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Hadrons and Nuclei under Extreme Conditions (HANEC2010)

Abstract

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J.A. Tostevin (Surrey/Tokyo Tech)

“ *Reaction tools for the study of exotic nuclei : theory and applications* ”

K. Ogata (Kyushu)

“ *Quantum scattering of three particles in stars: new understanding of the formation of* ^{12}C ”

T. Motobayashi (RIKEN)

“ *Nuclear processes in stellar burning* ”

M. Takechi (RIKEN)

“ *Study of Nuclear size for Exotic nuclei via Reaction Cross Sections* ”

D. Jido (YITP)

“ *Baryon resonance in chiral dynamics - Kaonic few-body systems -* ”

K. Sasaki (Tokyo Tech)

“ S*-wave* πK *scattering length from lattice QCD* ”

F. Sanftl (Tokyo Tech)

“ *Study of antiquarks in the proton with a high energy Drell-Yan experiment* ”

S. Uechi (RCNP, Osaka)

“ *Extended chiral* (σ, π, ω) *mean-field model with Vacuum Fluctuation Corrections* ”

B. Mohanty (VECC/LBNL)

“ *Results from the RHIC Experiments* ”

A. Macchiavelli (LBL)

“ *Pairing Correlations in Atomic Nuclei* ”

T. Matsumoto (Hokkaido)

“ *Systematic analyses of three-body and four-body breakup reactions* ”

Y. Ichikawa (RIKEN)

“ *g-factor measurement for isomeric state of* ^{32}Al
using two-step fragmentation reaction with dispersion matching ”

N. Kobayashi (Tokyo Tech)

“ *Inclusive Coulomb and nuclear breakup of* ^{31}Ne *and* ^{22}C ”

Reaction tools for the study of exotic nuclei: theory and applications

Jeff Tostevin

TIT/ University of Surrey, U.K

Atomic nuclei are complex many-body quantum systems composed, uniquely, of two Fermi fluids. Exotic nuclei, with very different neutron (N) to proton (Z) number ratios from the stable nuclei, provide an opportunity to study this strongly-interacting quantum behaviour in systems with large Fermi-surface asymmetries. These two lectures will discuss specific aspects of this highly international activity. Since the exotic nuclei are short-lived and produced most efficiently as fast secondary particle beams, this involves the interface between experiment and theoretical nuclear structure and reactions models. The first lecture will review essential features of nuclear shell structure and introduce why evolution from normal neutron to proton number ratios leads to changes to (i) our (textbook) understanding of nuclear stability and structures, (ii) to novel features such as the nuclear halo and (iii) that these changes are of importance astrophysically. The lecture will then concentrate on the simplifications to the description of nuclear collisions that arise at intermediate energies (100 MeV per nucleon, or more) and how these can be exploited to deduce structure information on short-lived nuclei; e.g. the occupation of quantum orbitals by nucleons or pairs of nucleons near the two (displaced) Fermi surfaces. The second lecture will then show how these ideas are being used. It will discuss a number of specific recent reaction studies, including oneand two-nucleon removal from and nucleon pickup by exotic nuclei. These are chosen to illustrative the capability of the techniques to (a) determine structure information, e.g. the reduction of shell gaps, the ordering of the nucleonic quantum levels and (b) to also assess nuclear structure models, such as the shell model and its effective interactions.
An introduction can be found at: http://www.nucleartheory.net/NPG/papers/NPN.pdf

Quantum scattering of three particles in stars: new understanding of the formation of ^{12}C

Kazuyuki Ogata
Kyushu University

One of the most important subjects of nuclear physics is to understand the origin of the elements surrounding us. In this talk I focus on ^{12}C, an essential element for life. It is well known that ^{12}C is formed from three alpha (^{4}He) particles in stars. Theoretical description of this reaction, however, has been oversimplified. I will explain how to formulate reaction rate of a ternary process, which begins with three-body scattering states, using the continuum- discretized coupled-channels method (CDCC). The reaction rate of the ^{12}C formation process is calculated with the accurate picture of the three-body quantum scattering. The new rate is markedly larger than the previous one by more than 20 orders of magnitude at 10^7 K. I will clarify where this difference comes from, by explaining what the previous model assumed. This study will lead one to new understanding of the "origin" of ^{12}C.

Nuclear processes in stellar burning

Tohru Motobayashi
RIKEN Nishina Center

In the universe, nuclear processes have been playing important roles in various aspects. They generate energy to make stars shine, they synthesize chemical elements which we see now, and so on. The circumstance of these nuclear processes has a large variety, from dense nuclear matter supposed to be realized in neutron stars or in the core-collapse phase of supernovae, to very thin inter-stellar medium where high-energy spallation reactions take place. Vast knowledge on nucleus, sometimes beyond the reach of the present nuclear physics, is required to wholly understand various astrophysical phenomena.

One of the current research-subjects drawing much interest is the explosive nuclear burning. In high-temperature and high-density stellar plasma, a short-lived nucleus can react with a nucleon or a nucleus before it decays. Experimental study on elementary processes involving unstable nuclei is difficult, because they cannot be served as targets for reaction experiments or even creation of them is not possible in many cases. Attempts to overcome these difficulties have been made in the last few decades by construction of facilities for producing beams of unstable nuclei and development of new experimental methods. New-generation facilities, including the RI Beam Factory (RIBF) at RIKEN, are expected to enhance the study of explosive burning. For example, most of the nuclei involved in the r-process, the process that creates about half of elements beyond iron, will be produced at RIBF.

Study of Nuclear size for Exotic nuclei via Reaction Cross Sections

M.Takechi
RIKEN Nishina Center

Nuclear size is one of the most basic physical quantities in the nucleus, and a number of radii for unstable nuclei have been studied through the measurements of interaction cross sections at high energies, using the Glauber-type calculation to investigate halo and skin structures of exotic nuclei. In the present talk, very recent studies of nuclear size for C isotopes at RIPS and Ne isotopes at RIBF will be presented.

Moreover, A newly modified method to deduce nucleon density distributions from the energy dependences of reaction cross sections at intermediate energies, which has been developed through the precise measurements of reaction cross sections and through some modifications of Glauber-type calculation will be introduced. and future plan to measure nucleon density distributions of exotic nuclei will be also presented.

Baryon resonance in chiral dynamics
- Kaonic few-body systems -

D. Jido

Yukawa Institute, Kyoto University

Our interest in the structure of baryon resonances has increased in the last decade since the experimental progress in measurements of hadron scattering has brought very precise and wide energy range data. Also in the theoretical side, recently, a powerful description of baryon resonances has been developed, being based on coupled-channels approaches and chiral dynamics. In this lecture, we will shortly review this recent developments, explaining the basic essences of the description. For the application of this technique, we discuss the structure of the $\Lambda(1405)$ resonance, which is now to be believed a hadronic quasibound state of $\bar{K}N$. We also discuss a recent extension of this idea that anti-kaon and nucleon form a two-body hadronic bound state, in which we propose possible three-body quasibound states, $\bar{K}KN$ and $\bar{K}KK$, as analogue states of the famous $\bar{K}NN$.

S-wave πK scattering length from lattice QCD

Kiyoshi Sasaki
Tokyo Institute of Technology

The S-wave πK scattering lengths are calculated for both the isospin 1/2 and 3/2 channels in the lattice QCD by using the finite size formula. We perform the calculation with $N_f = 2 + 1$ gauge configurations generated on $32^3 \times 64$ lattice using the Iwasaki gauge action and nonperturbatively $O(a)$-improved Wilson action at $1/a = 2.17$ GeV. The quark masses correspond to $m_\pi = 0.30 - 0.70$ GeV. For $I = 1/2$, to separate the contamination from excited states, we construct a 2×2 matrix of the time correlation function and diagonalize it. Here, we adopt the two kinds of operators, $\bar{s}u$ and πK. It is found that the signs of the scattering lengths are in agreement with experiment, namely attraction in $I = 1/2$ and repulsion in $I = 3/2$. We investigate the quark-mass dependence of the scattering lengths and also discuss the limitation of chiral perturbation theory.

Study of antiquarks in the proton with a high energy Drell-Yan experiment

Florian Sanftl
Tokyo Institute of Technology

My research is dedicated to experimental particle physics, especially to the quark-gluon structure of the proton. One way to investigate this sub-structure is by the so-called Drell-Yan process. It takes place when a quark of one proton and an antiquark of another proton annihilate, creating a virtual photon which then decays into a pair of oppositely-charged myons. This process also provides direct access to the anti-quark content of the proton. Due to their similar masses, one would naively assume that anti-up- and anti-down-quarks exist in equal amounts within the proton. Past experiments have shown though that the anti-quark content of the proton strongly depends on the kinematics of the Drell-Yan reaction, namely the Bjorken-x. The data which have been measured by past experiments were statistically not yet sufficient enough to fully explain the kinematic dependence. To extend these measurements to larger Bjorken-x, SeaQuest/E906 has been approved by Fermilab. It is a high rate fixed target experiment using Drell-Yan di-muons produced in 120 GeV proton interactions with hydrogen and deuterium targets. This 120 GeV proton beam will be provided by the Fermilab Main Injector. The experiment is currently being assembeled at Fermilab. It is expected to be comissioned in late 2010 and collect data for two years.

In my talk I will give an introduction into the physics motivation of the Fermilab SeaQuest/E906 experiment. In addition I will introduce the SeaQuest spectrometer and its Station3-Drift Chambers which have been designed and will be operated by Shibata laboratory at Tokyo Tech.

Extended chiral (σ, π, ω) mean-field model with Vacuum Fluctuation Corrections

Schun T. Uechi[1] and Hiroshi Uechi[2]

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Density-dependent relations among saturation properties of symmetric nuclear matter and hyperonic matter, the coupling ratios (strengths) of hyperon matter, and properties of hadronic stars are discussed by applying the conserving chiral nonlinear (σ, π, ω) hadronic mean-field theory. The chiral nonlinear (σ, π, ω) mean-field theory is an extension of the conserving nonlinear (nonchiral) σ-ω hadronic mean-field theory which is thermodynamically consistent, relativistic and Lorentz-covariant mean-field theory of hadrons. All the masses of hadrons are produced by chiral symmetry breaking. By comparing both nonchiral and chiral mean-field approximations, the effects of chiral symmetry breaking mechanism are investigated in nuclear matter, hyperonic matter, and neutron stars.

The full relativistic chiral Hartree approximation including vacuum fluctuation corrections (VFC) is derived and applied to properties of nuclear matter and neutron stars. The divergent integrals coming from occupied negative energy Dirac vacuum will be rendered finite by including appropriate counterterms in the current chiral lagrangian. By applying the method discussed in the linear σ-ω mean-field approximation [1] to the nonlinear σ-ω-ρ mean-field approximation [2], the baryon and meson propagators, self-energies are defined.

The finite vacuum fluctuation correction to energy density and pressure are included.

$$\Delta\mathcal{E}_{\rm VFC} = -\frac{1}{8\pi^2}\sum_B\left[M_B^{*4}\ln\left(\frac{M_B^*}{M_B}\right) + M_B^3(M_B - M_B^*) - \frac{7}{2}M_B^2(M_B - M_B^*)^2 + \frac{13}{3}M_B(M_B - M_B^*)^3 - \frac{25}{12}(M_B - M_B^*)^4\right] \tag{1}$$

$$\Delta p_{\rm VFC} = -\Delta\mathcal{E}_{\rm VFC}$$

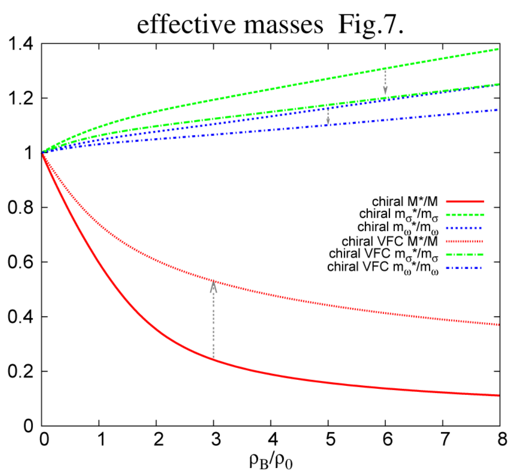

Fig.1. The effective masses with VFC. The arrows shows that the results of including VFC.

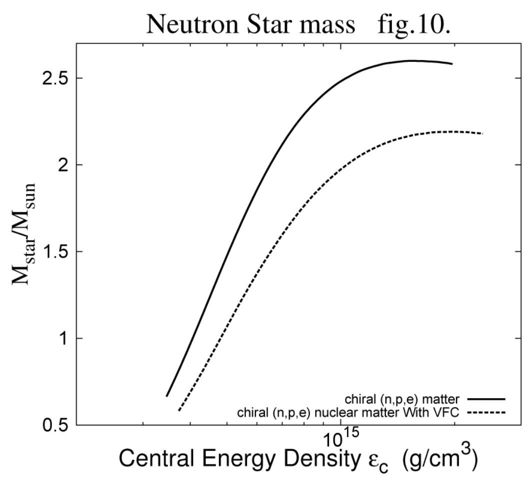

Fig.2. The masses of Neutron star with VFC. It reduce the maximum masses of Neutron star.

[1] B. D. Serot and J. D. Walecka, *Advances in Nuclear Physics*, edited by J. W. Negele and E. Vogt (Plenum, New York, 1986), Vol. 16.

[2] H. Uechi, Nucl. Phys. **A780** (2006) 247; H. Uechi, Nucl. Phys. **A 799** (2008) 181.

Results from the RHIC Experiments

Bedanga Mohanty
VECC/LBNL

The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory is a dedicated facility to study the properties of the QCD matter including its phase structure. RHIC is,at the moment, the world's highest energy heavy-ion collider and also the world's highest energy polarized proton collider to study the spin of proton.

This lecture will have three parts. In the first part, we will discuss various experimental aspects like the collider facility, two large detectors, PHENIX and STAR, and the common observables these detectors measure. The second part of the talk will focus on experimental observations related to establishing the Quark Gluon Plasma phase at RHIC. In this respect will be discuss the experimental observables related to the initial temperature and energy density of the system, strangeness enhancement, screening of the heavy-quark potential and partonic collectivity. In the last part of the talk, we will discuss some of the measurements related to hadronic phase of the system. These will include, the chemical and kinetic freeze-out properties. We will very briefly discuss about the experimental results on proton spin degrees of freedom.

Pairing Correlations in Atomic Nuclei

Augusto O. Macchiavelli
Lawrence Berkeley National Laboratory

In a landmark paper published in 1958, Bohr, Mottelson and Pines suggested a possible analogy between the excitation spectra in nuclei and those of superconductors. Subsequent work revealed that pairing correlations play a major role in defining many of the properties of atomic nuclei.

Today, the subject is still of much interest to the nuclear structure community and it has definite relevance to other finite fermion systems in atomic and condensed matter physics

In this lecture I will present examples of the experimental evidence of pairing in nuclei and review the basic ingredients required to understand this phenomenon within a theoretical framework.

I will also discuss some of aspects being actively pursued, for example:
1) The pairing-phase transition, 2) Neutron-proton pairing and 3) Pairing in weakly bound systems.

Systematic analyses of three-body and four-body breakup reactions

Takuma Matsumoto

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The study on neutron-rich nuclei has become one of the central subjects in nuclear physics. Breakup reactions have played key roles in investigating the properties of unstable nuclei. One of the most reliable methods for treating projectile breakup processes is the method of continuum-discretized coupled channels (CDCC). CDCC has successfully been applied to analyses of three-body breakup system, in which the projectile breaks up into two constituents. Recently, we have developed CDCC to treating four-body breakup reactions with three-body projectile. Thus CDCC is very useful for systematic analyses of scattering including right unstable nuclei, which have exotic properties such as the halo structure and the island of inversion.

In this talk, I will report results of analyses for ^{11}Be, ^{15}C, and ^{6}He breakup reactions with nuclear and Coulomb interactions, and discuss for those structure properties and reaction mechanisms.

g-factor measurement for isomeric state of ^{32}Al using two-step fragmentation reaction with dispersion matching

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We measured the g-factor for the isomeric state of ^{32}Al [1] at RIKEN RIBF [2], using a novel method to produce a radioactive-isotope (RI) beam with high spin-alignment, that was the two-step fragmentation method with a technique of momentum-dispersion matching.

Studies of nuclear-electromagnetic moments have progressed toward exotic nuclei far from the stability line using spin-oriented RI beams induced by the fragmentation reaction [3]. However the production of the spin-orientation is not effective for nuclei far from the primary beam because of small spin-orientation for many-nucleon removal reaction. The new method utilizes the mechanism of the spin-orientation in the fragmentation reaction [4], and enables to produce high spin-alignment in isomeric states for nuclei in any region. In this method, a desired nucleus is produced by the one-nucleon removal reaction as a secondary fragmentation reaction, in order to achieve a high degree of the spin-alignment. We should have the secondary reaction at a momentum-dispersive focal plane of a fragment separator. By re-focusing the momentum dispersion produced at the primary reaction under the dispersion-matching condition, we can achieve the increment of the yield of the desired nucleus without reducing spin-alignment.

The experiment was carried out at the BigRIPS [5] at RIKEN RIBF. For the primary reaction, ^{33}Al was produced by the projectile fragmentation with a primary ^{48}Ca beam. Then the isomeric state of ^{32}Al [1] was produced by the one-nucleon removal reaction from ^{33}Al at the momentum-dispersive focal plane of BigRIPS with a selection of a momentum region for the secondary reaction to produce the spin-alignment. We employed the time-dependent perturbed angular distribution (TD-PAD) method to determine the degree of the spin-alignment. The ^{32}Al beam was stopped at an annealed Cu target, and the de-excitation γ rays were detected using four Ge detectors located at ± 45, ± 135 degrees with respect to the beam axis. Using this method, we obtained an $R(t)$ function representing the anisotropy of the γ-ray emission. The g-factor of the isomeric state of ^{32}Al and the degree of the spin-alignment were determined from the cycle and the amplitude of the $R(t)$ function, respectively.

In this presentation, experimental results of the g-factor measurement using highly spin-aligned beam of ^{32}Al are given.

[1] M.Robinson *et al.*, Phys. Rev. C **52**, R1465 (1996).
[2] Y.Yano *et al.*, Nucl. Instrum. Methods B **261**, 1009(2007).
[3] K.Asahi *et al.*, Phys. Lett. **B251**, 488 (1990).
[4] K.Asahi *et al.*, Phys. Rev. C **43**, 456 (1991).
[5] T.Kubo *et al.*, Nucl. Instrum. Methods B **204**, 97 (2003).

Inclusive Coulomb and nuclear breakup of ^{31}Ne and ^{22}C

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The one-neutron removal cross section from ^{31}Ne and the two-neutron removal cross section from ^{22}C on a Pb target have been measured at around 230 MeV/nucleon at the RIBF (RI-Beam Factory) at RIKEN. This principle goal of the experiment was to extract the inclusive Coulomb breakup cross sections in order to probe possible halo structures through their enhanced low-energy E1 strengths - the so-called "soft" E1 excitations. The results indeed showed significant enhancement of the one- and two-neutron removal Coulomb breakup cross sections for ^{31}Ne and ^{22}C, respectively. This in turn provides strong evidence for the existence of halos in ^{31}Ne and ^{22}C.

In addition to the Coulomb cross sections, the nuclear breakup cross sections for ^{31}Ne and ^{22}C, together with the parallel momentum distributions for ^{30}Ne and ^{20}C fragments following reactions on a C target, were measured. At the same time, the gamma-rays from these fragments were measured. The combination of these data and the Coulomb dissociation cross sections has allowed the valence neutron configurations of both nuclei to be deduced. In the light of these results shell structure near the drip-line will be discussed.