested that the Λ may be contaminated by an admixture of the Σ plus pion. More recently, excited states of several light hypernuclei have been studied by the gamma spectroscopy. In the present analysis of the excited states in the light hypernuclei the admixture of a Σ in the Λ has been estimated to be less than

1% [6]. Therefore the two pion exchange via virtual Σ cannot be the explanation of the large Λ binding in the nucleus. Consequently also the two pion exchange via the virtual delta excitation is not very likely the proper explanation of the nucleon binding in the nucleus.

In the present paper we discuss a model which gives a proper ratio of the two bindings, for the nucleon and for the Λ. The two-pion admixtures suggest the ratio between the Λ-nucleus potential and the N-nucleus potential around 2/3. There is a slight destructive interference between two-pion and one-pion contributions which brings the Λ/N ratio from 2/3 sligtly towards 1/2 , but not enough. The contribution of the repulsive ω-field turns out to be small in the proposed model and we ignore it.

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Kvarkovski propagator v coulombski umeritvi kvantne kromodinamike

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Proučujemo kvarkovski propagator na konfiguracijah gašenega umeritvenega polja v coulombski umeritvi. Pri tem uporabimo kiralno simetrične "prekrivalne fermione". V tej umeritvi lahko povežemo "funkcijo oblačenja" kvarkovskega propagatorja s priporom in kiralno simetrijo kromodinamike. Pripor lahko pripišemo infrardeče divergentni vektorski "funkciji oblačenja". Izvrednotimo "funkcije oblačenja" kvarkovskega propagatorja, razberemo dinamično maso kvarka in ekstrapoliramo vse te količine proti kiralni limiti. Končno razpravljamo, kako se odstranijo nizke Diracove ekscitacije.

Mase oblečenih kvarkov in barionska spektroskopija

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Prikažemo hierarhijo mas oblečenih kvarkov, ki prevladujejo v efektivnih modelih kvantne kromodinamike, zlasti v relativističnem modelu z oblečenimi kvarki. Opazimo, da je presežek dinamično generirane mase nad golo maso bolj ali manj neodvisen od okusa kvarkov in znaša $\Delta m \approx (370 \pm 30)$ MeV. Podobne vrednosti dajo tudi alternativni efektivni opisi barionske spektroskopije, na primer Dyson-Schwingerjev pristop.

Primerjava jedrskih potencialov za hiperon Lambda in za nukleon

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Raziskujeva verjetni mehanizem, zakaj čuti hiperon Λ dvakrat šibkejše jedrsko polje (okrog −27 MeV) kot nukleon (okrog −50 MeV).