Symmetry Problems in
Low Energy Physics*

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ABSTRACT

Some recent experimental and theoretical work on 1) charge symmetry-breaking, 2) parity non-conservation, and 3) searches for breaking of time reversal invariance are reviewed. The examples illustrate the uses of symmetry to learn about underlying dynamics and/or structure.

INTRODUCTION

Nuclei are known to be a superb laboratory for studies of symmetries and symmetry-breaking as well as tests of our basic understanding of the physical world. It is easy to change mass, spin, isospin, charge, and other properties of the nuclear target to allow us to probe various aspects of basic theory. Symmetries are particularly useful because they serve to restrict the underlying dynamics, or, if the latter is known, allow a determination of (unknown) structure.

In the time allotted to this talk, it clearly is not possible to discuss all the symmetries useful in low energy physics. I intend to concentrate on charge symmetry, parity, and time reversal symmetries. As we have heard at this conference, there are many more symmetries one can discuss, such as chiral symmetry and those that occur in the standard model. Even within the above restriction, I find it necessary to pick out a

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sample of the many interesting features.

1. Charge Symmetry

It is well known that hadron (QCD) forces respect charge independence and charge symmetry at low energies. These symmetries are of particular interest because their violation is small and can be studied both experimentally and theoretically. The violation occurs due to electromagnetic effects and the mass difference of the up and down (d) quarks in the underlying QCD theory. The violation of charge independence is of the order of a few percent. It is readily measurable in low energy nucleon-nucleon scattering, in the energy spacings of isobaric analog states, and many other phenomena.

Recently, there has been more interest in the breaking of the looser charge symmetry. This symmetry does not require full rotational invariance in isospin (charge) space, but only invariance under reflection in a plane perpendicular to the charge (third component of isospin) axis. The symmetry violation is smaller than that of charge independence, but chiral perturbation theory indicates that the violation is considerably enhanced in processes that involve two neutral pions. The nuclear forces which break charge symmetry are of the form (classes III and IV),

\[
V_{III}(1, 2) = U_{III}[\tau_3(1) + \tau_3(2)]
\]

\[
V_{IV}(1, 2) = U_{IV}[\vec{\sigma}(1) - \vec{\sigma}(2)] \cdot \vec{L}[	au_3(1) - \tau_3(2)]
\]

\[
+ U'_{IV}[\vec{\sigma}(1) \times \vec{\sigma}(2)] \cdot \vec{L}[\vec{\tau}(1) \times \vec{\tau}(2)]
\]

where \( U \) is a space and spin dependent interaction, \( \vec{L} \) is the relative orbital angular momentum operator, \( \vec{\sigma} \) is a Pauli spin operator and \( \vec{\tau} \) is the corresponding isospin operator. \( V_{III} \) causes a difference between the nn and pp systems, whereas \( V_{IV} \) affects the n-p system. One of the dominant contributors to both \( V_{III} \) and \( V_{IV} \) is $\rho - \omega$ mixing. It is thus not surprising that there has been considerable recent interest in $\rho - \omega$ mixing.
This interest was sparked by Goldman, Henderson, and Thomas,\(^4\) who showed that a perturbative quark loop calculation predicted a large momentum (q) dependence of the mixing matrix element. The value of $\rho - \omega$ mixing is known at the $\omega$-mass, where it has been measured in the cross section for $e^+ e^- \to \pi^+ \pi^-$; its value at $q^2 = m_\omega^2$ is\(^5\) $\rho | H^\text{CSB} | \omega > = -(4520 \pm 600) \text{ MeV}^2$ and it arises mainly from the mass difference $m_d - m_u = \Delta m \approx 4 \text{MeV}$.\(^1\) Other methods have been used by a number of authors to evaluate the off-the-mass shell dependence,\(^6\) and all find that for the momenta (q) relevant for nuclear forces ($q^2 < 0$) the mixing matrix has changed sign (see Fig. 1).

Fig. 1. Momentum dependence of $\rho - \omega$ mixing.\(^1\)

This sign change gives rise to a much smaller $\rho - \omega$ mixing potential and spoils the agreement of theory and experiment; examples are the $^3\text{He} - ^3\text{H}$ mass difference due to $V_{III}$, the n-p polarization asymmetry due to $V_{IV}$.\(^1,6\) The sensitivity of this asymmetry to $\rho - \omega$ mixing is shown in Fig. 2. Charge symmetry predicts equal analyzing powers for the neutrons and protons,

$$A_n(\theta) = A_p(\theta) \quad (2)$$
in elastic scattering of polarized particles.\textsuperscript{1} Fig. 2 shows the sensitivity of the TRIUMF\textsuperscript{7} (477 MeV) and IUCF (183 MeV)\textsuperscript{8} experiments to $\rho - \omega$ mixing;\textsuperscript{1} the on-mass-shell value is used in this Figure.

Fig. 2. Sensitivity of asymmetry to $\rho - \omega$ mixing in $\vec{n} - \vec{p}$ elastic scattering.

If the off-mass-shell extrapolation is used, then the agreement of theory and experiment at 183 MeV would be absent, but the agreement at 477 MeV would be maintained, as would that at 347 MeV, reported by Van Oers at this conference.\textsuperscript{11} What is missing? For instance, it could be effects due to the simultaneous exchange of a $\pi$ and $\gamma$. However, Cohen and Miller\textsuperscript{9} and, more recently, Gardiner, Horowitz, and Pickarowicz\textsuperscript{10} have shown that the charge dependence of the $\rho$ and $\omega$ couplings to the nucleons also need to be taken into account. Indeed, the latter have used vector dominance and $\Delta m$ effects to show that this dependence gives rise to a class IV force of the right magnitude and sign for the difference in n and p analyzing powers in elastic $\vec{n} - \vec{p}$ scattering at 183 MeV.\textsuperscript{8} It clearly would be of interest to resolve the uncertainty caused by the various analyses. Precise experiments of $\pi^+\pi^-$ production by pions on protons at the $\omega$-mass may help to differentiate between the two mechanisms. If $\rho - \omega$ mixing occurs, then a $\pi^+\pi^-$ decay of the $\omega$ becomes possible; see Fig. 3a. It should be observed as a blip in the $\pi^+\pi^-$-decay
at the $\omega$-mass as seen in $e^+e^- \rightarrow \pi^+\pi^-$. On the other hand, a violation of isospin at the $\omega$-p vertex will not lead to such a decay; see Fig. 3b. Thus, one can detect $\rho - \omega$ mixing at $q^2 = m_\omega^2$, but not isospin nonconservation at the nucleon-$\omega^o$ vertex in this manner. Both mechanisms arise primarily from the up-down quark mass difference, $\delta m$. For space-like values of $q^2$, no experiment can differentiate between these two mechanisms because they are not really different. This is illustrated in Fig. 3c, where the $\rho - \omega$ mixing is regarded as a vertex correction for $\omega$-exchange. The reason this can be done is the finite size of the hadrons, e.g., form factors at the nucleon-vector meson vertices. To observe isospin mixing at the vertex, I can only think of doing $\rho$ production from a deuteron or $^4$He, $d + d \rightarrow ^4$He $\rho^o$ away from the $\omega^o$ mass. But this experiment will be difficult to analyze. (See ref. 7 for a more extensive discussion.)

Fig. 3. (a) $\pi^-p \rightarrow \pi^+\pi^-$ at the $\omega$ mass; (b) $\pi^-p \rightarrow n\omega^o$ with a charge symmetry-breaking vertex; (c) $\rho^o - \omega^o$ mixing for $q^2 < 0$ regarded as a charge-symmetry breaking $\omega$-N vertex.

How is the symmetry affected by the nuclear medium? We know that the nucleon mass is reduced, even at normal densities to about $3/4$ of its isolated value. Does this imply that the constituent quark mass is likewise reduced? Is $\rho - \omega$ mixing affected? It is
likely that many quantities are affected by being placed in a nuclear medium. The Nolen-Schiffer effect, the increased mass difference of mirror nuclei over that expected from the n-p mass difference and Coulomb effects has had a number of explanations. Among them are charge-symmetry-breaking effects, particularly $\rho - \omega$ mixing, and a decreased mass difference of the n-p in the nucleus. Both of these effects depend on the effective up and down quark mass difference. Both mechanisms may be effective, and it will be interesting to pursue other charge symmetry-breaking effects in nuclei.

In light nuclei, an example of a charge symmetry test is the forward-backward asymmetry predicted by class IV forces in the reaction $np \rightarrow d\pi^0$.\(^{14}\)

$$A_{fb} = \frac{\frac{d\sigma}{d\Omega}(\theta) - \frac{d\sigma}{d\Omega}(\pi - \theta)}{\frac{d\sigma}{d\Omega}(\theta) + \frac{d\sigma}{d\Omega}(\pi - \theta)}$$  \hspace{1cm} (3)

The asymmetry is expected to be $\approx 10^{-3} - 10^{-2}$ at $\approx 300$ MeV, where a new experiment is planned at TRIUMF. Another example is $d+d \rightarrow ^4\text{He}+\pi^0$, which is forbidden by charge symmetry. At about 600 MeV, the magnitude expected, primarily from $\pi - \eta - \eta'$ mixing, is $\approx 0.2$ pb / sr.\(^{15}\) This reaction may have been seen at Saturne at 1.1 GeV with $d\sigma/d\Omega = 0.97 \pm 0.20 \pm 0.15$ pb / sr at $\theta_{cm} = 107^\circ$.\(^{16}\) However, both the experiment and theory are difficult. These are but two such tests of charge symmetry in nuclei, which undoubtedly will be done more accurately in the future.

Charge symmetry-breaking can also be tested in hypernuclei\(^{1}\) (see also A. Gal at this conference). So far, only the mass difference of the mirror pair $^4\text{H}_\Lambda - ^4\text{He}_\Lambda$ has been determined.\(^{17}\) It would be interesting to study the A-dependence to see whether there is a Nolen-Schiffer type anomaly here and whether it can be explained due to $\Lambda^o - \Sigma^o$ mixing and/or other (i.e., mesonic) effects.

Charge symmetry does not apply in the weak interactions. However, charge symmetry can be and has been used to test features of the standard model and other symmetries. For instance, the conservation of the weak vector current (CVC) has been tested in the A=12 nuclei to about 6%\(^{18}\) and in the A=8 multiplet (see Fig. 4) to about
the same accuracy; here one uses the symmetry of the $^8$B and $^8$Li to make comparisons to the $^8$Be radiative decay. Further, the measurements allow one to limit the magnitude of possible second class currents which violate G-parity and/or time reversal invariance, and could arise due to $\Delta m$. No such currents were seen, with a lower limit which is $1/2$ of previous measurements ($d_{II} / A c \lesssim 0.4$).

Fig. 4. CVC test in $A = 8$ nuclei.

II. Parity Nonconservation

Parity nonconservation (PNC) can be used to test the standard model as well as to obtain structural information. I will give examples of both.

In discussions of PNC in nuclear forces, recent interest has centered on two facets. The first is to find neutral current effects at low energies; the second is to understand experiments related to compound nuclear formation.

PNC experiments in light nuclei are reasonably well understood. However, neutral current effects have not yet been seen in non-leptonic processes, despite considerable effort. Let me remind you that nuclei allow one to isolate neutral currents. The parity-violating (pv) nuclear forces of interest are isovector in nature. These forces cannot come from the normal charged currents, proportional to $\cos \theta_c$, where $\theta_c$ is the Cabibbo
angle, but only from strangeness-changing currents ($\Delta S = +1$ and -1), proportional to
$\sin \theta_c \approx 0.22$ and from neutral currents.\textsuperscript{19}

Furthermore, the isovector pv nuclear force is carried almost solely by the pion;
thus, it is a long-range force. The pv pion-nucleon coupling due to strangeness-changing
(charged) currents is reduced by $\sin^2 \theta_c$, and thus is only $f^{(\pm)}_\pi \sim 4 \times 10^{-8}$.

Fig. 5. Parity tests in light nuclei.\textsuperscript{31}

By contrast, the best quark model calculation (DDH)\textsuperscript{20} gives the coupling due to
neutral currents as $f^{(0)}_\pi \sim 5 \times 10^{-7}$ with large errors. (A more recent value by G.G.
Feldman et al\textsuperscript{21}, based on the same model, is $3 \times 10^{-7}$.) Experiments in light nuclei
allow one to isolate the isovector pv-force in nuclei where levels of the same spin and
isospin differing by one unit are close together in energy. Examples are shown in Fig. 5.
Experiments in $^{18}$F show that $f^{(0)}_\pi$ is at least a factor of three smaller than the “best”
DDH value.\textsuperscript{20} Indeed, PNC due to neutral currents has not been observed in nuclei
(e.g., $^{18}$F). As we heard at this meeting,\textsuperscript{22} QCD sum role calculations predict a $f^{(0)}_\pi$
that, due to a cancellation, is an order of magnitude smaller than that given by DDH. This result agrees with an earlier chiral perturbative result of Kaiser and Meissner.\textsuperscript{23}

If these calculations are correct, then the searches for neutral current effects in low energy nuclear physics are extremely difficult, because the resulting pv-force due to neutral currents is then of the same order of magnitude as that due to the charged (strangeness-changing) current ones, and the latter will mask the former. It is only the difference of $f^{(0)}_\pi + f^{(\pm)}_\pi$ from the readily calculable $f^{(\pm)}_\pi$, alone, which will signal the presence of neutral currents. It will be quite a while until the accuracy of experiments and theory are up to this challenge. This situation will be made even worse if the nucleon contains strange quarks, as suggested by a number of electron and muon deep inelastic scattering experiments. The effect of strange quarks has been examined by Kaplan and Savage;\textsuperscript{24} they could enhance the asymmetry due to the charged current pv force.

In a continuing search for enhanced PNC effects, it was natural to turn to compound nuclear resonances.\textsuperscript{25} Epithermal polarized neutron scattering at a compound nuclear P-wave resonance can give enhancements of many orders of magnitude, to the pv asymmetry $a$

$$a = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

where $\sigma_+ (\sigma_-)$ is the cross section for RH(LH) polarized neutrons. The enhancement arises from a number of causes. If we write

$$a \sim \sum_n \frac{\langle f | T | S_n \rangle \langle S_n | H_{W,K} | P \rangle}{E_P - E_S} \sim G_F m_\pi^2 E \approx 10^{-7} E$$

where $P$ is a P wave and $S$ its admixed opposite parity component, $a$ is enhanced by $E$ over its normal value $\sim G_F m_\pi^2$ by a number of factors. Here $G_F$ is the Fermi coupling constant and $m_\pi$ is the pion mass. These factors are: (i) an enhanced transmission factor for S-waves over P-waves, $E_1 \sim 1/kR \sim 10^2 - 10^3$, where $R$ is the nuclear radius and $k$ the
wave number of the incident neutrons; (ii) a small energy denominator \( \Delta E \simeq E_P - E_S \approx 1 \text{ MeV} / \mathcal{N} \), where \( \mathcal{N} \sim 10^4 - 10^6 \) is the number of underlying levels of a resonance. Although the matrix element \( \langle | H_{Wk} | \rangle \) is suppressed by \( \mathcal{N} \), we obtain a net enhancement factor \( E_2 \approx 10^2 - 10^3 \) and thus \( E = E_1 E_2 = 10^4 - 10^6 \).

This large enhancement means that asymmetries of several per cent can be obtained. Such asymmetries have been seen in a number of experiments,\(^{26}\) most recently at Los Alamos, e.g. on \(^{232}\)Th. The initial results appeared to indicate a non-statistical distribution of asymmetries, but these findings have disappeared with more careful measurements.\(^{26}\) An understanding of the experimental results\(^{25,26}\) is necessary in order to use the same targets for time reversal tests. Further developments will surely follow.

Fig. 6. (a) Standard PNC experiment in atoms; (b) The smaller PNC test with a weak neutral axial nuclear current; (c) The anapole moment contribution.

In semi-leptonic interactions, atomic PNC measurements and calculations have now reached a level of accuracy of 1\(^{\circ}\),\(^{27}\) e.g. in \(^{205}\)Tl. These experiments depend on a weak axial electronic current and a weak vector current coupling to the nucleus (Fig. 6a); the latter is enhanced by nuclear coherence \( \sim N \), where \( N \) is the number of neutrons.
By contrast, the vector electronic current and axial nuclear current (Fig. 6b) is not so enhanced, because the axial current is proportional to the nuclear spin, which is due to one, or at most a few, nucleons. However, in heavy atoms this effect is expected to be masked by the so-called nuclear anapole moment,\textsuperscript{28} which has yet to be seen. The nuclear anapole moment is an axial coupling of a photon to the nucleus (Fig. 6c), which arises from nuclear PNC. It would be interesting to determine whether the predicted masking actually occurs.

The experiments in Tl were just sufficiently accurate to have been able to see the predicted anapole moment, but was not observed. I am sure that further improvements will allow one to test the theoretical calculations and it will be interesting to see this novel effect. It requires nuclei, because for a nucleon or electron gauge invariance precludes its measurement.\textsuperscript{29} The effect there is of order $G_F\alpha$, where $\alpha$ is the fine structure constant for gauge invariance. Other diagrams of this order must be included. However, in nuclei the anapole, e.g., due to positive pion exchange currents, is enhanced by at least $Z$, the nuclear charge. This allows a measurement of this strange coupling of the form\textsuperscript{30,31}

\[
\langle p' | j_{\mu}^{em5} | p \rangle = \bar{u}(p') \left( \frac{\gamma\mu q^2 - 2Mq_\mu}{M^2} \right) \gamma^5 u(p) a(q^2) \tag{6}
\]

where $M$ is the nucleon mass, $q = p' - p$, $u$ is a spinor, and $a(0)$ is the anapole moment.

At higher energies, PNC in electron scattering with polarized electrons can be used to test the standard model \textit{and} provide information on structure. Let me give an example of the latter.\textsuperscript{31} If strange quarks are present in the nucleon, then there are two new and unmeasured form factors for the proton. Of course, some strangeness is expected ($\sim 3\%$)\textsuperscript{32}, but the SMC and SLAC NMC measurements (as well as $\nu$ elastic scattering) indicated that there could be as much as a 10-20\% polarized $s\bar{s}$ quarks presence in the proton.\textsuperscript{33} For elastic scattering of polarized electrons from protons, the
current can be written\textsuperscript{31,34}

\begin{equation}
J_{\mu}^{em} = \bar{u}\gamma_\mu u F_1^{em}(Q^2) + \bar{u}\sigma_{\mu\nu} q^\nu u \kappa_p F_2^{em}(Q^2) \tag{7}
\end{equation}

\begin{equation}
J_{\mu}^{wk} = \bar{u}\gamma_\mu u F_1^{wk}(Q^2) + \bar{u}\sigma_{\mu\nu} q^\nu u F_2^{wk}(Q^2) + \bar{u}\gamma_5 u F_A(Q^2) + \bar{u}\frac{q_\mu}{2M} \gamma^5 u F_P(Q^2)
\end{equation}

If there are no strange quarks present, then CVC guarantees

\begin{align*}
F_1^{wk} &= \frac{1}{4}(1 - 4\sin^2 \theta_W) F_1^{em} \\
F_2^{wk} &= \left[\frac{1}{4}(1 - 4\sin^2 \theta_W) - \frac{\kappa_n}{\kappa_p}\right] F_2^{em} \tag{8}
\end{align*}

where \(\kappa_n\) and \(\kappa_p\) are the neutron and proton anomalous magnetic moments, and \(\theta_W\) is the Weinberg angle. The observed asymmetry comes from an interference of the electromagnetic and weak interactions of the electron and proton. On the other hand, if strange quarks are present, then \(F_1^{wk}(Q^2)\) may not = \(F_1^{em}(Q^2)\), and

\begin{equation}
F_2^{wk'} \approx F_2^{wk} + \kappa_S F_2^S \tag{9}
\end{equation}

where \(\kappa_S\) is a new constant and \(F_2^S\) a new form factor.

The reason for the new constant and form factor is that in the structure of the proton, i.e. in hadronic interactions, the s quark is an isoscalar, but in the weak interactions, it has weak isospin = 1/2; this mismatch is not present for u and d quarks, which have the same weak and strong isospins. For the axial current, we have

\begin{equation}
F_A^{wk'} = F_A^{wk} + \frac{1}{4} g_A^S G^{wk}(Q^2) \tag{10}
\end{equation}

Whereas \(F_A^{wk}(0) = \frac{1}{4} g_A = -\frac{1.26}{4}\), \(g_A^S\) is an unconstrained and unknown constant and \(G^{wk}\) an unmeasured form factor with \(G^{wk}(0) = 1\). An experiment (SAMPLE) has been undertaken\textsuperscript{35} at MIT to determine \(\kappa_S\) and quasi-elastic \(\mu\) scattering on \(^{12}\text{C}\) has been proposed\textsuperscript{36} to determine \(g_A^S\). Further experiments are planned at CEBAF,\textsuperscript{37} and others
have been proposed.\textsuperscript{31,34} Again, nucleon and nuclear targets are particularly helpful in
determining some new nucleon structure factors.

\begin{center}
\textbf{III. Time Reversal Invariance}\textsuperscript{38} (TRI)
\end{center}

Although CP violation was discovered over 30 years ago, its cause still has not been
established, despite considerable effort. In nuclear physics, no violation of TRI has been
observed at a level of a few parts in $10^4$. In weak interactions, the $^8$Li and $^8$B beta
decays to $^8$Be are being used to improve these limits. The term in the decay rate of
$\propto \vec{s} \cdot \langle \vec{J} \rangle \times \hat{p}$ which is odd under both P and T transformations, has been sought. Here
$\langle \vec{J} \rangle$ is the polarization of the nucleus; $\vec{s}$ that of the electron and $\hat{p}$ is a unit vector along
a momentum [e.g., that of one of the alpha particles from the $^8$Be decay or that of the
electron (positron)]. The coefficient R multiplying this term has been measured in $^8$Li
and reported at this conference to be $(4 \pm 35) \times 10^{-4}$\textsuperscript{39}. This limits the T-odd axial
current matrix element

\begin{equation}
\langle p \mid j^{(5)} \mid p \rangle = C_T \vec{p}(p') i\sigma_{\mu\nu} \gamma_5 \frac{q}{2M} u(p) \text{ by } I_m C_T \lesssim 0.010.
\end{equation}

A related experiment to limit $C_T$ is being planned in Seattle.\textsuperscript{40}

\begin{center}
\textbf{Fig. 7.} A time reversal invariance test with polarized neutrons on a polarized target.
\end{center}

In addition, experiments can be carried out in heavy nuclei with polarized epithermal
neutrons. In this case, the same compound nucleus enhancement factors of $10^4 - 10^6$
which operate in the PNC experiments should be present. A possible experiment\textsuperscript{41} is to search for the (P-odd, T-odd) triple correlation $\vec{\sigma} \cdot \langle \vec{s} \rangle \times \hat{p}$ or the P-even, T-odd correlation $\vec{\sigma} \cdot \langle \vec{s} \rangle \vec{\sigma} \cdot \langle \vec{s} \rangle \times \hat{p}$, where $\hat{p}$ is a unit vector along the incident momentum of the polarized neutrons scattered coherently in the forward direction (see Fig. 7) from a polarized ($\langle \vec{J} \rangle$) heavy nuclear target, such as $^{139}$La or $^{232}$Th. Although the enhancement is likely to be insufficient to observe a TRI (and P) violation, the effort needs to be and is being made.\textsuperscript{41} Furthermore, the accuracy on the limit of $\theta$ (see below) could rival that of searches for a neutron dipole moment.

At this time, the most sensitive tests of TRI (and P) violation are searches for electric dipole moments ($d_E$). The electric dipole moment of the neutron is now known to be\textsuperscript{42} $\lesssim 8 \times 10^{-26}$ e-cm. New efforts to improve the limit are underway in Japan, Russia and at ILL, as reported at this conference.\textsuperscript{43} There also have been impressive improvements in searches for $d_E$ of atoms; their accuracy now rivals or exceeds that of the neutron,\textsuperscript{44} with $d_E$ ($^{199}$Hg) $8 \times 10^{-28}$e-cm. In terms of the strong CP parameter in the QCD Lagrangian, $L$ (T-odd) = $\frac{\alpha_S}{8\pi}\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$, where $G$ is the gluonic field operator and $\tilde{G}$ its dual, these experiments limit $\theta$ to $\theta \lesssim 10^{-10}$. Why $\theta$ should be so small is not known. Progress requires the observation of a non-zero value of a T-odd observable in a system other than $K^0 - \overline{K}^0$.

CONCLUDING REMARKS

Symmetries continue to be important in learning about the underlying dynamics (i.e. interactions) and obtaining structural information. In this talk I have given several examples of the usefulness of studying small symmetry-breakings that are of current and future interest. There are many other ones at both low and high energies.

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