Isospin symmetry and its breaking in nuclear structure

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I. PROBLEMATIC

The isospin symmetry is an approximate, but very useful symmetry of atomic nuclei. For many years, it serves as a stringent guideline for the construction of the nucleon-nucleon interaction. Some nuclear models such as the shell model are often constructed to be explicitly isospin conserving. For other models, such as self-consistent models based on energy density functionals, the wave functions are constructed without making explicit reference to isospin at all, which is consequently broken in an unphysical manner.

However, for a large class of problems the explicit physical breaking of isospin symmetry must be considered and well controlled theoretically. This includes the cases when a nucleus serves as a laboratory for precision tests of the fundamental symmetries underlying the Standard Model of the electroweak interaction.

- **Superallowed $0^+ \to 0^+$ transitions : test of CVC and evaluation of V_{ud}.** The measurement of lifetimes, decay branching ratios and Q-values of superallowed $0^+ \to 0^+$ transitions, has been a subject of intense studies for many decades. The constancy of the corrected $\mathcal{F}t$ values of these transitions, obtained from the measured ft values after correcting them for electromagnetic and nuclear structure effects, would signify the constancy of the vector coupling constant G_V, a key part of the CVC hypothesis. Once established, the V_{ud} matrix element of the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be extracted, which is involved in a top-row unitarity test of the CKM matrix.
  For the moment, ft-values for 13 transitions are known with a precision of the order 0.1%, providing thus the best accuracy for the extracted G_V. Other nuclei are being a subject of intensive experimental studies.
  The largest uncertainty in the extraction of the corrected $\mathcal{F}t$ value is due to the isospin-symmetry breaking correction which has to be estimated theoretically. Estimations of this correction, done within various microscopic nuclear structure models, vary in magnitude and there is no accuracy limit being worked out yet.
- **$T = 1/2$ mirror transitions : test of CVC and evaluation of V_{ud}.** The $T = 1/2$ mirror transitions have recently been proposed as an alternative way to extract the absolute $\mathcal{F}t$-value and V_{ud} matrix element, provided another experimental observable is known, such as the beta-neutrino angular correlation coefficient, the beta-asymmetry or neutrino-asymmetry parameter. The current accuracy of the extracted V_{ud} is comparable and even slightly better than that obtained from the neutron decay. Again, theoretical calculations of isospin-symmetry breaking corrections for both Fermi and Gamow-Teller transitions are vital.

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– **G-parity non-conserving terms of the axial-vector weak current**
Induced tensor terms in the axial-vector weak current, which is not constrained by PCAC, may in principle manifest itself in nuclear β-decay. First, it can be determined in correlation experiments, when one measures the correlation between the nuclear spin and the momentum of the emitted β-particle in the decay of oriented systems, or the correlation between the momentum of the emitted β-particle and of the radiation from a daughter state (β-α or β-γ correlations). In addition, induced tensor terms may contribute to the asymmetry of mirror Gamow-Teller transitions. Precise theoretical calculations of isospin-symmetry breaking effects, especially for the latter case, are required.

Thus, it is crucial to have a firm knowledge about the isospin impurities in nuclear states and valid theoretical predictions for the cases involved in the tests of fundamental symmetries described above. In addition, there is a substantial interest from a nuclear structure point of view to understand and to describe the isospin-symmetry breaking effects in nuclear states, such as **isospin-symmetry violation in nuclear mirror spectra and transitions** and **rates of isospin-forbidden processes on nuclei** :

– mirror energy differences
– difference in mirror electromagnetic transition rates
– isospin-forbidden nucleon emission (β-delayed proton emission, β-delayed two-proton emission)
– isospin-forbidden $0^+ \rightarrow 0^+$ β-decay (transitions between non-analogue states)
– isospin-forbidden Fermi component in Gamow-Teller dominated $J^\pi \rightarrow J^\pi$ ($J \neq 0$) β-decay
– $E1$-transitions in self-conjugated nuclei ($N = Z$)
– and so on

These manifestations of the isospin-symmetry breaking in nuclear states provide stringent tests for the nuclear models. Many of such measurements have been undertaken in recent years due to the development of experimental techniques towards the study of more proton-rich and heavier nuclei along the $N = Z$ line. Search for new phenomena which could shed light on isospin-symmetry violation is of importance.

Theoretical description of the isospin-symmetry breaking in nuclei is a challenging task. On a fundamental level, the isospin symmetry breaking is due to the electromagnetic interactions and the difference in masses between up and down quarks. Derivation of isospin-symmetry breaking components of the nucleon-nucleon interaction, for example, in the framework of chiral effective field theory, has largely progressed in the last years. This can be extremely beneficial for *ab-initio* calculations for very light nuclei, where the methods of solution can exploit the bare nucleon-nucleon interactions. However, up to now, many-body calculations for heavier nuclei require knowledge of effective forces, which at present are all based on different types of parameterizations. Thus, experimental measurements which can shed light onto the magnitude of isospin impurities in nuclear states and provide constraints to nuclear structure models are extremely important.

Theoretical calculations of isospin symmetry breaking in $N \approx Z$ nuclei have been performed by different groups and within different approaches. Starting from the earlier hydrodynamical model calculations and simplistic shell-model evaluations of the Coulomb effects, more refined microscopic models have been developed. Although the Coulomb force is largely dominating in nuclei as a source of isospin-symmetry breaking, understanding of the Nolen-Schiffer anomaly and precise reproduction of mirror energy differences required consideration of isospin-nonconserving (INC) nuclear forces in an effective interaction.

Within the shell model, the most ambitious realistic INC Hamiltonians are based on a well-established nuclear Hamiltonian within the isospin-symmetry concept and an empirical isospin-symmetry breaking two-body interaction is added as a perturbation. The strength parameters of the INC part (proton-proton, neutron-neutron and proton-neutron interactions) of the Hamiltonian are found by the requirement to reproduce the experimentally observed splitting of the isobaric mass multiplets. An extended data base of the experimental mirror energy differences and tremendous progress in large-scale shell-model calculations may lead to a new class of INC Hamiltonians. At the same time, applications of the shell model to the calculation of isospin-symmetry breaking corrections for nuclear β decay, mentioned above, require the change of the radial part of the wave functions from the harmonic oscillator ones to the more realistic spherical potential (Woods-Saxon or Hartree-Fock). This leads to more uncertainty and requires more constraints to fix the spherically symmetric potential.

Within the nuclear Energy Density Functional Theory, the principal challenge is to separate its inherent spurious breaking of isospin symmetry from the physical one. It is only very recently that isospin mixing and superallowed Fermi transition matrix elements could be obtained by diagonalization of the Coulomb interaction in a many-body basis built from an isospin and angular-momentum projected Hartree–Fock solution (i.e. neglecting pairing). A complementary attempt to calculate these observables is based on the Higher Tamm–Dancoff approximation (a highly truncated shell model built on a Hartree–Fock solution) and emphasizes the role of pairing correlations (unprojected basis)

Relativistic RPA calculations have recently been developed and applied to the calculations of the isospin-symmetry breaking correction to the superallowed Fermi transition matrix element. The results, being not very much sensitive to the effective interaction chosen, differ from existing shell-model predictions, thus augmenting the uncertainty of our knowledge on the correction.

An extensive theoretical study of such properties might also provide useful limits of acceptable parameter values in many of the microscopic many-body approaches described above. A specific example of this might be the ratio of $T = 0$ over $T = 1$ components of the residual interaction (or its equivalent in the so-called Energy Density Functional approach) whose knowledge still remains rather elusive.

II. GOALS OF THE WORKSHOP

The goals of the workshop are

1. To present recent developments in the theoretical description of the the physical breaking of isospin-symmetry in nuclei, and its manifestation within microscopic many-body approaches : *ab-initio* calculations, the nuclear shell model and methods based on nuclear density functional theory ; to organize a critical discussion on the ability of different many-body models to reach the required precision and possible constraints from experiments ;
2. To present recent results on precision measurements concerning isospin-symmetry violating processes and isospin impurities ;
3. To discuss details of theoretical calculations of isospin mixing and of isospin-symmetry breaking corrections to superallowed $0^+ \to 0^+$ transitions ;
4. To discuss the relation between the theoretical calculations of isospin impurities in nuclear states and the experimentally measured observables and, *vice versa*, to discuss constraints of, or insights into, theoretical models, provided by experimental measurements of Coulomb energy differences and rates of isospin-forbidden processes.

III. USEFUL REFERENCES

– I.S. Towner, J.C.Hardy and M. Harvey, Nucl. Phys. A **284**, 269 (1977).
– W.E Ormand and B.A Brown, Nucl. Phys. A **440**, 274 (1985) ; Nucl. Phys. A **491**, 1 (1989) ; Phys. Rev. Lett. **62**, 866 (1989) ; Phys. Rev. C **52**, 2455 (1995).
– G. Colo, M.A.Nagarajan, P. Van Isacker, A. Vitturi, Phys. Rev. C **52**, R1175 (1995).
– H. Sagawa, T. Suzuki, N. Van Giai, Phys. Rev. C **53**, 2126 (1996).
– P. Schuurmans et al, Nucl. Phys. A **672**, 89 (2000).
– S. Lenzi et al, Phys. Rev. Lett. **87**, 122501 (2001).
– A.P Zuker et al, Phys. Rev. Lett. **89**, 142502 (2002).
– N.A.Smirnova and C.Volpe, Nucl. Phys. A **714** (2003).
– J. Ekman et al, Phys. Rev. Lett. **92**, 132502 (2004).
– M.A. Bentley and S. Lenzi, Prog. Part. Nucl. Phys. **59**, 497 (2007).
– I.S. Towner and J.C.Hardy, Phys. Rev. C **77**, 025501 (2008).
– H. Liang, N. Van Giai, J. Meng, Phys.Rev. Lett. **101**, 122502 (2008).
– E. Epelbaum, H. Krebs, U.-G. Meissner, Phys. Rev. C **77**, 034006 (2008).
– M. Bhattacharya et al, Phys. Rev. C **77**, 065503 (2008).
– N.S.Pattabiraman et al, Phys.Rev. C **78**, 024301 (2008).
– G.A.Miller and A. Schwenk, Phys.Rev. C **78**, 035501 (2008).
– N. Severijns, M. Tandecki, T. Phalet, I.S. Towner, Phys. Rev. C **78**, 055501 (2008).
– A. Petrovici, K.W. Schmid, O.Radu, A. Faessler, Phys. Rev. C **78**, 064311 (2008).
– J.C. Hardy and I.S. Towner, Phys. Rev. C **79**, 055502 (2009).
– N. Auerbach, Phys.Rev. C **79**, 035502 (2009).
– H. Liang, N. Van Giai, J. Meng, Phys. Rev. C **79**, 064316 (2009).
– G.A.Miller and A. Schwenk, Phys.Rev. C **80**, 064319 (2009).
– O. Naviliat-Cuncic and N. Severijns, Phys. Rev. Lett. **102**, 142302 (2009).
– W. Satula, J. Dobaczewski, W. Nazarewicz, M. Rafalski, Phys. Rev. Lett.**103**, 012502 (2009).
– I.S. Towner and J.C.Hardy, Rep. Progr. Phys. **73**, 046301 (2010).
– N. Auerbach, Phys. Rev. C **81**, 067305 (2010).
– E. Epelbaum, H. Krebs, D. Lee, U.-G. Meissner, Phys. Rev. Lett. **104**, 142501 (2010)
– N. Michel, W. Nazarewicz, M. Ploszajczak, Phys. Rev. C **82**, 044315 (2010).
– A. Signoracci, B.A.Brown, nucl-th/1012.2402 (2010).
– W. Satula, J. Dobaczewski, W. Nazarewicz, M. Rafalski, nucl-th/1101.0939 (2011).

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V. TENTATIVE PROGRAM

April 26	April 27	April 28	April 29
Tuesday	Wednesday	Thursday	Friday
	9h30 M. Bentley	9h30 J.C. Hardy	9h30 N. Severijns[2]
	10h30 **Break**	10h30 **Break**	10h30 **Break**
	11h00 G. De Angelis	11h00 I.S. Towner	11h00 T. Kurtukian-Nieto
	12h00 P. Van Isacker	12h00 N. Severijns[1]	11h45 B. Blank
	12h40 **Lunch**	12h50 **Lunch**	12h30 **Lunch**
14h20 Welcome			
14h30 N. Auerbach	14h15 G. De France	14h30 E. Epelbaum	**End**
15h30 J. Le Bloas	15h15 A. Petrovici	15h30 W. Satula	
16h30 **Break**	16h15 **Break**	16h30 **Break**	
17h00 N. Michel	16h45 A. Signoracci	17h00 N. Van Giai	
	17h25 Y. Lam		
18h00 **End**	18h00 **End**	18h00 **End**	

[1] First talk from the list below
[2] Second talk from the list below

VI. LIST OF TALKS

– N. Auerbach, *"Isospin symmetry breaking and the role of the Isovector Monopole State"*

- M. Bentley, *"Isospin symmetry studied through mirror energy differences — latest experimental results in the fp shell"*
- B. Blank, *"Isospin impurity and beta-delayed proton emission"*
- G. De Angelis, *"Isospin Symmetry violation in mirror E1 transitions"*
- G. De France, *"T=0 pairing and possible measurement of isospin mixing in N=Z nuclei"*
- E. Epelbaum, *"Theory of isospin-breaking nuclear forces"*
- J.C. Hardy, *"Current status of superallowed* $0^+ \rightarrow 0^+$ *beta decay, and the unitarity of the CKM matrix"*
- T. Kurtukian-Nieto, *"Precision half-life determination of the superallowed* $0^+ \rightarrow 0^+$ β^+*-emitters* ^{42}Ti, ^{38}Ca, ^{30}S *and the mirror beta transitions of* ^{39}Ca, ^{31}S *and* ^{29}P*"*.
- Y. Lam, *"Isospin impurities in sd-shell nuclei"*
- J. Le Bloas, *"Isospin mixing and beta decay within the 'Highly Truncated Diagonalization Approach' "*
- N. Michel, *"Isospin mixing and continuum coupling in weakly bound and resonant nuclei"*
- A. Petrovici, *"Variational approach to isospin symmetry breaking in medium mass nuclei"*
- W. Satula, *"Microscopic calculations of isospin impurities and isospin symmetry breaking corrections using isospin and angular-momentum projected energy density functional theory"*
- N. Severijns,[1] *"Mirror beta transitions as a new probe for the determination of* V_{ud}*"*
- N. Severijns,[2] *"Experimental determination of isospin mixing in nuclear states ; the cases of* ^{59}Cu *and* ^{104m}Ag*"*
- A. Signoracci, *"Effects of isospin mixing in the A=32 quintet"*
- I.S. Towner, *"Isospin-symmetry breaking corrections in nuclear beta decay"*
- N. Van Giai, *"Evaluation of isospin mixing effects by RPA approaches. Application to* $0^+ \rightarrow 0^+$ *superallowed beta transitions."*
- P. Van Isacker, *"Measuring isospin mixing from E1 and E2 transitions"*