Modern Physics Letters A
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# SUMMARY OF APFB08

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Received (Day Month Year)
Revised (Day Month Year)

A personal perspective is given on topics which appears to be most promising during the fourth Asia Pacific Conference on Few-Body Problem in Physics 2008.

## 1. Overview

The conference in Depok successfully demonstrated the wealth of Few-Body physics. The traditional problems of our community involve more than two particles. However even in the two-body sector there are many investigations adding the interactions among exotic hadrons and mesons as well as photons. A further challenge is the study of the internal structure of the nucleon.

We start by viewing the nucleon-nucleon (NN) interaction. The so-called high-precision potential models (e.g., Argonne V18, Nijmegen I, II, CD-Bonn) are effectively equivalent to a scattering amplitude analysis of the physical observables with a $\chi^2/N \approx 1$ in the energy regime below 300 MeV laboratory energy. New approaches to the NN interaction are quark models and chiral effective field theory models ($\chi$EFT). They reduce the number of parameters, for instance, in the NNLO ($N^3LO$) version of $\chi$EFT there are only 9 (15) parameters. Those approaches provide a new representation of physics and obtain a $\chi^2/N$ comparable to the conventional models. However, they do not yet encompass all of the physics to fully justify their physical merit. More to this topic in Section 2.

Since all the modern potentials describe two-nucleon observables with equal quality, their difference appears only in their off-the-energy-shell properties. Examples for different off-shell behavior of NN interactions are those between local and nonlocal ones. A phenomenological potential entering a Schrödinger equation is most commonly expected to be local in configuration space. Under the assumption of a purely local potential, the inversion method (Gel'fand-Levitan-Marchenko integral equations[1]) proves that such a potential will be uniquely defined by the full data set of phase shifts ( up to 2- body bound state corrections). The non-locality of the CD-Bonn potential arises from the Dirac structure manifested in minimal relativity factors arising from the Blankenbecler-Sugar reduction of Bethe-Salpeter equation. There is however a question about the physical relevance of the size of the non-locality in the NN interaction[2].

A further development is given by low momentum effective potentials. It is an astonishing fact that in the restricted Hilbert space given by the limited low momentum range the on-shell properties of the potential is conserved by similarity transformations [3,4] based on renormalization group considerations. In this way any modern realistic potential can be transformed into a low momentum, effective potential leading to the same scattering observables.

We would like to bring up a further question : What features of the new alternative models (quark, $\chi$EFT, etc) will distinguish them from the one-boson-exchange (OBE) hypothesis[5]? Differences will possibly be revealed by forthcoming data of very high quality and/ or by investigations in the high energy region, where new physical complexities appear, needing more theoretical effort, e.g. multi channels, internal excitation, annihilation and creation of particles, and relativity. However, one should be aware that future high precision measurements will most likely not occur without a clear motivation based on theoretical predictions.

Furthermore it can be expected that ambiguities left unsolved by considering only the two-body system will be clarified in systems containing more than two particles. This however, requires consistency of two- and many-body forces. Systems consisting of only few particles are the main subject of study when looking at few-body problems. The idea is that few-particle systems are still simple enough to be examined with rigorous method, but already sufficiently complex to exhibit features of many-body physics. We come back to those problems in Section 3.

Cluster models were extensively discussed as being applied to various systems like neutron rich nuclei and hyper nuclei. Using the flavor SU3 symmetry, the OBE model and quark models are extended to incorporate Hyperons, specifically in YN and YY interactions. Experiments planned at J-PARC addressing hypernuclei are expected to give important information on how to fix the parameters in the potentials. The study of hypernuclei will also provide insights into the conventional NN interaction through SU3 symmetry. Not only baryon-baryon interactions but also meson-baryon interactions are described by the OBE models. Shinmura *et al.* presented the S=0 sector ($\pi N$ - $\eta N$ - $K\Lambda$ - $K\Sigma$) and the S=1 ($KN$).

In order to look into the inner structure of the nucleon, electron scattering and photo disintegration of nuclei are good reactions to investigate. That structure is reflected by the details of the nucleon-nucleon potential at short distances which is still unknown. However, the short range behavior of the interaction influences cold dense nuclear matter such as in neutron stars. New experiments at TJNAF and MIT-Bates were reported by Gilad, Ron and Baunack, together with new photoproduction data from LNS of Sendai by K. Suzuki and Tsukada. For instance, in electron scattering experiments a polarized triton target can be regarded as a polarized neutron target. The electro-magnetic form factors of the neutron can be analyzed with the help of exact Faddeev calculations. However, despite the sophisticated three-body calculations, there are still uncertainties since the available potentials do not lead to identical results in the intermediate energy region. One encounters a more complex situation since in that energy region the nucleon is easily excited into the $\Delta$ isobar, and therefore the response expressed in terms of form factors is shared by nucleons and $\Delta$s.

A lot of advanced techniques for few-body problems were presented. We will address them in Section 4.

## 2. NN interaction: Effective field theory and Quark models in few-body physics

The Jülich-Bonn-Bochum group continues to develop the $\chi$EFT potential to higher order. Krebs discussed its application to processes involving few nucleons. Combining Monte Carlo lattice simulations with $\chi$EFT he showed properties of light nuclei and nuclear matter. That scheme is a promising tool for quantitative studies of few- and many-body systems in the low energy regime.

Schiavilla presented meson exchange currents in electromagnetic processes, which are derived within the $\chi$EFT framework. Higa applied $\chi$EFT technique to neutron-alpha scattering. Ando and Hyun presented pion-less effective field theory for the $pp \to de^+\nu_e$ process.

A QCD-inspired spin-flavor SU6 quark model has been developed by the Kyoto-Niigata group. The fss2 version is available for the NN and NY sectors in a three-cluster Faddeev formalism as well as $G$-matrix calculations. Fujiwara showed $ls$ splitting of the ${}^{9}_{\Lambda}$Be excited state using quark model $G$-matrix $\Lambda$ - $\alpha$ kernel. We look forward to further applications of these potentials and their merits as compared to conventional OBE models.

## 3. Few-nucleon systems: three-body forces and few-nucleon dynamics

Despite large efforts to understand the details of the three-nucleon (3N) system, there still exist many discrepancies between 3N experimental data and theoretical predictions. This situation is summarized by Sagara and is presented in Fig. 1. Traditionally, a first step in the prediction of a certain 3N observable is to use only NN interactions. This, however, often fails and asks for a more extensive analysis and deeper understanding.

### 3.1. *The Coulomb problem*

The classical three-body problem has been known as one of the most complicated and difficult ones. In the era of Newtonian mechanics, in the strict and precise sense, it has not been solved up to now. A classic few-body problem is exemplified by the planets of the solar system controlled by gravity. In this conference such classical dynamical few-body problems were not treated, but our subjects were few-body

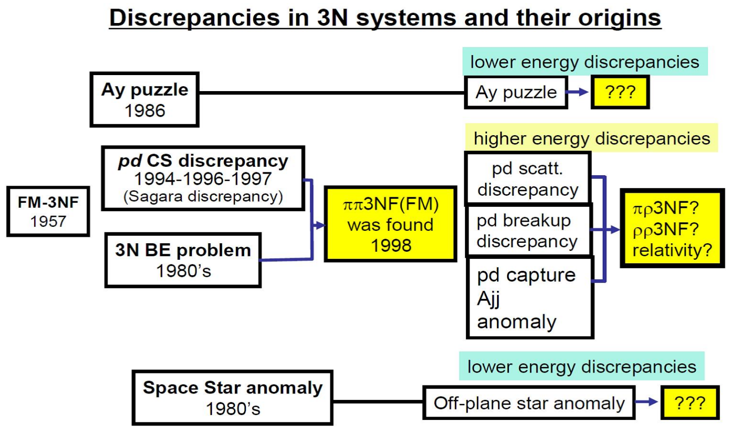


Fig. 1. Sagara's picture for discrepancies in 3N systems.

problems in quantum mechanics. In the limit $\hbar \to 0$ the three-body problems in quantum mechanics will encounter similar problems. Thus the asymptotic behavior of the three-body breakup wave function for three charged particles in all geometries is still unknown.

Even if the system has only a single Coulomb interaction, e.g. in proton-deuteron (*pd*) scattering, it is one of the most challenging subjects in few-body problems. Deltuva and Ishikawa independently analyzed the three-body breakup reaction (N+d $\to$ N+p+n) for the space star configuration at $E_N$ =13.0 MeV with different numerical approaches. Differences between their calculations and the experiment still remain. Shimoda and Sueda *et al.* are about to start systematic measurements of the off-plane star for this anomaly in the *pd* breakup at $E_p$=9.5 MeV and 13 MeV in the angle range from 0° to 105 °. Oryu *et al.* discussed not only the screened Coulomb interaction with renormalization [6] but also a new scheme based on a many-potential theory that is formulated as coupled channel NNN - NN$\Delta$ Faddeev equations. In the low energy region there are still some questions about a reliable treatment of three nucleon scattering with charged particles, which might be due to an insufficient convergence of the partial wave decomposition if the Coulomb interaction are present[7]. However, a lot of applications are waiting for solutions related to this problem.

### 3.2. *Three-nucleon forces*

At the time when the Fujita-Miyazawa type of three-nucleon force (3NF) became fashionable, the RIKEN data for the differential cross section in *pd* elastic scattering established its importance. The data at 135 MeV/u nearly overlapped with the theoretical prediction including this particular 3NF, which has a cut-off parameter fitted to the triton binding energy. Later, KVI measurements disagreed with these theoretical predictions, thus the two sets of data were in conflict with each other. The RIKEN data were remeasured and did not change. New KVI data were reported in this conference by Messchendorp *et al.*, and now the results of both experiments are getting closer. Messchendorp also showed preliminary results in the four-nucleon sector. There are many kinds of three-body forces, e.g. $\pi$ - $\rho$, $\rho$ - $\rho$ meson exchange type, Urbana IX, IL1-5 and the ones derived from $\chi$EFT, which should be tested by data.

A specific part of the 3NF is the effective force where the nucleon looses its identity because of inner excitation and the dynamical equation becomes a multi channel problem, e.g. for the nucleon and the $\Delta$ isobar. In this sense Deltuva *et al.* analyzed the few-body system including the Coulomb interaction. As an interesting result they found that the final state interaction peak in the breakup cross section caused by the $^1S_0$ NN interaction is depressed by Coulomb effect in case of proton-proton (pp) final states even if the energy of the pp pair is higher.

### 3.3. *The $A_y$ puzzle in few nucleon scattering*

Witała *et al.* pointed out that the inclusion of Wigner spin rotations further increases the discrepancy between theory and data below $\approx$ 25MeV, and thus a Poincaré invariant description of low energy scattering does not solve the $A_y$ puzzle. Deltuva *et al.* showed that for $p$ - $^3$He scattering there are also large deviations in the proton analyzing power while other observables are described quite reasonably. This indicates that the $A_y$ puzzle in 3N scattering is also present in 4N scattering.

### 3.4. *Tensor analyzing powers in pd radiative capture*

In *pd* radiative capture it is difficult to measure the cross section because its magnitude is much smaller than for ordinary *pd* scattering. Sagara presented new and re-analyzed data of $A_{xx}$, $A_{yy}$ and $A_{zz}$. The KVI data of these observables disagree with Sagaras ones and maybe agree with the Faddeev calculation.

### 3.5. *Cluster models and AMD*

Excited states of $^4$He, $^6$He and $^6$Li are studied using the model which expands the orbital part of the wave function into the correlated Gaussian with double global vectors (Horiuchi, *et al.*). Ito *et al.* showed that a molecular orbit gives a good description for low-lying state of isotopes, e.g. $^{10,12}$Be nuclei. Excited states may include Borromean states, where the few-body special properties, e.g. Effimov effect and Thomas effect are realized. Tomio discussed them for $^{20}C$ ($n-n-^{18}$C cluster model).

The anti-symmetrized molecular dynamics approach (AMD) [8] is applicable for systematic studies of neutron rich nuclei, together with their excited states and for quark models ( Aoyama, Murakami, Togashi, Watanabe *et al.*).

### 3.6. *Hypernuclear physics*

Because the measurements of 2-body YN and YY reactions are very difficult, experiments are performed for hyperon-nuclear reactions. Thus few-body physics can contribute to this research area. New experimental data from the KEK facility have been presented. Those include

- Weak decay of Hypernuclei (Outa)
- The $^4$He ($K^-_{\text{stopped}}$, n) reaction (Yim) and the $^3$He($K^-$, n) reaction (T. Koike)
- The $\pi^- p \to K^-$, $K^0$ reaction (S. J. Kim)
- Spin observables for kaon photo-production (Hutauruk)
- The $^{12}$C($K^-$, $K^+$) reaction (Choi)

For the same research effort many theoretical approaches have been presented, including

- Kaon photoproduction (Salam, Mart, Nelson)
- Nonmesonic weak decay of Λ- hypernuclei (Bhang)

Sofianos *et al.* showed bound state results for $^{6}_{\Lambda\Lambda}$He and $^{10}_{\Lambda\Lambda}$Be obtained from three- and four-body Faddeev calculations. Yan presented the Sturmian functions approach which is effective and accurate in Kaonic atom studies. Deeply bound kaonic nuclear states of the $\bar{K}NN$ system were predicted by Akaishi and Yamazaki. Sato reported results of $\bar{K}NN$ - $\pi\Sigma N$ coupled channel Faddeev calculations.

## 4. Techniques in Few-body physics

Witała presented a new scheme, in which the technical challenge of numerically handling of the well known logarithmic singularities of the three-body Faddeev kernel in the continuum is circumvented and replaced by kernels which contain only simple poles in one variable. Hadizadeh *et al.* demonstrated numerical accuracy of the three dimensional approach in the Faddeev equation. Fachruddin *et al.* presented a three-dimensional formalism for scattering of spin-zero and spin-half particles. Both approaches which do not rely on a partial wave decomposition are necessary at higher energies where in addition relativity has to be taken into account [9]. In addition, avoiding the complexity of a partial wave decomposition for the numerous 3NF's of $\chi$EFT will provide benefit.

Realistic potentials and the Jacobi coordinates in theoretical schemes of few-Body physics will likely also be used in the future; for calculations of properties of light nuclei different schemes like the Tensor optimized shell model with unitary correlation operator (Myo *et al.* ), and the M-scheme cluster orbital shell model (Masui) which also start with realistic bare potentials, have been applied.

## 5. Concluding Remarks

APFB08 was a very successful conference attracting about 70 participants from 19 countries. We congratulate the organizers Profs. I. Fachruddin and T. Mart, and the staff from University of Indonesia for this very satisfying conference experience for all participants. I understand that they would also like to acknowledge the assistance of Prof. K. Sagara and Dr. Amarilla Malik in supporting the meeting.

To encourage the young scientists in this field the conference presented awards continuing the tradition since the first APFB conference. Dr. T. Watanabe from Tokyo University of Science, Dr. W. Horiuchi from Niigata University, and Dr. A. Deltuva from University of Lisbon were the successful recipients of those awards.

During our stay in Indonesia we had an enjoyable time and made the acquaintance of Indonesian culture through non-scientific activities.

We look forward to further progress in the field of few-body physics by next year, 2009, when the International Few-Body conference will be held in Bonn and by the year 2012 in Japan, and to the European conference which will be held in 2010 in Spain.

## Acknowledgments

This work is supported by Kyushu Institute of Technology. The author would like to thank Profs. Ch. Elster and W. Glöckle for critically reading the manuscript.

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