Nuclear Isospin Violation — How It Turned out and Where It Is Going

Gerald A. Miller

Physics Department, Box 35-1560, University of Washington, Seattle, WA 98195-1560

Abstract

Nuclear isospin violation is reviewed, with emphasis on nucleon-nucleon scattering. The use of the term charge symmetry breaking and its implications are reviewed. Recent work on charge symmetry breaking in the nucleon electromagnetic form factors is outlined.

Keywords: *Charge independence; charge dependent forces; charge symmetry breaking*

1 Introduction

I was very happy to attend this NTSE conference in honor of James P. Vary. I first met James at MIT in the 1970's. I was a graduate student, working with Arthur Kerman and James was a post-doc in the Center for Theoretical Physics.

My Ph. D. project was to understand the formation and decays of double isobaric analog states in the reactions of protons with heavy nuclei. Isobaric analog states are isospin partners (members of the same multiplet) of stable nuclei that are in the continuum. A double analog states differs by two units of T_z from the stable state. My problem was that I could not find a sizable contribution. James made the brilliant suggestion that I should include pairing contributions in ^{210}Po. This enhanced the formation matrix element by a factor of 7. I was able to graduate and I am forever grateful to James Vary.

2 Next steps

Interest in isobaric analog states decayed and the focus changed to isospin violating nucleon-nucleon forces and their consequences in few-body nuclear reactions. It seems appropriate to comment in the present venue that the computational tools discussed at NTSE can lead to a much better treatment of nuclear isospin violations than in the days of my thesis. For example, in my opinion, the computations of the rate for nuclear super allowed beta decay, used to test the unitarity of the CKM matrix, could be improved [1, 2].

A particular focus is charge symmetry (CS) and its breaking. CS is invariance under a rotation in isospin space of π about the y axis. For example, a u quark is rotated into a d quark. CS is broken slightly by the light-quark mass difference and by electromagnetic effects. Isospin invariance or $[H, \vec{T}] = 0$ is invariance under all rotations in isospin space. This invariance is also called charge independence (CI), which refers to invariance amongst states with the same isospin quantum number. Charge symmetry does not imply isospin invariance. Various aspects of charge symmetry and its breaking have been reviewed, see, e. g., [3–6].

Proceedings of International Conference 'Nuclear Theory in the Supercomputing Era — 2013' (NTSE-2013), Ames, IA, USA, May 13–17, 2013. Eds. A. M. Shirokov and A. I. Mazur. Pacific National University, Khabarovsk, Russia, 2014, p. 73.
http://www.ntse-2013.khb.ru/Proc/Miller.pdf.

For example, the mass difference between charged and neutral pions exchanged between nucleons leads to forces that violate CI but not CS. This leads to a difference between ${}^1S_0$ scattering lengths for the np and nn systems. The Henley & Miller classification scheme is reviewed in the Appendix.

In general the size of CSB effects is much smaller than the breaking of isospin invariance, CIB. The scale of CSB is typified by the ratio of the neutron-proton mass difference to the proton mass which is about one part in 1000. This is much smaller than the pion mass difference effect which is one part in 27. The CIB of nucleon-nucleon scattering lengths was discovered well before 1965, but the measurement of their CSB had to wait until about 1979. Thus the expectation is that CSB is a small effect, uncovered only with special effort. The small relative size of CSB effects compared with those of CIB is a consistent with the power counting of of chiral perturbation theory [7].

3 Highlights since 1972

I summarize the progress. Measurements of the $\pi^- d \to nn\gamma$ cross section showed that the ${}^1S_0$ nn force is more attractive than the pp force. As a result the Nolen–Schiffer anomaly was explained. Charge symmetry breaking was observed in np elastic scattering [8–13], the reaction $np \to d\pi^0$ [14], and in the observation of the reaction $dd \to \alpha\pi^0$ [15]. More detail is presented in the reviews mentioned above.

4 Parity violating electron scattering and strangeness electromagnetic nucleon form factors

This subject formed the bulk of the talk. I will only explain the basic idea and an outline of the result here because the subject has already been written up as another conference proceeding [16].

The basic idea is that parity violating (PV) electron-proton scattering is sensitive to nucleon strangeness content [17], and also the value of the weak-mixing angle [18]. So far a convincing signal for strangeness in the nucleon has not been seen.

The relevance of charge symmetry or its breaking to PV electron scattering on the proton arises from the need to relate the amplitude for Z-boson absorption on the proton to measured proton and neutron electromagnetic form factors. This can be done if charge symmetry holds.

The breaking of charge symmetry brings in a correction that cannot be obtained directly from experimental observations [19–21]. The key question is whether the uncertainty in obtaining the correction is large compared to current and projected experimental uncertainties. Experimentalists have stated that charge symmetry is now limiting the ability to push further on the strange form factors because results obtained with improved precision would be hard to interpret cleanly in terms of strangeness or CSB.

We have addressed the question of whether or not CSB really limits the ability to push further. I wrote a paper in 1997 finding that the CSB corrections are less than 1% of the size of the electromagnetic form factors G_E, G_M [20]. When re-expressed in terms of absolute values of charge symmetry breaking form factors, the results were very small of order 2×10^{-3}. This is small enough to ignore.

However, I had ignored the effect of charge symmetry breaking arising from the influence of the neutron-proton mass difference on the pion cloud of the nucleon. This effect was included by Kubis & Lewis [21]. The effects are not small because of a log divergence in the loop integrals. In their resonance-saturation procedure the pion graph is cut off at the mass of the rho meson and rho-omega mixing graphs provide a finite counter term. The resulting effects can be very large and have much uncertainty.

The result, the charge symmetry breaking magnetic form factor ranges between 0.01 and 0.04, or about 10 times larger than my result. There is also a large uncertainty in the results due to lack of knowledge of the ω nucleon strong tensor coupling.

Kubis & Lewis [21] take the strong coupling constants from dispersion analyses of electromagnetic form factors based on vector meson dominance. Such fits are well known to be flexible. The strong coupling constants for omega-nucleon coupling are about seven times larger than used in NN scattering. So there is a conflict.

How can we tell which method (or if either method) is correct? One answer is that the effects of rho-omega mixing in nucleon-nucleon scattering is constrained. It is known to give a medium range class III CSB potential (see the Appendix for terminology) that can account for the scattering length difference between nn and pp systems [4, 22], and a class IV CSB potential that plays an important role in understanding CSB in np scattering. The class III potential accounts for the missing binding energy difference between ^{3}He and ^{3}H [23] and also the Nolen–Schiffer anomaly [24], see the review [5]. The use of the KL coupling constants gives potentials that are rather different than the one [23] needed phenomenologically.

We (student M. Wagman has joined me) have made new calculations of the CSB form factors using relativistic chiral perturbation theory. The use of relativistic chiral perturbation theory leads to finite and convergent results. The preliminary results are that the charge symmetry breaking form factors are very small.

5 Tasks ahead

One should use a model that describes $G_{E,M}$ well in the absence of CSB, and then use those models as a basis for CSB computations. One candidate model is that of Cloet & Miller [25].

More generally, I wish to address a bias. I did a quark *model* calculation. Kubis & Lewis did a chiral perturbation *theory* calculation. One usually thinks that a theory is better than a model. However, if an unconstrained counter term is needed to evaluate the theory, then the model is quite close to a theory.

6 Summary

I obtained small < 0.002 CSB effects in 1998. Kubis & Lewis (KL) obtained a range of about 0.04. However CSB in NN scattering constrains the strong coupling constants used in the KL resonance saturation calculation. The actual size of the CSB effect seems pretty small.

7 Acknowledgments

This work has been partially supported by U.S. DOE Grant No DE-FG02-97ER-41014.

8 Appendix

We review the CSB and CIB terminology of nucleon-nucleon forces [3].

Class (I): Forces which are isospin independent that commute with all components of the isospin operator. Such forces, V_I have an isoscalar form,

$$V_I = a + b\,\vec{\tau}(i)\cdot\vec{\tau}(j), \tag{1}$$

where a and b are Hermitian isospin independent operators and $i \neq j$.

Class (II): Forces which maintain charge symmetry, but break charge independence. These can be written in isotensor form,

$$V_{II} = c\left(\tau_3(i)\tau_3(j) - \vec{\tau}(i)\cdot\vec{\tau}(j)\right). \tag{2}$$

The Coulomb interaction leads to a Class II force as do the effects of the pion mass difference in pion exchange forces. Effects of charge-dependent coupling constants may also lead to such a Class II force.

Class (III): Forces which break both charge independence and charge symmetry, but which are symmetric under the interchange $i \leftrightarrow j$ in isospin space,

$$V_{III} = d\left(\tau_3(i) + \tau_3(j)\right). \tag{3}$$

A Class III force differentiates between *nn* and *pp* systems, but does not cause isospin mixing in the two-nucleon system because

$$[V_{III}, T^2] = 0. \tag{4}$$

The effects of ρ^0-ω mixing yields such a force, as does the Coulomb interaction.

Class (IV): Class IV forces break charge symmetry and therefore charge dependence; they cause isospin mixing. These forces take the form

$$V_{IV} = e\left(\vec{\sigma}(i) - \vec{\sigma}(j)\right)\cdot\vec{L}\big(\tau_3(i) - \tau_3(j)\big) + f\left(\vec{\sigma}(i)\times\vec{\sigma}(j)\right)\cdot\vec{L}\big(\tau_3(i)\times\tau_3(j)\big), \tag{5}$$

where $\vec{L}$ is the two-nucleon orbital angular momentum, e and f are Hermitian operators that commute with $\vec{T}$. Such forces give CSB spin-orbit effects that account for the *np* analyzing power differences [8–13] and contribute to nuclear isospin mixing [26]. Effective field theory [7] tells us that the ordering of the strengths is given by $V_I > V_{II} > V_{III} > V_{IV}$.

References

[1] G. A. Miller and A. Schwenk, Phys. Rev. C **78**, 035501 (2008).

[2] G. A. Miller and A. Schwenk, Phys. Rev. C **80**, 064319 (2009).

[3] E. M. Henley and G. A. Miller, in *Mesons in nuclei, vol. I*, edited by M. Rho and D. Wilkinson. North Holland, Amsterdam, 1979, p. 405.

[4] G. A. Miller, B. M. K. Nefkens and I. Slaus, Phys. Rept. **194**, 1 (1990).

[5] G. A. Miller and W. T. H. van Oers, In *Symmetries and fundamental interactions in nuclei*, edited by W. C. Haxton and E. M. Henley. World Scientific, Singapore, 1995, p. 127.

[6] G. A. Miller, A. K. Opper and E. J. Stephenson, Ann. Rev. Nucl. Part. Sci. **56**, 253 (2006).

[7] U. van Kolck, J. L. Friar and J. T. Goldman, Phys. Lett. B **371**, 169 (1996).

[8] R. Abegg, D. Bandyopadhyay, J. Birchall, E. W. Cairns, H. Coombes, C. A. Davis, N. E. Davison, P. P. J. Delheij *et al.*, Phys. Rev. Lett. **56**, 2571 (1986).

[9] R. Abegg, D. Bandyopadhyay, J. Birchall, E. B. Cairns, G. H. Coombes, C. A. Davis, N. E. Davison, P. P. J. Delheij *et al.*, Phys. Rev. D **39**, 2464 (1989).

[10] R. Abegg, A. R. Berdoz, J. Birchall , J. R. Campbell, C. A. Davis, P. P. J. Delheij, L. Gan, P. W. Green *et al.*, Phys. Rev. Lett. **75**, 1711 (1995).

[11] J. Zhao, R. Abegg, A. R. Berdoz, J. Birchall, J. R. Campbell, C. A. Davis, P. P. J. Delheij, L. Gan *et al.*, Phys. Rev. C **57**, 2126 (1998).

[12] L. D. Knutson, S. E. Vigdor, W. W. Jacobs, J. Sowinski, P. L. Jolivette, S. W. Wissink, C. Bloch, C. Whiddon *et al.*, Phys. Rev. Lett. **66**, 1410 (1991).

[13] S. E. Vigdor, W. W. Jacobs, L. D. Knutson, J. Sowinski, C. Bloch, P. L. Jolivette, S. W. Wissink, R. C. Byrd *et al.*, Phys. Rev. C **46**, 410 (1992).

[14] A. K. Opper, E. J. Korkmaz, D. A. Hutcheon, R. Abegg, C. A. Davis, R. W. Finlay, P. W. Green, L. G. Greeniaus *et al.*, Phys. Rev. Lett. **91**, 212302 (2003).

[15] E. J. Stephenson, A. D. Bacher, C. E. Allgower, A. Gardestig, C. Lavelle, G. A. Miller, H. Nann, J. Olmsted *et al.*, Phys. Rev. Lett. **91**, 142302 (2003).

[16] G. A. Miller, arXiv:1309.0879 [nucl-th] (2013).

[17] D. S. Armstrong and R. D. McKeown, Ann. Rev. Nucl. Part. Sci. **62**, 337 (2012).

[18] D. Androic *et al.* (Qweak Collaboration), arXiv:1307.5275 [nucl-ex] (2013).

[19] V. Dmitrasinovic and S. J. Pollock, Phys. Rev. C **52**, 1061 (1995).

[20] G. A. Miller, Phys. Rev. C **57**, 1492 (1998)

[21] B. Kubis and R. Lewis, Phys. Rev. C **74**, 015204 (2006).

[22] P. C. McNamee, M. D. Scadron and S. A. Coon, Nucl. Phys. A **249**, 483 (1975).

[23] S. A. Coon and R. C. Barrett, Phys. Rev. C **36**, 2189 (1987).

[24] P. G. Blunden and M. J. Iqbal, Phys. Lett. B **198**, 14 (1987).

[25] I. C. Cloet and G. A. Miller, Phys. Rev. C **86**, 015208 (2012).

[26] R. B. Wiringa, S. Pastore, S. C. Pieper and G. A. Miller, arXiv:1308.5670 [nucl-th] (2013).