Nuclear Physics News

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Integrating in Europe

During the last 20 years the process of integrating the European Countries within the structure of the European Union was much harder for Eastern Countries where the starting point was behind the Iron Curtain. However, nuclear physicists from these countries integrated much faster than their respective societies; they were already, more or less, integrated mostly due to the previous personal scientific collaborations. During the transition period these collaborations were fruitful and beneficial for scientific and financial survival.

Today the situation is changed. The Eastern European Countries are politically integrated in EU and we have to find the right way to fully integrate in the European nuclear physics community. In order to keep our strengths we have to concentrate in two directions: developing strong in-house programs and participation into European collaborations centered on the Large Scale Facilities (LSF): GSI, GANIL, ISOLDE, and so on.

These facilities are concentrated in Western Europe, whereas in Central and Eastern Europe the facilities are, by comparison, Small Scale Facilities (SSF). The European Research Infrastructure inventory should continue to keep both types of facilities, thought to be mutually complementary and seminal. A correct attitude and consequent practical approach should be developed in order to properly balance the two kinds of research. The LSF activities are and will be centered on the frontline research in the hottest topics of nuclear physics. Such experiments will generally target and investigate new nuclei, very far from the line of stability, therefore addressing the most exotic and perhaps ambitious aspects of nuclear structure physics. Such research would inherently draw on an extensive collaboration between groups from different institutes and universities, as well as on complex experimental setups, a large infrastructure and high running costs. For such an enterprise to thrive on a sustainable basis there will be a permanent need of well-educated and custom-trained physicists. From this point of view, SSFs could play a time-verified, substantial, and important part. Small scale facilities represent, even in a long run, a useful and profitable complement to the large scale facilities, and in more than one way.

Although there is no doubt that the activities conducted at LSFs are the most likely to generate breakthroughs in knowledge, commensurate with the money invested, it is also a fact that there are many other, more “classical” directions worth pursuing—because of their potential to add important contributions to the general development of the domain. Physicists with a deep knowledge of the domain—as there are many in the SSF groups—are constantly proving that there are experimental areas where low-energy accelerators and tools, much more modest than those at LSFs, may contribute with new, exciting results. In the context, the observation is perhaps worth making that, while the LSF may well make the cutting edge of modern Physics, it will continue to fall on the SSFs the natural burden of securing the “genetic diversity” of the research, and researchers—coming from a vitally important variety of geo-cultural environments, the absence of which would certainly jeopardize the future of the LSFs in the long run. The SSFs are essential in enhancing the contribution of the nuclear physics community in the big European Projects such as FAIR and SPIRAL2. And we are doing it with full enthusiasm and responsibility! Another aspect that was enduringly verified as profitable in the practice of the inter-laboratory cooperation in Europe is that an SSF may make an appropriate place for developing instruments, or measuring methods, or parts of these, that are intended for an LSF, saving in this way expensive beam time at LSFs.

SSFs are, traditionally, highly productive, performing excellent research. In all honesty, the simple fact is that the SSFs are, for decades now, the very cradle wherefrom top scientists have emerged to contribute to the personnel environment of the large installations—a process still ongoing. That would make the SSFs ideal places for educating and training young scientists in the field of nuclear physics. SSF-sized experiments addressing well defined and significant queries in Physics have a great potential in education and training of young researchers. At SSFs there is usually comparatively ampler “beam time,” and also one can iterate an experiment until the best results are achieved.
Moreover, the young people will go through all the steps: designing the experiment; building the experimental set-up; the preparation of the beam; performing the experiment; proper data acquisition and analysis; performing theoretical calculations and comparisons with various theoretical predictions; writing a paper for a peer-reviewed journal. All these stages, which of course parallel, at a smaller scale, a “large scale” experiment, are well under the control of the learning young person, making the research activity very attractive; even young students can be involved in real experiments early in their classes, at acceptable costs, to enjoy such activities and really acquire experimental and theoretical skills that would make them eligible, some time in their careers, for work in LSF groups.

Last, but not least, by the communities developed around them, by their diversity, by their experimental programs including various applications of nuclear physics, spin-offs of basic nuclear physics research, the SSFs contribute significantly to the public acceptance of nuclear research, a delicate issue with which the modern society is confronted.

The existing SSFs are usually financed by national authorities. This type of support may, in many cases, become stronger, if it can be demonstrated that such domestic activity enjoys international relevance; is able to improve the ability of the R&D realm to absorb EU funding, a deficit area, especially with some EU newcomers. The recognition of the positive role of the SSF and the effective support of the NuPECC and of all European Nuclear Physics scientists played and plays an important role in preserving and developing the East European Nuclear Physics Community.

In conclusion, the ambitious plans of developing Nuclear Physics in Europe can be accomplished only by common scientific programs sharing both resources and experience of the entire European Nuclear Physics Community from North to South and from West to East.

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Overview

MAMI, the MAInz Microntron, has become a synonym for a cw electron scattering facility in the 1.5 GeV range with an outstanding beam quality and reliability. The Institute for Nuclear Physics (IKP) at the Johannes Gutenberg University of Mainz, the home of MAMI, has developed and built this cascade of four recirculating machines for precision scattering experiments mostly with polarized electrons and photons for research in the field of hadron and nuclear physics. The central physics topic is the investigation of strongly interacting systems with the electroweak probe. This field, nowadays called strong QCD, which means QCD in the strongly coupled, non perturbative regime, still poses a number of fundamental questions. The emergence of hadrons with their masses, charges, magnetization, and flavors, together with the corresponding spatial distributions, is not yet fully understood and still very far from precise predictions. This is also true for the response of hadrons to external fields known as polarizabilities, which are related to the generalized structure functions (GPDs).

The Institute runs four major experimental facilities, which are the basis of the experimental programme, and that have delivered data of exceptional quality. The most prominent facility is the 3-spectrometer setup, which is optimized for precision coincidence measurements of charged particles in exclusive electron scattering experiments. Its extraordinary missing mass resolution allows the detection of neutrals with high resolution and purity, which provides an excellent basis for virtual Compton scattering experiments. There is a long-standing collaboration with French institutes for these experiments. These days the spectrometer setup is being complemented with a new facility: the KAOS spectrometer, which has already served for the GSI kaon program and is now adapted for the strange hadron program at the new 1.5 GeV MAMI-C stage. Hyperons, strange mesons, and hypernuclei will become a focus of research at MAMI. Another highlight is the Crystal Ball detector, on leave from Brookhaven, now equipped with contemporary electronics and installed at the tagged photon facility setup built and upgraded with a major contribution from Glasgow University. An international collaboration makes use of the outstanding Crystal Ball facility for precision spectroscopy and polarized photon reactions. Finally, the PV-A4 spectrometer, also set up by an international collaboration, is running the world’s fastest counting homogeneous calorimeter for small parity violating effects in the scattering of polarized electrons, hunting for the strange contributions to the nucleon form factors.

A major trump card is the strong theory group of the institute, working in close collaboration with experimenters. Their work on effective field theories and lattice gauge field theory together with the application of classical tools like sum rules, dispersion theory, and partial wave analysis is both of high practical use and a guidance for future experimental efforts.

A comprehensive recent overview on the physics achievements at MAMI can be found in Ref. [1]. The scientific work at the institute is significantly supported by the German Science Foundation (DFG-SFB443).

The MAMI Accelerator Facility

The Institute has a long-lasting experience in the development, construction, and operation of electron accelerators for nuclear physics. Since 1967 it has operated a pulsed 400 MeV linear accelerator, which was built as a turn-key system by industry. Very soon it became clear that one’s own expertise in the field of accelerator physics is needed to cope with the increasing requirements concerning beam quality and stability. Therefore, a dedicated accelerator physics collaboration under the guidance of H. Herminghaus was founded. The increasing demand of the 1970s for coincidence experiments, not accomplishable with the 0.1% duty cycle linac, led in 1975 to the proposal of MAMI, an 800 MeV cw electron accelerator based on the Race Track Microtron (RTM) principle. The electron beam is recirculated by two 180° bending magnets many times through the same linac with moderate energy gain (~1 MeV/m), which is the prerequisite for cw-operation. This scheme makes efficient use of the rf-power and the inherent strong longitudinal phase focusing guarantees excellent beam quality and stability. Following the successful realization of a first 14 MeV demonstration RTM1 in 1979, a cascade of 3 RTMs was constructed in the framework
of a collaborative research center (see Figure 1). A first milestone was reached in 1983 when MAMI A, consisting of two RTMs yielding 180 MeV, came into operation for five successful years. After a period of construction to integrate the third RTM3, MAMI B was started in 1990. This machine delivers a low-emittance electron beam with 883 MeV maximum energy and an energy width of only 30 keV with the central value stabilized to 1 keV.

For the past two decades, under the responsibility of K.-H. Kaiser, MAMI B operated on average 6,000 hours per year for nuclear physics and for X-ray experiments. The latter especially benefit from possible beam sizes of less than 1 μm. Of steadily growing importance is the delivery of a spin-polarized electron beam. Presently, beam currents of up to 40 μA with a polarization in excess of 80% are routinely operated for more than 50% of the total run time of MAMI.

By the end of the 1990s, the demand for an energy increase up to 1,500 MeV arose. This was accomplished by adding a fourth accelerator stage, making use of the available resources and expertise. Adding another RTM was not possible because it would have required end magnets of ~2,200 tons each (compared to 450 tons of RTM3). Therefore, K.-H. Kaiser took up an earlier idea from the late 1970s, not realizable at that time, the Double Sided Microtron (DSM) consisting of two symmetric pairs of 90°-dipoles, each forming an achromatic 180° bending system with magnets of only 250 tons each (see Figure 2). To compensate for the strong vertical defocusing due to the 45° pole face inclination at beam entrance and exit, these dipoles incorporate an appropriate field gradient normal to the pole edge. One linac operates at 4.90 GHz (twice the MAMI standard frequency) for a low synchronous acceleration energy gain per turn (16.6–14 MeV) and thus a moderately powered rf-system. The other linac operates at 2.45 GHz for enhanced longitudinal stability. This rf-scheme gave rise to the name Harmonic Double Sided Microtron (HDSM). The construction work started in 2000. All important components were designed in house,
prototypes were built and tested in the institute prior to industrial fabrication. End of December 2006, within one day, the first test beam was guided through all 43 recirculations and reached the design energy of 1,508 MeV. After only a few weeks of beam tests the first nuclear physics experiment was conducted in February 2007. About 50% of the MAMI beam time in 2007 (7,180 h) was used for 1.5 GeV operation. All design parameters of the HDSM, including the max. current of 100 μA (151 kW of beam power), have been verified. The mean availability of the beam for experiments (>80%) is already on the same high level as in the past, a clear demonstration that the HDSM scheme is the best upgrade of the reliable and stable RTM cascade.

A1 Collaboration

The largest experimental hall of the MAMI accelerator complex houses the spectrometer setup for electron scattering experiments (Figure 3) operated by the A1 collaboration with 50 members from 20 countries.

The working horses of the setup are three high-resolution spectrometers with a resolution \( \delta p/p < 10^{-4} \) with a large solid angle acceptance of up to 28 msr and a momentum acceptance of up to 25%. As a unique feature of the setup all three high-resolution spectrometers are available at the same time for triple coincidence experiments. One of the spectrometers can be tilted up to an out-of-plane angle of 10 degrees. A proton recoil polarimeter gives, in combination with the polarized MAMI beam and a polarized Helium gas target, access to a broad variety of polarization observables up to triple polarization experiments.

In addition, several other detectors are installed on demand. For the detection of neutrons with large solid angle, time-of-flight scintillator walls are situated at backward angles. For neutron detection in forward direction highly shielded scintillator detectors are available. A short-orbit spectrometer is used to detect low-energetic pions. A new spectrometer covering high momenta with a moderate path length for the detection of kaons is currently in the commissioning phase (Figure 4).

The physical program of the A1 collaboration is focused on hadron structure. The setup is well suited to explore fundamental properties of the nucleon, for example, charge distributions by elastic form factor measurements and generalized polarizabilities by virtual Compton scattering. Meson production gives access to the resonance structure of the nucleon and meson properties.

A2 Collaboration

A photon incident on a nucleon couples to the nucleon electromagnetic current causing it to radiate

Figure 3. The spectrometer setup of the A1 collaboration. Three high resolution spectrometers pointing to a target at the common pivot point are used for electron scattering experiments.
mesons if the photon energy is sufficiently high.

Such reactions induced by circularly and linearly polarized real photons up to energies of 1.5 GeV are being studied by the international A2 collaboration at MAMI. Quasimonochromatic, energy-tagged photons are produced via Bremsstrahlung using a dedicated tagging spectrometer provided by the University of Glasgow.

As an example for a pioneering effort over several years, Figure 5 shows the helicity difference $s_{3/2}-s_{1/2}$ measured with circularly polarized photons and longitudinally polarized protons compared to the total photo absorption cross-section.

Since 2004, the Crystal Ball calorimeter, which was moved from BNL/AGS to Mainz, has been the central part of a hermetic detector system for present and future experiments. The Crystal Ball consists of 672 NaI(Tl) crystals covering 93% of the full solid angle with an excellent energy resolution of 1.7% for electromagnetic showers at 1 GeV. For charged particle tracking and identification two layers of coaxial multi-wire proportional chambers and a barrel of 24 scintillation counters surrounding the target are installed inside the cavity of the Crystal Ball sphere. The forward angular range is covered by the TAPS calorimeter consisting of 384 BaF₂ detectors (Figure 6).

As spin degrees of freedom are essential to understand nucleon excitations, the experimental setup is being complemented by polarized targets and a recoil polarimeter. In addition to the study of meson production processes the high intensity photon beam in combination with a hermetic detector allows us to investigate also hadronic and even rare meson decays. Especially, decays of the isoscalar h and h’ mesons offer unique possibilities to study symmetries and symmetry breaking patterns in QCD. Several experiments aiming at a precise determination of neutral decay parameters as well as the mass of the h meson have already been performed.

**A4 Collaboration**

The A4 experiment comprises a dedicated setup to measure small (order ppm) cross-section asymmetries in elastic scattering of polarized electrons off unpolarized protons. The small asymmetries require high luminosity, high count rate scattering experiments with data taking times in the order of 1,000 h. The experiment consists of a 1,022-channel, fast, electromagnetic, homogeneous PbF₂ calorimeter (see Figure 7) with its associated fast electronics. A high-power hydrogen and deuterium target allows to operate at luminosities between $5 \times 10^{37}$ and $10^{38}$. The setup includes two polarimeters, an absolute laser Compton-backscatter polarimeter, and a relative transmission Compton polarimeter.

The A4 collaboration (Mainz, Orsay, MIT, St. Petersburg) has studied in three measurements the parity violating cross-section asymmetry using longitudinally polarized protons at forward ($\theta_e=35^\circ$) and backward ($\theta_e=145^\circ$) electron scattering angles in order to extract the contribution of the strange quarks to the electromagnetic form factors $G_E$ and $G_M$. This is a clean study of the effects of the virtual quark sea in the low-$Q^2$, non-perturbative regime of QCD. In addition, measurements with transverse electron spin have unambiguously determined the imaginary part of the two-photon exchange amplitude, which has recently been under discussion.
Immediately after MAMI B became fully operational for nuclear physics experiments in the early 1990s, also a research program was launched to explore the potential of the high quality 855 MeV electron beam for applications. Various processes were examined for the production of soft and hard X-ray beams. These are transition radiation (TR), channeling radiation, parametric X-ray radiation, undulator radiation, and Smith-Purcell radiation.

The excellent transverse emittance of a 600 MeV electron beam, \( \varepsilon_h = 2.3 \mu\text{m mrad} \) and \( \varepsilon_v = 0.52 \mu\text{m mrad} \) in horizontal and vertical directions, respectively, allows the preparation of a beam spot with \( \mu\text{m} \) dimensions. Via TR production in a foil stack an X-ray beam with high transverse coherence can be prepared. An example of a hologram, taken with a monochromatic 6keV X-rays beam, is shown in Figure 8. Clearly visible are inhomogeneties within the string, which may be air bubbles or impurity inclusions that can not be recognized by an optical microscope. Worth mentioning are the small source-to-object and source-to-detector distances, as compared to synchrotron radiation sources.

The excellent energy breadth of the electron beam of \( 3.5 \times 10^{-5} \) enables the coherent production of soft and hard X-rays in two successive undulators or foils on the basis of which novel interferometers were developed with which the complex index of refraction of thin self-supporting foils can be measured.

**Activities of the Institute at COMPASS**

The measurements done at MAMI are complemented by investigations of the spin structure of the nucleon and hadron spectroscopy performed by the CsCOMPASS collaboration making use of the high-energy, high-quality M2 beams at the CERN SPS.

**Applied Physics with Coherent Radiation**

Figure 5. Helicity difference \( s_{3/2}^2 s_{1/2}^2 \) compared to the total absorption cross-section measured at MAMI and ELSA (Bonn) by the GDH collaboration.

Figure 6. Crystal Ball/TAPS calorimeter.
The spin structure measurements are done with a highly polarized 190 GeV/c muon beam and a large solid state target. Scattering muons inelastically off longitudinally polarized protons and neutrons allows one to extract the helicity distributions of quarks and gluons inside the nucleon and to study the contribution of the constituents to the nucleon spin. Using a transversely polarized target the distributions of transversely polarized quarks are measured in semi-inclusive deep inelastic scattering.

In addition, a program using high energy (190–220 GeV/c) hadron beams (\(\pi, K, p\)) has been started using diffractive and central meson production to search for exotic states like glueballs and hybrids.

A group of about 10 scientists from Mainz is participating in both electromagnetic and hadronic COMPASS programs. The main activities are the trigger system and data analysis for the muon and hadron programs.

Activities of the IKP Mainz at GSI/FAIR

Complementary to the electromagnetic probe, hadron structure can be addressed with hadronic probes at the close-by accelerator complex of the Gesellschaft für Schwerionenforschung (GSI) near Darmstadt. Moreover, hadron and nuclear physics with antiprotons are among the main scientific motivations of the future international Facility for Antiproton and Ion Research (FAIR) at GSI. Construction work for FAIR will start in late 2008. Mainz groups are involved in several activities both at GSI and FAIR.

Making use of the exotic heavy ion beams available at the present GSI facility, a Helmholtz research group at the IKP Mainz aims at the production and spectroscopy of proton- and neutron-rich exotic hypernuclei with the Hypernucleus experiment with Heavy Ions (HypHI) at GSI. This program is a natural complement of the hypernuclear program with the KAOS spectrometer at MAMI.

At FAIR, the High Energy Storage Ring (HESR) was designed to deliver cooled antiproton beams of unprecedented intensity and quality in the energy range of 1.5 to 15 GeV. Two groups at the IKP Mainz will examine the strong force in the framework of the PANDA experiment (antiProton ANnihilation at DArmstadt). On one hand, precision \(\gamma\)-ray spectroscopy of single and double hypernuclei represent a future extension of the present...
program at KAOS and HypHi. On the other hand, studies of the time-like structure of the proton by measuring Distribution Amplitudes, “spin” structure functions, and electro-magnetic form factors in the time-like region are a natural extension of the nucleon structure program at MAMI.

Theoretical Studies
The theory group’s activities are focused on the study of the strong interaction in the low-energy regime, using different and complementary approaches, comprising lattice simulations of Quantum Chromodynamics (QCD), effective field theories and other widely used methods in phenomenology such as dispersion relations.

Lattice QCD is a new activity at the Institute, which has recently established a research group working in that field. In order to meet the challenges of state-of-the-art simulations of QCD with dynamical quarks, the group is currently building up a large PC cluster with nearly 2,000 processor cores and a fast communication network. The aim is to generate large ensembles of gauge configurations with dynamical quarks that are light enough so that lattice results can be extrapolated reliably to the chiral regime, while keeping lattice artefacts under control. Research is focused on hadron structure and spectroscopy. To this end, hadron masses and matrix elements will be computed in order to determine the relevant form factors and structure functions and to study the interplay with effective field theories. Another line of research is aimed at topics in kaon and B-meson physics.

In addition to lattice simulations, effective field theory (EFT) provides a rigorous approach to QCD in the non-perturbative regime. The EFT resulting from the spontaneous breakdown of chiral symmetry is mesonic chiral perturbation theory (ChPT). The dynamics at low energies is described in terms of effective degrees of freedom, namely the almost massless Goldstone bosons (pions, kaons, and eta). One major part of the present activities deals with a covariant description of the baryonic sector of ChPT. The analysis of electromagnetically induced reactions on the nucleon, such as Compton scattering and pion production, plays a central role. Moreover, in order to increase the range of applicability, the EFT program is extended to also include meson as well as baryon resonances. In particular, the chiral EFT has recently been extended to include the $\Delta (1232)$ resonance, allowing the study of the nucleon and $\Delta$-resonance properties in a profoundly different way. It provides a new challenge as it involves the interplay of two light mass scales (the pion mass and the $N - \Delta$ mass difference). The systematic calculation of the pion mass dependence already provides a connection with present lattice QCD results, whereas the signatures of the opening of a decay channel (due to the unstable nature of the resonance) are being studied as a testing ground to connect with lattice QCD results (which are being performed for stable particles).

Present results include the electromagnetic $N \rightarrow \Delta$ transition form factors and the $\Delta$ magnetic dipole moment guiding an experimental program using the Crystal Ball detector.

Further support to the experimental program at MAMI is also being performed by different phenomenological approaches. Notably, a unitary isobar model analysis (MAID) in combination with input from dispersion relations has been developed and is being used by the community to extract properties of higher nucleon resonances from experiments at the different electron scattering facilities. An extensive dispersion relation framework for real and virtual Compton scattering has been developed to guide and interpret the experiments at MAMI and elsewhere aimed at extracting nucleon polarizabilities. Such formalism is also being applied to quantify the two-photon processes studied by the A4 Collaboration using a transverse electron beam polarization.

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Reference
Non-Spherical Shapes of the Proton: Existence, Measurement, and Computation

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Introduction

How can the spin 1/2 object known as the proton have a non-spherical shape? Why would a physicist even think of such a concept? Can a non-sphericity (or pretzelocity) be measured or computed? This article is concerned with such questions.

The notion that the proton might not have a spherical shape has its impetus in the discovery that the spins of quarks and anti-quarks account for only about 30% of the total angular momentum [1]. Many experiments have sought the origins of the remainder, expected to arise from quark and gluon orbital angular momentum or from pairs of strange quarks.

This article is concerned with the relation between the quark orbital angular momentum and the non-spherical shape of the proton. A number of concerns arise immediately. As a particle of spin 1/2, the proton can have no quadrupole moment, according to the Wigner-Eckart theorem. In elastic electron-proton scattering experiments, the effects of relativity cause the initial and final wave functions to differ because their momenta differ. For example, one thinks of a particle in relativistic motion having a pancake shape because of the effects of Lorentz contraction. Such an effect is not a manifestation of the intrinsic proton shape.

The presence of significant orbital angular momentum can only lead to a non-spherical shape if such can be defined by an appropriate operator. We used the proton model of Ref. [2]–[4] to show [5] that the rest-frame ground-state matrix elements of spin-dependent density operators reveal a host of non-spherical shapes.

Experimental Genesis

The electromagnetic current matrix element can be written in terms of the Dirac \( F_1(Q^2) \) and Pauli \( F_2(Q^2) \) form factors, \( Q^2 \) is the negative of the square of the space-like four-momentum transfer. These form factors are probability amplitudes that the proton can absorb a squared four momentum transfer \( Q^2 \) and still remain a proton. Two exist because the rapidly moving quarks within the proton carry both charge and magnetization densities. For \( Q^2 = 0 \) the form factors \( F_1 \) and \( \kappa F_2 \) are the charge and the anomalous magnetic moment \( \kappa \) in units \( e \) and \( e/2M_N \) and the magnetic moment \( \mu - 1 + \kappa \). The Sachs form factors are

\[
G_E = F_1 - \frac{Q^2}{4M_N^2} \kappa F_2, \quad G_M = F_1 + \kappa F_2.
\]

In the non-relativistic quark model, \( G_E \) and \( G_M \) are Fourier transforms of the ground state matrix elements of the quark charge \( (\Sigma_{i=1,3} e_i \delta(\mathbf{r} - \mathbf{r}_i) \) and magnetization \( \Sigma_{i=1,3} \frac{\mathbf{e}_i}{2m_i} \delta(\mathbf{r} - \mathbf{r}_i) \) density operators. Thus, non-relativistically, one expects that

\[
G_E(Q^2)/G_M(Q^2) = 1.
\]

Interestingly, the opposite highly relativistic limit, in which dimensional counting applies, predicted [6] (using the notion of helicity conservation in the interactions between photons and massless fermions) that

\[
\lim_{Q^2 \to \infty} QF_2/F_1 = m_q/Q^2, \quad \text{where } m_q \text{ is the small mass of a down or up quark.}
\]

This is equivalent to the non-relativistic expectation. Thus theoretical expectations (and early data) were that the ratio of the Sachs form factors would be constant. These expectations were dramatically thrown aside with the discovery that \( GE/GM \) falls rapidly with increasing values of \( Q^2 \) and that \( QF_2/F_1 \) is approximately constant [7], [8]. See Figure 1, which also displays the results of our 1995 theory [2, 3].

An explanation [3] of how the model of [2] describes the data showed that the constant ratio \( QF_2/F_1 \) emerges from the model’s relativistic aspects. For the proton wave function, only the component in which the first two quarks have a vanishing total angular momentum enters in computing the electromagnetic form factors. Then the angular momentum of the proton \( S \) is governed by that of the third quark. The relevant Dirac spinor is:

\[
u(K, S) = \frac{1}{\sqrt{E(K) + m_q}} \left( \frac{(E(K) + m_q) |S\rangle}{\sigma \cdot K |S\rangle} \right). \quad (1)
\]
with $E(K) = (K^2 + m^2)^{1/2}$. The magnetic quantum number of the proton is denoted by $S$, and the lower component contains a term $\sigma \cdot K$ that allows the quark to have a spin opposite to that of the proton’s total angular momentum. The vector $K$ reveals the presence of the quark orbital angular momentum: the struck quark may carry a spin that is opposite to that of the proton. Consequently nucleon helicity [9] is not conserved [10, 11].

**Spin-Dependent Density Operators**

We interpret orbital angular momentum in terms of the shapes of the proton by these are exhibited through the rest-frame ground-state matrix elements of spin-dependent density operators [5]. The usual quantum mechanical density operator is $\hat{\rho}(\mathbf{r}) = \sum_i \delta(\mathbf{r} - \mathbf{r}_i)$, where $\mathbf{r}_i$ is the position operator of the $i$’th particle; but for particles of spin 1/2 one can measure the combined probability that particle is at a given position $\mathbf{r}$ and has a spin in an arbitrary, fixed direction specified by a unit vector $\mathbf{n}$. The resulting spin-dependent density SDD operator is

$$\rho(\mathbf{r}, \mathbf{n}) = \sum_i \delta(\mathbf{r} - \mathbf{r}_i) \frac{1}{2} (1 + \sigma_i \cdot \mathbf{n}).$$  

To understand the connection between the spin-dependent density and orbital angular momentum, consider a first example of a single charged particle moving in a fixed, rotationally invariant potential in an energy eigenstate $|\Psi_{l,1/2,\alpha}\rangle$ of quantum numbers: $l = 1, j = 1/2$, polarized in the direction $\hat{s}$ and radial wave function $R(r_i)$. The wave function can be written as $(\mathbf{r}_i | \Psi_{l,1/2,\alpha}\rangle = R(r_i) \hat{s} \cdot \hat{r}_i | \alpha\rangle$. The ordinary density $\rho(r) = \langle \Psi_{l,1/2,\alpha}|(\mathbf{r}_i - \mathbf{r}_j)|\Psi_{l,1/2,\alpha}\rangle = R^2(r)$, a spherically symmetric result because the effects of the Pauli spin operator square to unity. But the matrix element of the SDD is more interesting:

$$\rho(\mathbf{r}, \mathbf{n}) = \frac{R^2(r)}{2} \langle \hat{s} | \sigma \cdot \hat{r}(1 + \sigma \cdot \hat{n}) \sigma \cdot \hat{r} | \hat{s}\rangle.$$  

The magnetic quantum defines an axis, $\mathbf{s}$ and the direction of vectors can be represented in terms of this axis: $\hat{s} \cdot \hat{r} = \cos \theta$. Suppose $\hat{n}$ is either parallel or anti-parallel to the direction of the proton angular momentum vector $\hat{s}$. Then

$$\rho(\mathbf{r}, \mathbf{n} = \hat{s}) = R^2(r) \cos^2 \theta, \; \rho(\mathbf{r}, \mathbf{n} = -\hat{s}) = R^2(r) \sin^2 \theta,$$

and the

**Figure 1.** The ratio $Q_2/F_1$. The curves from the 1995 theory [2] for the ratio are labeled by the value of a model parameter. The data are from Ref. [7] and [8]. Figure reprinted with permission from [3]. Copyright 2002 by the American Physical Society.

**Figure 2.** (Color online) Shapes of the proton. $\mathbf{S}$ is in the vertical direction. Left column: quark spin parallel to nucleon spin. Right column: quark spin anti-parallel to nucleon spin. The value of $K$ increases from 0 to 1 to 4 GeV/c. Figure reprinted with permission from Ref. [5]. Copyright 2003 by the American Physical Society.
non-spherical shape is exhibited. The average of these two cases is a spherical shape.

Another useful example is that of the Dirac four-component spinor electron wave function of the hydrogen atom ground state, with relative size of the lower component governed by the fine structure constant, \( \alpha \). The expectation value of the spin-dependent density operator, computed using Dirac matrices, with \( \sigma = \gamma^0 \gamma \cdot n \), is \( \rho(\mathbf{r}, \hat{n} = \hat{s}) \approx [1 + \alpha^2/4 \cos^2 \theta] \sim 1 + 10^{-5} \cos^2 \theta \) with \( n = \hat{s} \). For \( n = -\hat{s}, \rho(\mathbf{r}, \hat{n} = -\hat{s}) = \alpha^2 \sin^2 \theta/4 \).

Relativity as manifest by lower components of the Dirac wave function causes the hydrogen atom to be slightly, but definitely, non-spherical!

The notion of the SDD can be extended. In condensed matter applications [12] neutrons interact with atomic electrons, and only the (electronic) spin-dependent term of Eq. (2) is used. For quark systems, the densities could be weighted by the charge or flavor of the quarks, or use other operators. In particular, we use [13]

\[
\hat{\rho} \mathbf{R}(\mathbf{r}, \mathbf{n}) \equiv \sum \delta(\mathbf{r} - \mathbf{r}_i) \frac{1}{2} (1 + \gamma_i^0 \sigma_i \cdot \mathbf{n}), \tag{4}
\]

which is more experimentally accessible.

Now turn to the proton. Its wave function is specified in momentum space, so we define [5] a charge-weighted SDD operator (the probability that a quark has a momentum \( \mathbf{K} \) and spin direction \( \mathbf{n} \)):

\[
\hat{\rho}(\mathbf{K}, \mathbf{n}) = \int \frac{d^3 \xi}{(2\pi)^3} e^{i \mathbf{K} \cdot \xi} \bar{\psi}(\xi) \frac{Q}{\epsilon} (\gamma^0 + \gamma \cdot \mathbf{n} \gamma_5) \psi(0), \tag{5}
\]

where \( Q/\epsilon \) is the quark charge operator in units of the proton charge. The quark field operators are evaluated at equal time, \( \xi^0 = 0 \). For the case of \( \hat{\rho}_R \) the term \( \gamma \cdot \mathbf{n} \) is replaced by \( \gamma^0 \gamma \cdot \mathbf{n} \). For a spin-polarized (in the \( \hat{S} \) direction) proton at rest \( |\psi_R \rangle \), the matrix elements of \( \hat{\rho}, \hat{\rho}_R \) (SDDs) are given by

\[
\rho(\mathbf{K}, \mathbf{n}, \mathbf{S}) = A \mathbf{n} \cdot \hat{S} + C(\mathbf{K} \cdot \hat{S}) \mathbf{K} \cdot \hat{S} - \frac{1}{3} \mathbf{n} \cdot \hat{S}, \tag{6}
\]

\[
\hat{\rho}_R(\mathbf{K}, \mathbf{n}, \mathbf{S}) = A_R \mathbf{n} \cdot \hat{S} + C_R(\mathbf{K} \cdot \hat{S}) \mathbf{K} \cdot \hat{S} - \frac{1}{3} \mathbf{n} \cdot \hat{S},
\]

where \( A, B, \ldots \) are scalar coefficients. These forms represent the most general rest frame shape of the proton, if parity and rotational invariance are upheld [5].

We display the shapes of \( \rho(\mathbf{K}, \mathbf{n}, \mathbf{S}) \) [5] in Figure 2 for the cases of quark spin parallel and anti-parallel to the polarization direction of the proton \( \mathbf{S} \). The shape for a given value of \( K \) is determined by the ratio of the upper to lower components of the quark Dirac spinor, Eq. (1). The relatively large value of the ratio implies considerable non-sphericity and a sharp contrast between the proton and hydrogen atom. As the value of \( K \) increases from 0 to 4 GeV/c the shape varies from that of a sphere to that of a peanut, if \( n \parallel S \). The torus or bagel shape is obtained if \( -n \parallel S \). Taking \( n \perp S \) leads to some very unusual shapes shown in Figure 3. Using the given model [5], one may also obtain in coordinate space SDDs. Possible shapes include a pretzel form [5].

Any wave function yielding a non-zero value of the coefficient \( C(\mathbf{K}^0) \) or \( C_R(\mathbf{K}^0) \) represents a system of a non-spherical shape. If the relativistic constituent quark model

Figure 3. Shapes of the proton with \( n \cdot s = 0 \). Left column, \( n \) points (out of page), central: \( n \) points sideways, right \( n \) is out of the page at a 45° angle. The momentum \( K \) increases from 1 to 4 GeV/c. Figure reprinted with permission from Ref. [5]. Copyright 2003 by the American Physical Society.

\[
\sqrt{2} \hat{\rho}_R(\mathbf{K}_T, \mathbf{n})/\tilde{f}(\mathbf{K}_T^2). \quad \text{The horizontal axis is the direction of } S_T \text{ and } n = \hat{s}, \phi_b = \pi. \quad \text{The shapes vary from circular to highly deformed as } K_T \text{ is increased from 0 to 2.0 GeV in steps of 0.25 GeV. Figure reprinted with permission from Ref. [13]. Copyright 2007 by the American Physical Society.}
\]
of [2] is used, the extra $\xi^0$ changes the sign of the lower component of the wave function, causing $C_R = -C$. Thus either $C_R$ or $C$ can be used to infer information about the possible shapes of the nucleon. Measuring either would require controlling the three different vectors $n$, $S$, and $K$.

A specific aspect of $\hat{\rho}(K, n)$ is easily related to completed experiments because $\{dK \hat{\rho}(K, n)\}$ is a local operator. Its matrix element is a linear combination of the charge, integrals of spin-dependent structure functions $\Delta q$ (quark contribution to the proton total angular momentum), and $gA$ that can be determined from previous measurements. We find

$$\int d^3K \left( \hat{\rho}(K, n = \hat{S}, S) - \hat{\rho}(K, n = \hat{S}, S) \right) | N \rangle = \frac{1}{6}(\Delta q + \frac{1}{2}gA) = 0.68,$$

in which $\Delta q = 0.3$ [1] and $gA = 1.26$. The model we use gives 0.74 for the above quantity, indicating that shapes discussed here may not be unrealistic.

**Measuring the Non-Spherical Shape of the Nucleon**

Can non-spherical shapes be measured? While measurements of the matrix elements of the non-relativistic spin-density operator [12] reveal highly non-spherical densities, finding the non-spherical nature of the proton has remained a challenge. Here we explain how matrix elements of the spin-dependent density may be measured using their close connection with transverse momentum dependent parton densities.

The densities of Eq. (6) require that the system be probed with identical initial and final states. But this condition also enters in measurements of both ordinary and transverse-momentum-dependent TMD parton distributions. The latter [14] are:

$$F^{[\Gamma]}(x', K_T) = \frac{d^3K}{(2\pi)^3} e^{iK \cdot \xi} \langle P, S | 0 \rangle \langle 0 | \Gamma L(0, \xi; n) \psi(\xi) | P, S \rangle |_{\xi = 0},$$

where the specific path $n$ is that of Appendix B of [14]. The functions $\Phi^{[\Gamma]}$ depend on the fractional momentum $x = K^2/P^2$, $K_T$ and on the hadron momentum $P$. The operator $\Gamma$ can be any Dirac operator, for example, $\Gamma = i\gamma^+ = \frac{1}{2}\gamma^0 \gamma^i \gamma^5$, related to $h_{1T}^L$, which causes the non-spherical nature of $\hat{\rho}^L$.

It is therefore tempting to try to associate an SDD such as that of Eq. (5) with TMDs, but one difference is essential. Parton density operators, Eq. (8), depend on quark-field operators defined at a fixed light cone time $\xi^+ = \xi^0 = 0$ while our SDD is an equal-time, $\xi^0 = 0$, correlation function. However, a relation between the two sets of operators is obtained [13] by integrating the TMD over all values of $x$ setting $\xi^-$ to zero, and integrating Eq. (5) over all values of $K_T$ so that $\xi^3 = 0$. After integration, $\xi^2 = 0$ for both functions. The density operators, derived from those of Eq. (6), are denoted by adding a $T$ to the subscript. Thus

$$\hat{\rho}_{RT}(K_T, n, S_T) = \int_{-\infty}^{\infty} dK_z \hat{\rho}_R(K, n),$$

is therefore a matter of algebra to show that

$$\hat{\rho}_{RT}(K_T, n_T, S_T) = \int_{-\infty}^{\infty} dK_z \hat{\rho}(K_T, n_T, S_T) = \frac{1}{M^2} \tilde{h}_{1T}(K_T) \hat{K}_T \cdot \hat{n} \cdot \hat{S}_T,$$

in the rest frame, where a tilde is placed over each TMD parton distribution to denote an $x$-integrated function. Finding that non-zero value of $\tilde{h}_{1T} \neq 0$ would demonstrate that the proton is not spherical.

The term $\tilde{h}_{1T}^L$ causes distinctive experimental signatures in semi-inclusive lepton production hadron production experiments [15, 16]. If the target is polarized in a direction $S_T$ transverse to the lepton scattering plane, the cross-section acquires a term proportional to $\cos(3\phi_{h})$ where $\phi_{h}$ is the angle between the hadron production plane (defined by the momenta of the incoming virtual photon and the outgoing hadron) and the lepton scattering plane. A similar effect occurs in electroweak semiinclusive deep inelastic lepton-prodution [17]. In each of these cases, the momentum of the virtual photon and its vector nature provide the analogue of the vector $n$ needed to define the spin-dependent density. The hadronic transverse momentum provides the third, $K_T$. Another possibility occurs in the Drell-Yan reaction $pp(\Upsilon) \rightarrow \gamma l\bar{\nu}$, using one transversely polarized proton [18].

The shapes inherent in Eq. (9) are illustrated using the spectator model of Ref. [19]. Here $\phi$ is the angle between $K_T$ and $S_T$ and $\phi_{h}$ is the angle between $n$ and $S_T$. The transverse shapes of the proton (assuming a struck $u$ quark) are shown in Figure 4, taking $\phi_{h} = \pi$. This emphasizes the non-spherical nature because the first two terms of Eq. (9) tend to cancel. The shapes of Eq. (9) can be thought of as projections of the shapes displayed in previous figures.
The model [19] indicates that the functions \( f_1, h_1, \) and \( h_1^{+} \) have very similar \( x \) dependence, so that measurements at values of \( x \) for which these functions peak should be sufficient to construct the required integrals over \( x \).

The non-spherical nature of the nucleon shape is determined by the non-vanishing of the TMD \( h_1^{+} \). It is very exciting that experiments planned at Jefferson Laboratory aim to specifically measure \( h_1^{+} \) [20] and therefore determine whether or not the proton is round.

**Connection with Lattice QCD**

The non-spherical shape of the nucleon can be established in lattice QCD by computing the lattice version of the angular integral of the matrix element:

\[
F_T(r) = \int d^3r \left< \Psi_s \left| \psi(r) \left( \gamma_0 + \Gamma \gamma \cdot \mathbf{n} \gamma_5 \right) \psi(0) \right| \Psi_s \right>
\]

where \( \Lambda = 1 \) or \( \gamma^0 \) and the link operator is not displayed. A non-zero value of \( F_T(r) \) for any value of \( r \) would immediately tell us that the proton does not have a spherical shape. Matrix elements of \( \left< \Psi_s \left| \psi(0) \right| \right> \) have been evaluated for the case when the separation is one or two links. Thus the relevant information is available. Preliminary results for \( F_T(r) \) exist only for separations of one-link, and current statistics are not high [21]. Another possibility, closely related to finding \( h_1^{+} \), would be to take the spatial component of \( r \) to be perpendicular to \( s \) and integrate over the transverse directions. I hope that the lattice QCD community will find it of sufficient interest to warrant the effort of a detailed, high-statistics calculation.

**Summary**

The nature of the proton wave function can be elucidated by studying the matrix elements of a generalized density operator. Spin-dependent quark densities SDD are defined as matrix elements of density operators in proton states of definite spin-polarization, and shown to have an infinite variety of non-spherical shapes. For high momentum quarks with spin parallel to that of the proton, the shape resembles that of a peanut, but for quarks with anti-parallel spin the shape is that of a bagel. The matrix elements of the SDDs are closely related to specific transverse momentum-dependent TMD parton distributions accessible in the angular dependence of the semi-inclusive processes \( ep \to enX \) and the Drell-Yan reaction \( pp \to X \). New measurements or analyses would allow the direct exhibition of the non-spherical nature of the proton. The TMDs can be computed using lattice QCD so that the non-spherical shapes could be measured experimentally and computed using fundamental theory.

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**References**

9. The ratio of \( Q_2/F_1 \) is a ratio of a helicity-changing to a helicity-preserving matrix element.
Baryon-Baryon Interactions in a Quark Model and their Applications to Few-Baryon Systems

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Introduction

Strong interactions acting between baryons, the nucleon-nucleon (NN) interaction among others, play a basic role in building nuclei. Because of its importance enormous efforts, both experimental and theoretical, have hitherto been paid to understand the nature of the NN interaction. The quantum chromodynamics (QCD) [1] is nowadays believed to be a fundamental theory of the strong interaction. From this modern view, Yukawa’s meson theory [2] for the nuclear force is regarded an effective description of the interaction of the composite nucleons, governed by the strongly nonperturbative dynamics of quarks and gluons.

A recent lattice QCD calculation [3] confirms this view by producing both the short-range repulsion and medium-range attraction for the three-quark plus three-quark (3q-3q) configuration. Further studies in this direction have to be made for a quantitative description of the nuclear force.

The compositeness of baryons was exploited in the 1960s in a spin-flavor SU6 quark model to understand their ground-state properties. It was in the late 1970s that the QCD-inspired constituent quark model was initiated for the study of the NN interaction [4, 5]. Here the dynamics of the 3q-3q system was formulated in a microscopic theory called the resonating-group method (RGM). The inputs needed in the RGM are a quark-quark potential and a wave function ansatz for the baryons. The asymptotic freedom of QCD and the color confinement of the baryons are important ingredients to be reflected in the quark-quark potential. The former is modeled by the color analogue of the Fermi-Breit (FB) interaction, that is, the dominant one-gluon exchange interaction, and the latter is expressed by a phenomenological confinement potential that is assumed to be flavor independent. It has become vital to supplement the mesonic degrees of freedom for a realistic description of the medium- and long-ranged parts of the baryon-baryon interactions.

The quark-model baryon-baryon interaction has been extended by the Kyoto-Niigata group [6] to cover all pairs of the octet baryons B8 (N, Λ, Σ, Ξ). In the most recent model called fss2 [7], the meson-exchange effect is supplemented by effective meson-exchange potentials (EMEPs) acting between the quarks. The available data on the NN and hyperon-nucleon (YN) interactions are reproduced by including the scalar-, pseudoscalar-, and vector-meson nonets. The accuracy of fss2 is comparable to that of realistic meson-exchange models. An earlier model called FSS [8] does not include the vector-meson exchanges, reproducing the NN phase shifts less accurately than fss2. It should be noted that the RGM treatment of the composite baryons renders the baryon-baryon interaction non-local and energy-dependent.

There are all together 26 interactions for a pair of the B8B8 systems, depending on the isospin of the composite system and the even, odd partial waves of the relative motion. These are classified by the flavor-SU3 label, strangeness and isospin. One may think that it is almost impossible to discuss even the qualitative features of these interactions, but in fact introducing the EMEPs at the quark level has an important consequence in relating them [9], that is, the B8B8 interactions belonging to the same SU3 label are found to be similar to each other. This is because the spatial part of the spin-flavor SU6 3q-baryon is described with a common (0s)\(^3\) harmonic-oscillator wave function, and because the quark-model Hamiltonian with the EMEP’s is approximately flavor-SU3 scalar, except for the important roles of pions with the very small mass.

In this article, we review the results and predictions based on the quark model concerning the B8B8 interaction, together with its application to three-baryon systems, the triton and hypertriton.

NN Phase Shifts and YN Cross-Sections in the Quark Model

Figures 1(a)–1(d) compare the np phase shifts and a mixing angle \(\epsilon_1\) predicted by fss2 with those of SP99 by Arndt et al. [10]. The fss2 reproduces the NN phase-shift
parameters very well for $T_{lab} < 300$ MeV. More information is available in QMFPACK homepage [11]. Figure 2 displays the total cross sections of some YN scatterings. Here the “total” cross-sections in the $\Sigma^+$ and $\Sigma^-$ systems are evaluated by integrating the differential cross-sections from $\cos \theta_{min} = 0.5$ to $\cos \theta_{max} = -0.5$. The quark model reproduces the YN data fairly well although the experimental error bars are large.

**Flavor SU$_3$ Symmetry for Two Octet-Baryons**

Because the quark-model Hamiltonian is approximately flavor-SU$_3$ scalar, a unified view of the $B_B$ interactions emerges from the characteristics of the SU$_3$ classification. As the $B_B$ baryon belongs to a multiplet of the SU$_3$ label $(\lambda \mu) = (11)$, any $B_B B_B$ system can be decomposed into six SU$_3$ labels as follows: $(11) \times (11) = (22) + (30) + (03) + (11) + (11) + (00)$. The SU$_3$ label $(11)$ appears twice, so that it is convenient to define them as symmetric $(11)$, or antisymmetric $(11)$, according to flavor-exchange symmetry P of the two baryons. The other unique labels have definite symmetry $P = (-1)^{\lambda+\mu}$. Table 1 lists the relationship between the particle basis, $B_B B_B$, with a definite isospin I and the flavor-SU$_3$ label $(\lambda \mu)$. All the $B_B B_B$ interactions are obtained as a combination of the six interactions: $(22)$, $(11)_s$, $(00)$ for the symmetric $(P = 1)$ states and $(03)$, $(11)_a$, $(30)$ for the antisymmetric $(P = -1)$ states. Possible isospins I are determined for each $(\lambda \mu)$ label: I=0, 1/2, 1, 3/2, 2 for $(22)$, I=0, 1/2, 1, 3/2 for $(30)$ and $(03)$, I=0, 1/2, 1 for $(11)_s$ and $(11)_a$, and I=0 for $(00)$.

The most important factors for the interactions in the S wave are the effect of the quark Pauli principle and the color-magnetic term contained in the FB interaction.

**Figure 1.** np phase shifts calculated by fss2. SP99 is the phase-shift analysis taken from Arndt et al. [10].
The Pauli effect becomes crucial when the two baryons overlap on the top of each other forming a compact 6q configuration. The color-magnetic interaction usually gives a short-range repulsion for the B8B8 interactions except for the flavor-singlet (00) case. Table 2 summarizes the features of the S-wave interactions. The NN system is either in (22) for I = 1 or in (03) for I = 0. The latter involves the 3S1 state, and is strongly attractive due to the 3S1-3D1 tensor coupling induced by the one-pion exchange. The strong short-range repulsion in the NN interaction is generated not by the Pauli principle, but by the color-magnetic interaction. The 1S state of (11)s symmetry involves the Pauli-forbidden state and the 3S state of (30) symmetry involves the almost Pauli-forbidden state. Because of these kinematical effects, their S-wave interactions are strongly repulsive. For example, the 3S state of the ΣN interaction with I = 3/2 is strongly repulsive, because it consists of the pure (30) state. The experimental evidence for this Pauli repulsion is found in the single-particle potential of the Σ hyperon. Many recent analyses [12–14] of inclusive (p, K+) spectra for the Σ formation indicate that the σ-nucleus potential is in general repulsive with the strength of about 30 MeV [15].

The most prominent feature of the quark-model B8B8 interaction appears in the so-called H-particle channel. The H particle has a compact (0s)6 structure with spin zero, isospin I = 0, and flavor-SU3 symmetry (00). It is represented in the particle basis as

\[ |H\rangle = \frac{1}{\sqrt{8}} |ΛΛ\rangle + \frac{2}{\sqrt{8}} |ΞN\rangle - \frac{\sqrt{3}}{\sqrt{8}} |ΣΣ\rangle \]
This channel is special because the color-magnetic interaction gives strong attraction, a reason for possible existence of the H particle. Our quark model, however, predicts no H-particle bound state because the attraction is largely canceled by repulsive effects due to the strange-meson exchange EMEP’s, the \( \kappa \)-meson exchange in particular [16]. Most ambiguous in Table 2 is the interaction in the \((11)\) state, which occurs as the \( \Xi N \; ^3S_1 \) state with \( I=0 \). This interaction is weakly attractive in our quark-model, but no experimental information is available yet. Because the flavor-SU\(_3\) symmetry, unlike the isospin, is only approximately conserved, the coupling of different B\(_8\)B\(_8\) systems actually causes complexity in their interactions, as will be discussed below. The strong effect of the one-pion exchange tensor force also largely modifies the coupling features even within the framework of explicit SU\(_3\) relations for the EMEP coupling constants.

**YN Interactions in the Strangeness S = \(-1\) Sector**

There are two isospin channels with \( I = 3/2 \) and 1/2. Let us first discuss the simplest case, \( \Sigma N \) with \( I = 3/2 \). The \(^1\)E and \(^1\)O states of this system belong to the \((22)\) label. The phase-shift behavior of these partial waves therefore resembles that of the NN system with \( I = 1 \), provided the effect of the flavor symmetry breaking is not significant. Actually the attraction in the \(^1\)S\(_0\) state is much weaker than that of the NN system, and the phase-shift peak is about 27° around \( p\Sigma = 200 \text{ MeV}/c \). The \(^3\)P\(_1\) phase shifts show energy dependence characteristic in the NN phase shifts, resulting from the different roles of the central, tensor and LS forces. The observed asymmetry of the \( \Sigma p \) elastic scattering [17] shows a pattern similar to the np polarization data [18]. The \(^3\)E and \(^1\)O states of the \( \Sigma N \) system with \( I = 3/2 \) consist of pure \((30)\) symmetry, indicating that the interaction in the \(^3\)S\(_1\) state is strongly repulsive. The \(^3\)P\(_1\) phase shift turns out to be weakly attractive owing to the contribution from the RGM exchange kinetic-energy kernel.

The interaction with \( I = 1/2 \) is somewhat complicated because of the \( \Lambda N - \Sigma N \) coupling. In the flavor-symmetric channels, the \( \Lambda N \) state consists of 22 symmetry by 90%, while the \( \Sigma N \) contains the \((11)\), component by 90%. Table 2 suggests that the \( \Lambda N \; ^1\)S\(_0\) interaction is attractive and the \( \Sigma N \; ^1\)S\(_0\) interaction is repulsive. In the flavor-asymmetric channels with \( I = 1/2 \), we have \( \Lambda N = 1/\sqrt{2} \; [- (11) \text{ } + \text{ } (03)] \) and \( \Sigma N = 1/\sqrt{2} \; [(11) \text{ } + \text{ } (03)] \). Here the weakness of the \((11)\) interaction makes discussion a little simpler. In so far as one neglects this interaction and assumes the strict SU\(_3\) symmetry of the quark Hamiltonian, the YN interactions with \( I = 1/2 \) are related to the NN interaction with \( I = 0 \) as follows:

\[
V_{I=1/2}^{\Lambda N} = \frac{1}{2} V_{I=0}^{\Lambda N} = V_{I=1/2}^{\Sigma N} = \frac{1}{2} V_{I=0}^{\Sigma N} \text{ in } ^3S_1.
\]

Unfortunately, the strong one-pion tensor force makes such a simple discussion somewhat unrealistic. In fact, the cusp structure of the \( \Lambda p \) total cross-sections in Figure 2(c) is the result of a very strong \(^3\)S\(_1\)-\(^3\)D\(_1\) coupling due to the one-pion tensor force acting between the \( \Lambda N \) and \( \Sigma N \) channels. A further enhancement of the cusp structure in the \( \Lambda p \) total cross-sections could be brought by the P-wave \( \Lambda N-\Sigma N \) coupling through the antisymmetric LS force (LS\(^{\mp}\)), which is generated from the FB interaction [8]. This interaction has the matrix element between \((11)_k \; ^3\)P\(_1\) and \((11)_k \; ^1\)P\(_1\) states even in the strict SU\(_1\) limit. We thus find that this \( \Lambda N-\Sigma N \; ^1\)P\(_1\)-\(^3\)P\(_1\) coupling is the main reason for very small \( \bar{s} \) splitting observed in many of the light \( \Lambda \)-hypernuclei, particularly in \(^9\)Be [19].

Large cancellation between the ordinary LS force and the LS\(^{\pm}\) force leads to the very small LS effect of the \( \Lambda N \) interaction, which is consistent with the small asymmetry parameter recently observed [17]. For the even parity states, the relative strength of the attractive \(^1\)S\(_0\) and \(^3\)S\(_1\) \( \Lambda N \) interactions is very sensitive to the binding energy of the hypertriton \(^3\)H [20]. As to the \( \Sigma N \; ^3\)S\(_1\) interaction with \( I = 1/2 \), the exact strength of attraction in this channel is still not clear. We definitely need experimental information to determine this strength. The experimental data available at present are only the low-energy \( \Sigma p \) cross sections and some of the \( \Sigma p \) inelastic capture ratio at rest for the transition \( \Sigma \rightarrow \Lambda n \) and the charge exchange reaction \( \Sigma \rightarrow \Sigma n \) [21, 22].

**Baryon-Baryon Interactions in Strangeness \( S \leq -2 \) Sector**

The \( B_8B_8 \) interaction in \( S = -2 \) gets valuable information from the existence/non-existence of the H-particle bound state and the discovery of the lightest double \( \Lambda \)-hypernuclei called the Nagara event [23]. If the H particle exist in nuclear medium, it would be unlikely that double \( \Lambda \)-hypernuclei exist. The very clear sequential decay process of \(^6\)\( _\Lambda \)\( _\Lambda \)He, found in the experiment at KEK, has given the binding energy of two \( \Lambda \) particles, \( B_{\Lambda \Lambda} \). The \( \Lambda \Lambda \) interaction energy, defined by

\[
\text{Table 2. Qualitative features of the S-wave } B_8B_8 \text{ interactions in the flavor-SU}_3 \text{ basis.}
\]

<table>
<thead>
<tr>
<th>( s )</th>
<th>( \bar{s} )</th>
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<tbody>
<tr>
<td>((22))</td>
<td>attractive</td>
</tr>
<tr>
<td>((11)_k)</td>
<td>strongly repulsive</td>
</tr>
<tr>
<td>((00))</td>
<td>attractive</td>
</tr>
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</table>
\[ \Delta B_{\Lambda\Lambda}(^{6}\Lambda\Lambda\text{He}) = B_{\Lambda\Lambda}(^{6}\Lambda\Lambda\text{He}) - 2B_{\Lambda}(^{5}\Lambda\text{He}), \]

is found to be \(1.01 \pm 0.20 \pm 0.018\) MeV [23]. This value is considerably smaller than a similar quantity of the \(\Lambda\text{N}\) interaction energy, \(\Delta B_{\Lambda\Lambda}(^{6}\Lambda\Lambda\text{He}) = 1.73 \pm 0.04\) MeV, estimated from the \(\Lambda\) separation energy of \(^{5}\Lambda\text{He}\) and the \(0^+, 1^+\) binding energies of \(^{4}\Lambda\text{H}\) and \(^{4}\Lambda\text{He}\) [24]. The strength of the attraction of the \(\Lambda\text{N}\), \(\Lambda\Lambda\text{N}\) and \(\Lambda\Lambda\) interactions is estimated from the maximum of the phase shifts in the low-momentum region. It then follows in our model that

\[ |V_{\Lambda\Lambda}^{I=0}| < |V_{\Lambda\Lambda}^{I=1/2}| < |V_{\Lambda\Lambda}^{I=1/2}| \text{ in } ^{1}S_{0}. \]

The attractive feature of the SU\(_3\) (00) state appears more effectively in the \(\Xi\text{N}\) channel with \(I = 0\) than in the \(\Lambda\Lambda\) channel, because the former contains the (00) component by 50% as seen in Table 1. Due to the subtle balance of the color-magnetic interaction for the (00), (22), and (11)\(_h\) states, it turns out that the EMEP contribution from the flavor-singlet scalar-meson \(\sigma\) (or \(\epsilon\)) is the main source of the attraction in the \(\Xi\text{N}\) system with \(I = 0\). The flavor antisymmetric \(\Xi\text{N}\) \(^3S\) state with \(I = 0\) is purely (11)\(_h\) and our quark-model gives very weak attraction for this channel. On the other hand, the SU\(_3\) structure of the \(\Xi\text{N}\) interaction for \(I = 1\) suggests a very strong \(\Xi\text{N}-\Sigma\Lambda\) coupling both in the \(^1S_0\) and \(^3S_1\) states. It is interesting to see that the contribution of the strange-meson exchange reduces the \(\Lambda\Lambda-\Xi\text{N}\) coupling for \(I = 0\), while it enhances the \(\Xi\text{N}-\Sigma\Lambda\) coupling for \(I = 1\) in the quark-model [16]. Owing to this strong coupling effect, the \(^1S_0\) and \(^3S_1\) phase shifts show prominent cusp structure at the \(\Sigma\Lambda\) threshold around \(p_{\Sigma\Lambda} = 600\) MeV/c [9]. Experimental data on \(\Xi^+\text{p}\) total cross-sections in-medium [25, 26] and low-energy \(\Xi^+\text{p} \rightarrow \Lambda\Lambda\) total cross-sections [27] are reported and further data with high statistics are certainly needed to examine predictions by the quark-model interactions.

The flavor-SU\(_3\) structure of the \(B_8\) states with \(S = -3\) and \(-4\) also makes it possible to expect some prominent features of the \(\Xi\Lambda\), \(\Xi\Sigma\), and \(\Xi\Xi\) interactions [9]. In the flavor-symmetric configurations including the \(^1E\) and \(^3O\) states, these interactions resemble the \(\Lambda\Lambda\), \(\Sigma\Lambda\), and \(\Sigma\Sigma\) interactions with somewhat reduced magnitude. This reduction is related to the weaker pion-exchange effect in the strangeness sector and the effect of the flavor symmetry breaking. For instance, the SU\(_3\) relation of the \(\pi\)-baryon coupling constants indicates \(f_{\Xi\Xi}/f_{\Xi\Lambda} = -1/5\) in the quark model. As the result, the direct

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**Figure 2.** \(YN\) total cross-sections calculated with fss2. For experimental data, see Ref. [6] and references therein.
coupling between the pion and the \( \Xi \) hyperon is strongly hindered. The \( ^3E \) and \( ^1O \) interactions with the flavor-antisymmetric configurations should have features quite different from those in the \( S = -1 \) and 0 sectors because the attractive SU\( _3 \) (03) interaction is replaced with the repulsive (30) interaction. The \( \Xi \Lambda \) interaction does not have any prominent cusp structure unlike the \( \Lambda N \) interaction, because the \( \Xi \Lambda - \Xi \Sigma \) coupling with \( I = 1/2 \) is not induced by the direct one-pion exchange but by the strange-meson exchange. The \( \Xi \Sigma \) interaction with \( I = 3/2 \) is attractive both in \( ^1S_0 \) and \( ^3S_1 \) states as these correspond to the (22) and (03) states, respectively. However, the attraction in the \( ^3S_1 \) state is not so strong, because the one-pion exchange hardly works due to the small \( \pi \Xi \) coupling. The \( \Xi \Xi ^3S_1 \) interaction with \( I = 0 \) is strongly repulsive like the \( \Sigma N \) \( ^3S_1 \) interaction with \( I = 3/2 \), because both interactions are characterized by pure (30) in the flavor-SU\( _3 \) limit.

**Few-Body Calculations of the Three-Nucleon and Hypertriton Systems**

Because the quark-model description of the short-range part is different from that of meson-exchange potentials, it is interesting to apply the present interaction to calculate the binding energies of the triton \( ^3H \) and the hypertriton \( ^3\Lambda H \) [28]. As mentioned in Introduction, the quark-model interactions are nonlocal and energy-dependent. Although the energy-dependence causes no problem for a two-body system, its application to the three-body systems requires a careful treatment. A clear-cut and unambiguous method is to eliminate the energy-dependence from the RGM equation using the well-known transformation of the relative motion function between the clusters [29]. Results shown later are based on this energy-independent \( B_{\Xi\Xi} \) interaction.

Table 3 lists the \( ^3H \) and \( ^3\Lambda H \) properties predicted by our quark-model interactions. The prediction for the \( ^3H \) energy is \(-8.326 \text{ MeV}\) for fss2. Compared to the observed value \(-8.482 \text{ MeV}\), the calculated value is too high by 156 keV. In fact, we have to take into account the charge-dependence effect of the two-nucleon force, which is estimated to lead to an energy loss of about 190 keV [30]. Therefore our calculation using the quark-model NN interaction misses the triton binding energy by about 350 keV. In order to demonstrate the correlation between the triton binding energy, \( B_t = -E( ^3H ) \), and the deuteron D-state probability PD, we display in Figure 3 the results given by fss2 and FSS together with the values calculated by various realistic NN potentials. We find that fss2 gives a larger binding energy than the modern realistic meson-exchange potentials such as Bonn-C and AV18. In Figure 3, the binding energies denoted by closed circles are reduced by about 190 keV when the charge dependence of the NN interaction is taken into account. Then the energies of all the modern meson-exchange potentials but Chiral potential fall on a line, but quite interestingly our quark-model points are apparently off that line.

The \( \Lambda \) separation energy, \( B_\Lambda = -E( ^3\Lambda H ) - e_d \), is calculated to be 262 keV as in Table 3. Here the calculated deuteron binding energy is \(-2.487 \text{ MeV}\) for fss2, and \(-2.35 \pm 0.05 \text{ MeV}\) for the Faddeev calculations with fss2 in the isospin basis, compared with experiment. The probability of the \( \Sigma NN \) component in the \( ^3\Lambda H \) ground state is 0.83%.

### Table 3. Triton \(^3H\) and hypertriton \(^3\Lambda H\) properties from the Faddeev calculations with fss2 in the isospin basis.

<table>
<thead>
<tr>
<th>( ^3H )</th>
<th>( E( ^3H ) ) (MeV)</th>
<th>( \sqrt{&lt;r^2&gt;_{^3H}} ) (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cal.</td>
<td>-8.326</td>
<td>1.75</td>
</tr>
<tr>
<td>exp.</td>
<td>-8.482</td>
<td>1.755 ± 0.086</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( ^3\Lambda H )</th>
<th>( E( ^3\Lambda H ) ) (MeV)</th>
<th>( B_\Lambda ) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cal.</td>
<td>-2.487</td>
<td>262</td>
</tr>
<tr>
<td>exp.</td>
<td>-2.35 ± 0.05</td>
<td>130 ± 50</td>
</tr>
</tbody>
</table>
energy is $\epsilon_{d}=2.2247\text{MeV}$ ($\epsilon_{d}^{\exp}=2.2246\text{MeV}$). Compared with the experimental value $130\pm50\text{keV}$, our quark-model $\Lambda N$ and $2N$ interactions overbind $^3\Lambda\text{H}$ by $82–182\text{keV}$. Although our $\Lambda N$ interaction seems to be too attractive, this overbinding is not directly connected with the overall strength of the $\Lambda N$ interaction. A detailed discussion on the relative strength of attractions in the $^1S_0$ and $^3S_1$ states leads to that the $^1S_0$ $\Lambda N$ interaction is only slightly more attractive than the $^3S_1$ $\Lambda N$ interaction. For the precise determination of the $^1S_0$ and $^3S_1$ $\Lambda N$ interactions, one must await a simultaneous description of all the experimental data of s-shell $\Lambda$-hypernuclei, including the $0^+$ and $1^+$ states of $^4\Lambda\text{H}$ and $^4\Lambda\text{He}$, and the $^5\Lambda\text{He}$ ground state. We still need lots of experimental and theoretical efforts to clarify the effects of the $\Lambda N$ interactions overbind $3\Lambda\text{H}$ by $82–182\text{keV}$.

**Outlook**

We have outlined the study of baryon-baryon interactions constructed in the quark model. The results are found successful in achieving most accurate descriptions of the strong interactions with a natural picture for the quark compositeness of baryons. Specific in the present quark model is that the short-range part of the interaction is appropriately described by the quark-gluon degrees of freedom and that the medium- and long-range parts are dominated by meson-exchange processes. An important principle of the framework is the explicit treatment of symmetries including color and flavor degrees of freedom as well as the quark antisymmetrization. Recent accumulation of experimental data especially in the strangeness sector is extremely important for further improvement of our model.

The nonlocality of the quark-model interactions is related to the composite structure of baryons, and its short-distance description is different from that of meson-exchange models. The calculation of the triton binding energy suggests that this difference influences physical quantities. It will thus be interesting to study the quark-model predictions in few-baryon problems, including three-nucleon scatterings and four-body systems. For this purpose we think that a simple parameterization of the quark-model baryon-baryon interactions will be useful to make them easily accessible.

**Acknowledgment**

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Atom Trap, Krypton-81, and Saharan Water

Much can be learned from the analysis of the ubiquitous long-lived radioactive isotopes. In the late 1940s, Willard Libby and coworkers first detected the cosmogenic $^{14}$C ($t_{1/2} = 5.7 \times 10^3$ yr, isotopic abundance $^{14}$C/$^{12}$C = $1 \times 10^{-12}$) in nature and demonstrated that such analysis could be used for archaeological dating. Since then, two by now well-established methods, Low-Level Counting (LLC) and Accelerator Mass Spectrometry (AMS), have been used to analyze $^{14}$C and many other radioisotopes and to extract valuable information encoded in the production, transport, and decay processes of these isotopes. Ultrasensitive analysis of long-lived radioisotopes is presently used in a broad range of scientific and technological fields including earth and environmental science, archeology, cosmochemistry, physics, biomedicine, as well as applications designed to ensure nuclear safety and security. In this report, we introduce Atom Trap Trace Analysis (ATTA), a recently developed atom-counting method capable of analyzing trace isotopes at the parts-per-trillion level. This method was developed by our group at Argonne National Laboratory and was used to analyze both $^{81}$Kr ($t_{1/2} = 2.3 \times 10^5$ years, $^{81}$Kr/$^{86}$Kr ~ $1 \times 10^{-12}$) and $^{85}$Kr ($t_{1/2} = 10.8$ years, $^{85}$Kr/$^{86}$Kr ~ $10^{-11}$) in environmental samples. As the first real-world application of ATTA, $^{81}$Kr dating was performed to determine the mean residence time, or the “age,” of the old groundwater in the Nubian Aquifer located underneath the Sahara Desert.

The dream of radiokrypton dating began in 1969 when Heinz Hugo Loosli and Hans Oeschger of the University of Bern first detected the decay of natural $^{81}$Kr in krypton gas extracted from the atmosphere. They proposed $^{81}$Kr as the ideal tracer isotope for dating water and ice in the age range of $10^5$–$10^6$ years, a range beyond the reach of $^{14}$C dating. $^{81}$Kr is mainly produced in the upper atmosphere by cosmic-ray induced spallation and neutron activation of stable krypton. Due to the constancy of the cosmic ray flux and the fact that the atmosphere is well-mixed and represents the only significant terrestrial krypton reservoir, the $^{81}$Kr isotopic abundance is expected to be uniform throughout the atmosphere and constant on the time scale of its lifetime. Subsurface sources and sinks for $^{81}$Kr other than radioactive decay are most likely negligible. Human activities involving nuclear fission have a negligible effect on the $^{81}$Kr concentration because the stable $^{81}$Br shields $^{81}$Kr from the decay of fission products. All of these favorable conditions combine to support the case of $^{81}$Kr dating. The situation is entirely different for the other long-lived krypton isotope, $^{85}$Kr, which is a fission product of $^{235}$U and $^{239}$Pu, and is released into the atmosphere primarily by nuclear fuel reprocessing. Its abundance has increased by six orders of magnitude since the 1950s. $^{85}$Kr can be used as a tracer to study air and ocean currents, determine

![Figure 1. Schematic layout of the ATTA apparatus. Metastable krypton atoms are produced in the discharge. The $^{81}$Kr atoms are transversely cooled, slowed, and trapped by the laser beams shown as solid arrows. The fluorescence of individual trapped $^{81}$Kr atoms is imaged to a detector. Total length of the apparatus is about 2.5 meters.](image1)

![Figure 2. Fluorescence signal of a single trapped $^{81}$Kr atom. The background is due to light scattered off walls.](image2)
residence time of young groundwater in shallow aquifers, and monitor nuclear-fuel processing activities.

For $^{85}$Kr analysis, LLC is performed routinely in several specialized laboratories around the world. LLC was also the first method used to detect $^{81}$Kr and measure its abundance in the atmosphere. However, LLC is too inefficient for practical analysis of $^{81}$Kr because only a fraction $3 \times 10^{-8}$ of $^{81}$Kr atoms in a sample decay during a typical 100-hour measurement. In general, counting atoms (neutral or ionized) is much more preferable to counting decays for analyses of long-lived isotopes such as $^{81}$Kr. An AMS method of counting $^{81}$Kr ions was successfully developed by Walter Kutschera of the University of Vienna and his collaborators in the 1990s. Their effort culminated in the $^{81}$Kr dating of old groundwater samples from the Great Artesian Basin of Australia—the very first realization of $^{81}$Kr dating. The accelerator used in this experiment was the K1200 Cyclotron at Michigan State University. This large, high energy (~4 GeV) cyclotron was needed to produce fully stripped $^{81}$Kr ions, which then can be cleanly separated from its abundant isobar, $^{81}$Br.

### Atom Trap Trace Analysis (ATTA)

Atom Trap Trace Analysis (ATTA) uses a tabletop apparatus in a regular laboratory environment. In ATTA, an atom of a particular isotope is selectively captured by resonant laser light in a magneto-optical trap and detected by observing its fluorescence (Figure 1). When the laser frequency is tuned to the resonance of the desired isotope, $^{81}$Kr or $^{85}$Kr, only atoms of this particular isotope are trapped. Atoms of other isotopes are either deflected before reaching the trap or are allowed to pass through the trap without being captured. An atom can be trapped and observed for 100 ms or longer, during which $10^6$ fluorescence photons can be induced from a single trapped atom and as many as $10^4$ photons can be detected, thereby allowing the counting of single atoms to be done with a high signal-to-noise ratio as well as a superb selectivity (Figure 2). Indeed ATTA is immune to interference from other isotopes, elements, or molecules.

Following the first demonstration of ATTA in 1999, we have steadily improved the reliability and counting efficiency of the ATTA instrument. In 2003–2004, we completed the development of the ATTA-2 instrument. With a modern atmospheric krypton sample, ATTA-2 can count $^{85}$Kr atoms at the rate of $240 \text{ hr}^{-1}$ and $^{81}$Kr atoms at the rate of $12 \text{ hr}^{-1}$. In order to achieve a statistical precision of ±10%, approximately 100 $^{81}$Kr atom counts need to be accumulated. At the ATTA-2 counting efficiency of $1 \times 10^{-4}$, such an analysis requires a modern krypton sample of 50 μL STP, which can be extracted from either 50 L STP of air or 1000 L of water.

![Figure 3. Proportional correlation between the $^{85}$Kr/$^{81}$Kr ratios measured with ATTA and the $^{85}$Kr/$^{81}$Kr ratios measured with LLC.](image)

![Figure 4. Ruler of progress. As the efficiency of the analyzer approaches unity (100%), the required water or ice sample size for $^{81}$Kr dating reduces to a fraction of one liter. Bars show the sample size required for dating water and ice.](image)
This system has met the minimum requirements of implementing practical \(^{81}\text{Kr}\) dating of old groundwater, as we have demonstrated in the study of the Nubian Aquifer in Egypt.

In order to demonstrate the validity of ATTA for quantitative analysis, we collaborated with a group led by Dr. Roland Purtschert at the University of Bern, and performed a set of inter-laboratory calibration measurements. The Bern group has expertise in noble gas sampling and LLC analysis of \(^{85}\text{Kr}/\text{Kr}\). They prepared ten different samples based on krypton extracted from modern air (age < 100 yr). Among the young samples, the \(^{81}\text{Kr}/\text{Kr}\) ratios are expected to be identical; on the other hand, the \(^{85}\text{Kr}/\text{Kr}\) ratios are expected to vary and were measured using LLC at Bern. The \(^{81}\text{Kr}/^{85}\text{Kr}\) values independently measured using ATTA by our group were then compared with the \(^{85}\text{Kr}/\text{Kr}\) values obtained using LLC by the Bern group. We demonstrated that the ratios measured by ATTA and LLC were directly proportional to each other within the measurement error of ±10% (Figure 3); we calibrated the \(^{81}\text{Kr}/\text{Kr}\) ratio of modern air measured using ATTA, which serves as the initial ratio in the calculation of groundwater residence times; and we showed that the \(^{81}\text{Kr}/\text{Kr}\) ratios of samples extracted from air before and after the development of the nuclear industry are identical within the measurement error.

The efficiency of atom counting still has room for large improvements. Figure 4 shows our “ruler of progress” for the \(^{81}\text{Kr}\) dating of old groundwater and polar ice. With the present ATTA-2 instrument, an analysis requires a sample of approximately one ton of water, which is not always feasible (e.g., for ice cores or submarine hydrothermal fluids). At present, we are developing ATTA-3 with the goal of further improving the efficiency to approximately 1% and reducing sample size for \(^{81}\text{Kr}\) dating down to ~10 kg. From ATTA-2 to ATTA-3, we aim to make the transition from a physics experiment to a practical trace analysis method. Meanwhile, we are exploring technologies on and communicating with experts of vacuum ultraviolet sources for the excitation of krypton atoms, which may lead to further improvements.

Applications

For the first real-world application of ATTA, measurements of \(^{81}\text{Kr}/\text{Kr}\) in deep groundwater from the Nubian Aquifer in the Western Desert of Egypt (at the eastern end of the Sahara Desert) were performed. This field study was done by a collaboration led by geologist Neil Sturchio of the University of Illinois at Chicago. For \(^{81}\text{Kr}\) dating, dissolved gas was extracted from several tons of water in the field at six sites (Figure 5). The \(^{81}\text{Kr}\) data indicate that ages increase progressively along flow vectors.

Figure 5. Map showing sample locations (red circles) and their \(^{81}\text{Kr}\) ages (in units of 10^5 years) in relation to oasis areas (shaded green), Precambrian basement outcrops (patterned), and other regional features. Groundwater flow in Nubian Aquifer is toward northeast.
predicted by numerical hydrodynamic models, verifying distant lateral flow of deep groundwater toward the northeast from a recharge area southwest of Dakhla. Furthermore, the $^{81}$Kr data indicate relatively high flow velocities (~2 m/yr) from Dakhla toward Farafra, and low velocities (~0.2 m/yr) from Dakhla toward Kharga and from Farafra to Bahariya. These observations are consistent with the areal distribution of hydraulically conductive sandstone within the aquifer and they provide support to some of the existing hydrodynamic models. Southwestward extrapolation of the ~2 m/yr flow rate inferred from the difference in $^{81}$Kr ages for Dakhla and Farafra is consistent with recharge in the area of the Uweinat Uplift near the Egypt–Sudan border. In this area, the Nubian sandstone is exposed (or buried beneath sand sheets or dunes) at elevations between 200 and 600 m above sea level over a wide area, forming a broad catchment for recharge of the Nubian Aquifer.

Ice cores found in Greenland and Antarctica are the most important archives to study the composition of the atmosphere, reaching back in time perhaps one million years. Through precipitation and air bubble occlusion a direct imprint of atmospheric conditions is preserved in time. Ice cores can be dated most accurately as long as annual layers can be counted back in time (similar to counting tree rings). This can be accomplished by various methods such as annual grey-scale variations and seasonal $^{818}$O oscillations. However, eventually the annual structure disappears under the enormous pressure of the overlying ice, and ice accumulation models have to be employed to determine the age of deep ice. In principle, $^{81}$Kr would be well suited to date ice back to one million years, and perhaps beyond. The main obstacle so far is the low $^{81}$Kr concentration in ice (~1000 $^{81}$Kr atoms per kilogram of modern ice) combined with only small amounts of ice (a few kg) available from deep ice cores. The counting of such small amounts of $^{81}$Kr atoms requires an extremely high efficiency (at least 10%), currently beyond the capabilities of both AMS and ATTA.

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Suggested Reading


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NuPNET: Toward a Transnational Funding Plan for Nuclear Physics in Europe

Introduction

Since its foundation more than 18 years ago, NuPECC (Nuclear Physics European Collaboration Committee), an Expert Committee of the ESF (European Science Foundation), has played a crucial role in providing independent views on the direction of nuclear physics within Europe, in the form of periodic Forward Looks (Long-Range Plans). Over a number of years, NuPECC has gained the respect of the European nuclear physics community, and its authority is now recognized by the EU Commission, the national Funding Agencies and, most recently, by ESFRI (European Strategic Forum for Research Infrastructures).

In addition to science vision given by NuPECC, the EU framework (from 4th to the 7th) programs and instruments (Round table, Networks, I3, Design Study) have been adopted with considerable success by the nuclear physics community and therefore have played a decisive role in the emergence of common projects.

Today within Europe the challenge is to merge the national programs in Nuclear Physics in order to create a stronger and more cohesive research activity that is truly European in scope. The current funding procedures, where groups are funded by separate national funding agencies that reflect national priorities, have to be given a strategic direction to help align some of the national decisions to the common goals.

NuPNET–ERA-NET Proposal

Scientists who wish to collaborate on the science goals or the facility development have to approach their separate funding bodies and through their separate efforts to generate the combined funding needed to deliver the science. These “ad-hoc” procedures are very time-consuming and their efficiency in terms of achieved cooperation schemes are certainly not optimum. Local or national approaches to Research infrastructures and associated equipments in the field of Nuclear Physics cannot reach the dimension of competitiveness due to the increasing complexity and overall cost related to such future developments.

What is required now is that Europe puts in place a mechanism to meet the challenge of an effective coordination of national funding procedures on the common agreed priorities for infrastructures and R&D investments. In the FP6 program, the European commission has launched a new tool—ERA-NET—dedicated to the following goals:

To step up the cooperation and coordination of national or regional research activities through networking of programs including their mutual opening and the development and implementation of joint activities.

The ERA-NET does not finance research activities as such, but the coordination of nationally funded research activities. The partnership composition allows as eligible partners legal entities such as public bodies responsible for financing or managing research activities carried out at national or regional levels and other national or regional organisations that finance or manage such research activities.

Less than 2 years ago more than 15 representatives of Nuclear Physics funding agencies and/or corresponding organizations, a NuPECC delegation, and EU officers met in Paris to discuss the opportunity to launch such an ERA-NET scheme for our field in Europe. The participants unanimously agreed to build up such an ERA-NET proposal on the basis of the scientific recommendations made by NuPECC in the last edition of its long-range plan. As such, NuPECC is considered as the Science Advisory Body of this Committee and is proposed to be an associated member of the ERA-NET.

The proposal took the name of NuPNET (for Nuclear Physics Network), and was planned to be ready for the first call of the FP7 program (under the EU FP7 program CAPACITIES) in May 2007. The scientific coordination of the proposal will be led by the French partner, and a Coordination Committee composed of members of funding agencies from France, Germany, Italy, and Spain had the responsibilities to work out the full proposal. Thanks to the excellent collaboration between the Coordination Committee and the managers of 19 European institutions who agreed to be part of this new venture, in May 2007 the NuPNET proposal was submitted in due time to the ERA-NET-FP7 first call.

In the particular field of nuclear physics, our ERA-NET proposal adopted a stepwise approach over a period of three years with the following goals:
Goal 1: Compare reviewing and funding systems in participating funding agencies. Provide a Census of Resources and Agents in Nuclear Physics and Infrastructures that paves the way to common decisions. Liaison with I3, DS, and other European and International initiatives (ESFRI, OCD). Integration of new associates. (Work package led by Germany)

Goal 2: Propose a set of joint transnational activities (based on the science priorities set in the Long-Range Plan of NuPECC) that can be launched by Funding Agencies thanks to NuPNET coordination. (Work package led by Italy)

Goal 3: Launch one or more of those proposed joint transnational activities in the field of Nuclear Physics Infrastructures. (Work package led by Spain)

Goal 4: Provide Europe with a sustainable scheme beyond the project duration.

The overall coordination of the project is (Work package management) under the responsibility of the French partner. The requested budget for the 3-year period was 1.7 M€. Evaluation of our proposal took place during the summer of 2007 and by September, the NuPNET proposal was accepted and contract negotiations have been completed by March 13, 2008 (Budget granted 1.3 M€ for 3 years). The Kick-off meeting will take place on March 27 in Paris.

Embarking for a New Venture

With the help of the working program described herein, with the close relationship with NuPECC and its Long-Range Plans, which provide a clear vision for the development of the science in Europe, we believe that NuPNET, if successful, will have a major impact on European Nuclear Physics. NuPNET will provide for the first time the instruments (structure, organization, common action plan), needed to proceed toward European strategic decisions on the funding of nuclear science and related research infrastructures in Europe. The funding agencies that form NuPNET will be able to agree on multilateral approaches (“à la carte”) or truly European approaches to specific projects.

This initiative will have also an impact worldwide due to the international character of the field and the strong competition between the major research infrastructures of the leading regions of the world (Europe, North America, and Asia, connection with the OECD Global Science Forum).

As examples of possible common strategic decisions for funding we may think of the new major RI facilities for nuclear physics to be built in Europe, the new international project FAIR in Germany, as well as SPIRAL2 in France, which have recently received approval. They could strongly benefit from the NuPNET as well as in a longer term the EURISOL project.

As further examples we may think of a financial agreement to consolidate truly European existing RI like the ECT* (European Center for Nuclear Theory) at Trento (Italy). Another important issue could be the decision on the funding scheme of the AGATA project (Advanced Gamma Tracking Array, a world-leading gamma-ray spectrometer), an instrument that will be employed in experimental campaigns at several radioactive and stable beam facilities in Europe.

In the NuPNET governing board representatives of all European Funding agencies and ministries concerned with the construction, operation, and instrumentation needed by these new ventures would be able to use tools developed for NuPNET.

In conclusion, combining an independent science vision through NuPECC, with an transnational funding plan through NuPNET, will give to our community the tools to prepare and accomplish its ambitious science goals for the next decade.

SYDNEY GALES
Scientific Coordinator of NuPNET
On January 1, 2008, DAPNIA became IRFU!

The Saclay DAPNIA, a world-leading laboratory in the realm of particle, nuclear, and astro-physics, is now dubbed Institute for Research into the Fundamental Laws of the Universe (IRFU). This change of name is the result of a process triggered by the CEA Director General aiming at giving to the Divisions of CEA a more appropriate denomination in the world of research, especially in its English version. To this end, and with no other changes, the various departments of the DSM, DSV, and DRT directorates at CEA are becoming “Institutes.”

The new name of IRFU retains the former denomination “Laboratoire de recherche sur les lois fondamentales de l’Univers”—Laboratory for research into the fundamental laws of the universe.

This change has no other consequence on the IRFU, affecting neither its internal structure nor its operational capabilities. Obviously, it does not efface the history of DAPNIA since 1991, of which IRFU members may still legitimately continue to be proud.

Note that IRFU is a part of CEA’s Matter Science Directorate in Saclay, near Paris (France). Its fundamental research activities cover astrophysics, nuclear physics, and particle physics. It is a major actor in physics instruments development, detectors, or accelerators; its expertise encompasses cryomagnetism, space technologies, engineering, electronics, and data processing. IRFU is strongly involved in academic training. Its scientific and technical skills, its fruitful implementation into CEA, the coherence of its organization, and its project management culture all add up to a world-class institution.


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NICOLAS ALAMANOS
IRFU Saclay
Call for Candidates

The Board of the EPS-NPD is organizing elections to replace outgoing members.

Two vacancies are announced herewith. Nominations, together with a short CV (1 A4 page) and a statement of acceptance from the candidate, should be sent either by e-mail to d.lee@eps.org, or by regular mail to:

EPS
Nuclear Physics Division Board
Candidate

BP 2136
F-68060
Mulhouse Cedex
France

The dead line for receipt of nominations is May 31, 2008. Self nomination is not possible.

The members of the Board of the Nuclear Physics Division are expected to attend Board meetings, which take place twice a year. Among the activities of the Nuclear Physics Division are: the organization of the EPS Conference on Nuclear Physics; awarding two prestigious prizes, the Lise Meitner Prize and the IBA Prize in Applied Nuclear Science; providing input to the EPS on issues related to nuclear physics; and relations with other European and international bodies interested in nuclear physics and policy.

For further information go to http://ific.uv.es/epsnpb/

MATTI LEINO
Jyväskylä
Obituary for József Zimányi (1931–2006)

József Zimányi, one of the founders of high energy heavy ion physics, passed away in Budapest, Hungary on September 26, 2006. His death is a great loss for science, in particular for the heavy-ion community in Hungary.

Jozsó (as he was addressed by friends) was born in Budapest in 1931. He studied at the Roman Catholic Piarist High School in Budapest before starting his formal education in physics at Eötvös Loránd University, Budapest. He started his physics research as a graduate student in the Central Research Institute for Physics (KFKI) in Budapest in 1954. He stayed affiliated with KFKI during his whole life. Jozsó’s first works were on nuclear spectroscopy, measurements of the spin and parity of nuclear states. In the late 1960s, his interest turned to the theory of isobaric analogue resonances, including the interplay of resonances with threshold effects. In the 1970s, he was one of the pioneers of the “pygmy resonance,” which has gained attention recently, as a signature of the halo structure.

In 1969–70 he spent a year at the Niels Bohr Institute in Copenhagen, Denmark. In 1973 Jozsó became head of the Theoretical Physics Department of KFKI, which he gradually transformed into one of the leading theoretical centers for heavy-ion physics. One of his widely appreciated theoretical results was the Bondorf–Garpman–Zimányi solution of fireball hydrodynamics. To describe nonequilibrium processes, he developed the Montvay–Zimányi hadrochemical model. When data from the Berkeley BEVALAC triggered broad interest, he investigated the Bose–Einstein distribution and possible condensation of pions. The following years saw the birth of the Zimányi–Moszkowski model for an advanced mean-field theoretical description of nuclear matter and the ALCOR quark coalescence model to explain hadron production in Pb+Pb reactions at CERN SPS. One of his favorite topics was the analytic solution of the pion-laser model.

Jozsó was instrumental in setting the rules for OTKA, the Hungarian National Fund for Scientific Research, as an independent, peer-review-based grant system for basic science. In 1991–98, he acted as the first Chair of the Science College of OTKA. Jozsó played an essential role in negotiating CERN membership for Hungary in 1992. He himself became a member of the NA49 Collaboration. He represented Hungary on the CERN Council and was a member of the Hungarian CERN Committee from 1992 to 2004. Jozsó fully supported the Hungarian activities in the ALICE and CMS experiments at the LHC and the creation of the Budapest LHC Grid station on the KFKI Campus. As the Chair of the Science Council of the KFKI Research Institute for Particle and Nuclear Physics, he played an important role in the creation and operation of a Hungarian group in the PHENIX experiment at the RHIC accelerator, Brookhaven National Laboratory, USA.

Jozsó became a member of the Hungarian Academy of Sciences in 1990 and of the European Academy of Arts, Sciences and Humanities in 1997. In 1992, he was decorated with the Officer Cross of the Order of Merit of the Hungarian Republic, and in 2000 he was awarded the Széchenyi Prize, the highest national award given to a researcher in Hungary.

Jozsó was working until his last days with the same outstanding activity and driving force that has been an inspiration to his students and close colleagues throughout his life. His family, his students, friends, and followers feel a great loss; they will try to keep his heritage alive in Budapest and around the world.

A workshop was dedicated to Jozsó Zimányi’s memory in Budapest, in July 2007 http://www.kfki.hu/~zj75/, where 46 participants were invited from 9 countries, 4 continents, including some of Jozsó’s best students. In the spirit of keeping the Zimányi School alive even after the death of its founder, a series of Schools on Relativistic Heavy Ion Collisions has been named after him. The Zimányi 2007 Winter School was organized in KFKI RMKI, Budapest, Hungary, during December 5–7, 2007.
attracting 14 students and 23 senior lecturers from 7 countries.

It is our pleasure to invite the readers of NuPECC News and in particular their students to participate in the Zimányi 2008 Winter School on Heavy Ion Physics that will take place at KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences, Budapest, Hungary, during November 25–28, 2008. Although Jozsó passed away, may we hope that his spirit remains with us and that the Zimányi School will maintain the high standards and scientific traditions established by the late Jozsó Zimányi.

T. S. Bíró, T. Csörgő, and P. Lévai—students of Jozsó—have compiled this report for Nuclear Physics News. They gratefully acknowledge contributions of Mrs. M. Zimányi and R. Lovas.
June 8–13
Giens, France. EURORIB’08
http://eurorib08.ganil.fr/

June 8–14
Crete, Greece. 9th International Conference on Applications of Nuclear Techniques
http://www.crete08.org/

June 9–15
Kyiv, Ukraine. 2-nd International Conference on Current Problems in Nuclear Physics and Atomic Energy (NPAE-Kyiv2008)
http://www.kinr.kiev.ua/ NPAE-Kyiv2008/

June 15–20
New London, New Hampshire, USA. Nuclear Chemistry Gordon Research Conference

June 23–25
Kloster Irsee, Bavaria, Germany. Symmetries and Phases in the Universe

June 23–25
University of Surrey, Guildford, UK. 50th Anniversary Symposium on Nuclear Sizes and Shapes
http://www.isp.org.Conferences/Forthcoming_Institute_Conferences/Nuclear08/event_26105.html

July 7–11
Mulhouse, France. LIGHT CONE 2008, Relativistic Nuclear and Particle Physics

July 18–22
Barcelona, Spain. Euroscience Open Forum ESOF2008
http://www.esof2008.org

July 20–25
Debrecen, Hungary. 11th International Conference on Nuclear Microprobe Technology and Applications
http://icnmta.atomki.hu/

July 27–August 1
Mackinac Island, Michigan, USA. 10th Symposium on Nuclei in the Cosmos (NIC X)
http://meetings.nscl.msu.edu/nic2008/

August 10–15
Fort Worth, Texas, USA. CAARI 2008: 20th International Conference on the Application of Accelerators in Research & Industry
http://www.caari.com/

August 24–September 6
Wittenberg, Germany. Atomic Properties of the Heaviest Elements
http://www.superheavies.de/

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August 25–29  
Cologne, Germany. 13-th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics  
http://www.ikp.uni-koeln.de/cgs13/

August 31–September 5  
Dresden, Germany. 16th International Conference of Ion Beam Modification of Materials  

September 1–7  
Zakopane, Poland. Zakopane Conference on Nuclear Physics  

September 7–13  
Ryn, Poland. ENAM08  
http://enam08.fuw.edu.pl/

September 8–11  
Ulaanbaatar, Mongolia. Ulaanbaatar Conference on Nuclear Physics and Applications  
http://www.monamescience.org/ulaanbaatarconference.html

September 14–18  
Lanzhou, China. 7th International Conference on Nuclear Physics at Storage Rings, STORI’08  
http://ribll.impcas.ac.cn/conf/stori08/

September 15–18  
Vienna, Austria International Conference on Exotic Atoms EXA08  
http://www.oeaw.ac.at/smi/event/exa08/

September 16–19  
Vienna, Austria International Conference on Low Energy Antiproton Physics LEAP08  
http://www.oeaw.ac.at/smi/event/leap08/

September 22–26  
Chicago, USA. International Conference on New Aspects of Heavy-ion Collisions near the Coulomb Barrier FUSION08  
http://www.phy.anl.gov/fusion08/

October 7–11  
München, Germany 3rd Biennial Leopoldina Conference on “DARK ENERGY”  
http://www.mpe.mpg.de/events/dark-energy-2008/

October 10–18  
Erice, Sicily, Italy Critical Stability of Quantum Few-Body Systems  
http://lpsc.in2p3.fr/Indico/conferenceDisplay.py?confId=29

November 9–14  
Eilat, Israel. 18th Particles And Nuclei International Conference PANIC 08  
http://www.weizmann.ac.il/conferences/panic08/

December 1–5  
Queenstown, New Zealand. International Conference on Interfacing Structure and Reactions at the Centre of the Atom  
http://www.kernz.org/

2009  
March 16–20  
Bochum, Germany. European Nuclear Physics Conference  
http://www.ep1.rub.de/EUNPC

June 2–5  
Mackinac Island, Michigan, USA. 3rd International Conference on “Collective Motion in Nuclei under Extreme Conditions” (COMEX 3)  
http://meetings.nscl.msu.edu/COMEX3/

September 27–October 3  
Milos, Greece. 8th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei (EINN 2009)  
http://www.iasa.gr/EINN_2009

More information available under: http://www.nupecc.org/calendar.html . . . and check also http://www.ect.it→MEETINGS