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Short Note

Flavour asymmetry of anti-quarks in nuclei

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Abstract. A novel nuclear effect on the flavour asymmetry of anti-quarks in the nucleon bound in a nucleus is discussed in terms of the meson cloud model and the Pauli exclusion principle. It is expected that the flavour asymmetry is enhanced in a nucleus.

PACS. 13.60.Hb Total and inclusive cross sections (including deep-inelastic processes) – 21.90.+f Other topics in nuclear structure (restricted to new topics in section 21)

It is rather surprising that the distribution of $\bar{u}$ is different from that of $\bar{d}$ in the free proton (p) because those distributions are expected to be almost flavour symmetric within perturbative quantum chromodynamics (pQCD). The measurement of the flavour nonsinglet structure function, $F_2^p(x,Q^2) - F_2^n(x,Q^2)$, where $F_2^{p(n)}(x,Q^2)$ is the proton (neutron (n)) structure function, performed by the New Muon Collaboration (NMC) [1] led to a large ($\sim$ 30%) violation of Gottfried sum rule (GSR), which implies that the distribution of $\bar{d}$ overcomes that of $\bar{u}$ in p. Later, this was confirmed by the Drell-Yan and semi-inclusive measurements of NA51 [2], E866 (NuSea) [3] and HERMES [4] collaborations.

So far, various models have been proposed to understand the flavour asymmetry in p. Among those, the meson cloud model [5,6] is successful in explaining the observed results. The physical proton contains many virtual meson-baryon components, and the valence anti-quark in the meson can contribute to the anti-quark distributions in the proton sea

$$\begin{aligned} |p\rangle_{\text{phys}} = Z^{1/2}|p\rangle_{\text{bare}} + f_{\pi^0 p}|\pi^0\rangle|p\rangle_{\text{bare}} + f_{\pi^+ n}|\pi^+\rangle|n\rangle_{\text{bare}} \\ + f_{\pi^- \Delta^{++}}|\pi^-\rangle|\Delta^{++}\rangle_{\text{bare}} + \cdots, \end{aligned} \tag{1}$$

where $Z^{1/2}$ is the renormalization constant for the wave function, f_{MB} stands for the amplitude of Fock component containing a meson $M(=\pi,\rho,\cdots)$ and a baryon $B(=p,n,\Delta,\cdots)$, and $|B\rangle_{\text{bare}}$ is the bare baryon state. Note that the pion cloud provides the largest contribution because of its small mass. Since the probability of the π^+-n Fock component is larger than that of the π^--Δ^{++} state in p, a surplus of $\bar{d}$ is naturally explained in the meson cloud model.

An alternative explanation for an excess of $\bar{d}$ over $\bar{u}$ in p involved the Pauli exclusion principle at quark level [6], given that there are two valence u quarks in the proton and one valence d. In a model such as the bag model, where the quarks are confined by a scalar potential, the vacuum inside a hadron is different from the vacuum outside. This manifests itself as a distortion in the Dirac sea, which is full outside, whereas there will be empty states inside the hadron. To an external probe this change in vacuum structure appears as an intrinsic, nonperturbative sea of $q\bar{q}$ pairs even in the bare proton state (see eq. (1) and ref. [7]). Hence, because of Pauli blocking the presence of a valence quark in the hadron ground state lowers the probability of a negative-energy state being empty, which is the same as lowering the probability of finding a positive-energy anti-quark. If the number of valence u quarks is equal to that of d quarks in the hadron ground state, no flavour asymmetry appears. However, as the proton consists of two valence u and one valence d quarks, the asymmetry is realized and it is expected to be $\bar{d}/\bar{u} \sim 5/4$ from a naive counting estimate in the free proton [6]. It may well be that the experimentally observed excess involves contributions from both of those effects.

It is a very interesting problem to see how the flavour asymmetry changes in a nucleus. Such a study would give us more information on the nonperturbative structure of the nucleon. Recently, we have proposed [8–10] that the flavour asymmetry in a nuclear medium can be investigated by measuring the nonsinglet difference between structure functions of a pair of mirror nuclei (A, A'), where $A = Z + N (Z > N)$ (proton rich) and

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$A' = Z' + N'(N' > Z')$ (neutron rich) with Z the proton number and N the neutron number.

How is the meson field modified in a nucleus? To consider it we concentrate here on only Fock states involving the bare nucleon and pion. (See again eq. (1). The admixture of π-N component in the physical proton is about 20%, while those for ρ-N and π-Δ are, respectively, about 10% and 5% [6].) First, we suppose that there is *no* charge symmetry breaking (CSB) in a nucleus. Then, in the proton-rich nucleus A the virtual emission of $\pi^-(\bar{u}d)$ from a neutron ($n \to \pi^- + p$) is *more suppressed* than the $\pi^+(u\bar{d})$ from p ($p \to \pi^+ + n$) because of the Pauli-blocking effect on the proton in the final state. On the contrary, in A' (neutron rich) the π^+ emission is more suppressed than the π^- emission. Note that from the point of view of Pauli blocking the π^0 field is not changed a great deal in a nucleus.

This effect is quite similar to the Pauli exclusion effect at quark level for the free proton. Usually a nucleus can be regarded as a sum of a closed-shell, core nucleus and some valence nucleons. If we treat the core nucleus as a new vacuum, the difference between the numbers of valence p and n decides how the individual pion field in isospin space is modified in the nucleus.

Taking the flavour nonsinglet combination of the structure functions, *i.e.*, $F_2^A(x) - F_2^{A'}(x)$, one can study the flavour asymmetry in the *bound* proton and neutron. Because of the Pauli exclusion principle at hadron level, the flavour asymmetry in the bound proton is expected to be more enhanced than that for the free proton: $(\bar{d} - \bar{u})_{\rm bound} > (\bar{d} - \bar{u})_{\rm free}$. This is a novel nuclear effect on the flavour asymmetry of the anti-quarks, in addition to the asymmetry observed in free space. Note that if the number of valence p is identical to that of n, the present asymmetry vanishes.

It is not allowed to ignore the effect of CSB (mainly Coulomb effect) in reality. Owing to the Coulomb repulsion the energy levels for the protons are slightly shallowed, which helps to enhance the virtual emission of π^+ from a proton in A. In A' this effect acts on the π^- emission (from a neutron) oppositely. However, for light (stable) nuclei the Coulomb effect on the pion emission may be small, compared with the Pauli-blocking effect discussed above.

There is an anticipated possibility of finding exotic configurations, such as 6-quark states in a nucleus. As a consequence, the effect of the Pauli exclusion principle at quark level is different from that for the free proton. In A (proton rich) the possibility of finding a 6-quark state created from two protons [11] would be larger than that of a two-neutron 6-quark state. In such a case, 4 valence u and 2 valence d quarks are supposed to be put into one confining potential. The naive counting estimate then gives $\bar{d}/\bar{u} \sim 2$ in the two-proton 6-quark state. In A' the opposite situation would occur. Hence, we again expect that the excess of $\bar{d}$ over $\bar{u}$ is enhanced in the proton bound in A.

Experimentally there is *only* one pair of *stable* mirror nuclei, that is, ^{3}He-^{3}H. In our recent work [10] we have discussed this $A = 3$ system and reported that the change of the pion fields leads to an enhancement of the asymmetry, which predicts a reduction of the (nuclear) GSR by about 10% compared with the GSR value in free space. The pair of ^{7}Li-^{7}Be is the next candidate, but unfortunately ^{7}Be is unstable although its half-life time is long (53 days). For other candidates one can find several pairs of mirror nuclei. But, because of short half-life times, it is nearly impossible for the present to measure those structure functions with fixed-target experiments.

If deep-inelastic scattering with high-energy electrons (or muons) off *unstable* nuclei is realized by using a collider machine [12] in the future, available mirror pair would be widely extended [13] and we could measure structure functions of unstable nuclei systematically [14].

In particular, a nucleus, which is in the vicinity of the neutron or proton drip line, is quite interesting —such a nucleus is sometimes called a halo nucleus. For a stable nucleus ($Z \approx N$) the potentials for protons and neutrons are almost the same except that the protons see a shallower potential due to the Coulomb effect. As a number of neutrons increases and hence the nucleus is closer to the neutron drip line, the potential felt by protons becomes deeper because of an attractive p-n interaction. This phenomenon leads to an enhancement of the π^- emission from a neutron in such a (neutron-rich) halo nucleus (A'). On the contrary, in a (proton-rich) halo nucleus (A) the π^+ emission from p is enhanced due to the Coulomb effect (as discussed above). Hence, the flavour symmetry of anti-quarks in the proton bound in an unstable, proton-rich nucleus would be more broken compared with the case of stable one. At present, we can find two candidates for mirror nuclei with halos: (^{8}B-^{8}Li) and (^{17}Ne-^{17}N) [13].

It is very interesting to study the flavour asymmetry in the spin structure function. Recently several people have calculated the polarized anti-quark distributions in the meson cloud model [15,16]. It is clear that the ρ-meson plays an important role in the spin structure function, but the situation seems to be still confusing about how it contributes to the spin asymmetry [15,16]. In the meson cloud model, as in the case of the pion field, the $\rho^+(\rho^-)$ emission from a proton (neutron) in $A(A')$ would be more enhanced than that in free space. Therefore, the flavour asymmetry in the spin asymmetry, $\Delta\bar{d} - \Delta\bar{u}$, is again expected to be enhanced in the proton bound in A. However, Cao and Signal [16] have reported that in the free proton the Pauli-blocking effect at quark level has an opposite sign to the ρ-meson contribution and that its magnitude is much larger than the meson cloud effect. Thus, in the case of spin-dependent nuclear-structure functions it would be difficult to measure an enhancement of the flavour asymmetry caused by the change of the ρ fields in nuclei. Nevertheless, it is very intriguing to study the Bjorken sum rule for a pair of mirror nuclei (see, for example, ref. [17]).

So far, we have restricted ourselves to only Fock states containing the nucleon and pion in the meson cloud model. We have then found that the Pauli-blocking effect plays an important role in the process of a virtual pion emission in a nucleus. Since Δ is not affected at all by the Pauli blocking at hadron level, Fock states containing Δ would not modify the asymmetry in a nucleus. However, the nuclear medium effect through the Δ-hole excitation would change the pion fields [18] although such an effect may not be large in light nuclei (like $A = 3$ or 7 system).

In this short note we have considered the nuclear effect on the flavour asymmetry of anti-quark distributions in a bound nucleon in terms of the meson cloud model and the Pauli exclusion principle. It is expected that the flavour asymmetry is enhanced in a nucleus.

References

1. NMC collaboration (P. Amaudruz et al.), Phys. Rev. Lett. **66**, 2712 (1991); M. Arneodo et al., Phys. Rev. D **50**, R1 (1994).
2. NA51 collaboration (A. Baldit et al.), Phys. Lett. B **332**, 244 (1994).
3. NuSea collaboration (J.C. Peng et al.), Phys. Rev. D **58**, 092004 (1998); R.S. Towell et al., Phys. Rev. D **64**, 052002 (2001).
4. HERMES collaboration (K. Ackerstaff et al.), Phys. Rev. Lett. **81**, 5519 (1998).
5. A.W. Thomas, Phys. Lett. B **126**, 97 (1983).
6. S. Kumano, Phys. Rep. **303**, 183 (1998); J. Speth, A.W. Thomas, Adv. Nucl. Phys. **24**, 83 (1998); R. Vogt, Prog. Part. Nucl. Phys. **45**, S105 (2000).
7. A.I. Signal, A.W. Thomas, Phys. Rev. D **40**, 2832 (1989); A.W. Schreiber, A.I. Signal, A.W. Thomas, Phys. Rev. D **44**, 2653 (1991); M. Wakamatsu, Phys. Rev. D **46**, 3762 (1992); D. Diakonov et al., Nucl. Phys. B **480**, 314 (1996); P.V. Pobylitsa et al., Phys. Rev. D **59**, 034024 (1999).
8. K. Saito, C. Boros, K. Tsushima, F. Bissey, I.R. Afnan, A.W. Thomas, Phys. Lett. B **493**, 288 (2000).
9. V. Guzey, K. Saito, M. Strikman, A.W. Thomas, K. Tsushima, Phys. Rev. D **64**, 054503 (2001).
10. K. Saito, V. Guzey, K. Tsushima, A.W. Thomas, Phys. Lett. B **517**, 93 (2001).
11. H. Sato, K. Saito, Phys. Rev. Lett. **50**, 648 (1983); K. Saito, Prog. Theor. Phys. **72**, 674 (1984).
12. See, for example, MUSES project at RIKEN, `http://www.rarf.riken.go.jp`; eRHIC project at BNL, preprint hep-ph/0102087; THERA project at DESY, `http://www.desy.de/html/home/index.html`.
13. I. Tanihata, Nucl. Phys. A **654**, 235c (1999).
14. K. Saito, M. Ueda, K. Tsushima, A.W. Thomas, preprint nucl-th/0110024.
15. R.J. Fries, A. Schäfer, Phys. Lett. B **443**, 40 (1998); S. Kumano, M. Miyama, preprint hep-ph/0110097.
16. F.-G. Cao, A.I. Signal, Eur. Phys. J. C **21**, 105 (2001).
17. F. Bissey, V. Guzey, M. Strikman, A.W. Thomas, preprint hep-ph/0109069.
18. C.L. Korpa, A.E.L Dieperink, Phys. Lett. B **446**, 15 (1999).