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ANNUAL CONTINUATION AND PROGRESS REPORT FOR LOW-ENERGY NUCLEAR PHYSICS RESEARCH AT LAWRENCE LIVERMORE NATIONAL LABORATORY

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INVESTIGATING NUCLEOSYNTHESIS AND THE STANDARD MODEL WITH BETA DECAY

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Accomplishments

In this project, the Beta-decay Paul Trap, an open-geometry RFQ ion trap that can be instrumented with sophisticated radiation detection arrays, is used for precision β-decay studies. Measurements of β-decay angular correlations, which are sensitive to exotic particles and other phenomena beyond the Standard Model (SM) of particle physics that may occur at the TeV-energy scale, are being performed by taking advantage of the favorable properties of the mirror ^{8}Li and ^{8}B $\beta^\pm$ decays and the benefits afforded by using trapped ions. By detecting the β and two α particles emitted in these decays, the complete kinematics can be reconstructed. This allows a simultaneous measurement of the β-n, β-n-α, and β–α correlations and a determination of the neutrino energy and momentum event by event. In addition, the ^{8}B neutrino spectrum, of great interest in solar neutrino oscillation studies, can be determined in a new way. Beta-delayed neutron spectroscopy is also being performed on neutron-rich isotopes by studying the β-decay recoil ions that emerge from the trap with high efficiency, good energy resolution, and practically no backgrounds. This novel technique is being used to study isotopes of mass-number A~130 in the vicinity of the N=82 neutron magic number to help understand the rapid neutron-capture process (r-process) that creates many of the heavy isotopes observed in the cosmos.

Our studies of the β decay of ^{8}Li have led to the first improvement in general limits on tensor currents from β decay in 50 years. In this work, which was just accepted in Physical Review Letters, the β-n-α correlation in the β decay of ^{8}Li and subsequent α-particle breakup of the ^{8}Be* daughter was measured. The result gives a β-n angular correlation of $a_{\beta n}$ = -0.3342 ± 0.0026_{stat} ± 0.0029_{syst} which is consistent with a purely V-A interaction ($a_{\beta n}$ = -1/3) and, in the case of couplings to right-handed neutrinos, limits the tensor fraction to $|C_T/C_A|^2 < 0.011$ (at 95.5% confidence level) [1]. The measurement confirms the ^{6}He result from 1963 [2] using a different nuclear system and employing modern ion trapping techniques subject to different systematic uncertainties. Results from Ref. [1] are shown in Fig. 1.

Since the measurements performed in Ref. [1], we have implemented several improvements to increase the number of mass-8 ions that can be delivered to the BPT. We have modified the gas target to allow more reaction products to exit unhindered from the gas volume. We also installed a new gas catcher that has been designed to better handle light ions and reduce space-charge saturation issues that had hampered previous runs. These improvements have enabled us to deliver ions to the trap at a rate 10 times higher than in previous runs.

This increase in production and transport efficiency allowed us to collect data with a comparable precision to that in Ref. [1] for the b decay of the mirror nucleus ^{8}B, which has a production cross section an order of magnitude smaller than that of ^{8}Li. The analysis of the ^{8}B data is well underway and will serve to (1) determine the β-decay angular correlations with precision comparable to the ^{8}Li work, (2) quantify the recoil-order contributions to β decay that are sensitive to the conserved-vector-current hypothesis and second-class currents as part of our program to test fundamental symmetries of the SM, and (3) provide a precise

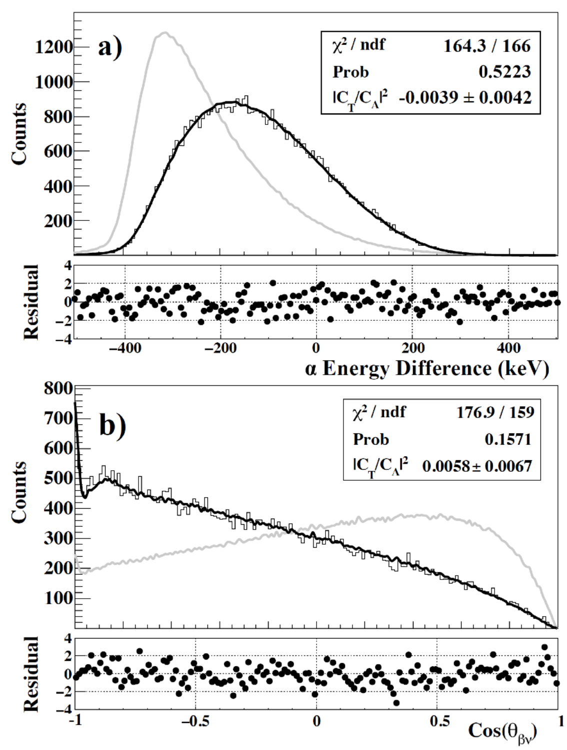

Fig. 1. Spectra from our recently-accepted manuscript [1] showing events with β and α particles detected on the top and bottom detector. (a) Alpha-particle energy difference along with the fit to the simulated spectrum and the normalized residuals. (b) The reconstructed $\cos(\theta_{\beta n})$ spectrum for the same events with a fit to the simulated spectrum and the normalized residuals. The gray curves show the expected spectra for a pure tensor interaction. The result in [1] is $a_{\beta n}$ = -0.3342 ± 0.0026_{stat} ± 0.0029_{syst}.

determination of the ^{8}B solar neutrino energy spectrum.

We have also recently implemented a number of improvements to the detection system. We have recently installed a plastic scintillator detector behind each double-sided silicon strip detector (DSSSD) in order to directly measure the energy of the β particles. This additional information, combined with the high statistics, will allow us to isolate events that are most sensitive to the relative angle between the leptons and to perform additional consistency checks of our data. These detectors are similar to the β detectors used in a recent β-delayed neutron campaign at CARIBU. In addition, the *in situ* ^{148}Gd and ^{244}Cm a sources used for energy calibrations in our earlier experiments gave a lines that had broad line shapes with extended low-energy tails due to energy loss and straggling within the sources. These sources have recently all been replaced with spectroscopy-grade a sources that have peaks with FWHM of better than 20 keV and negligible low-energy tails, allowing for a much better measure of the DSSSD energy calibration and line-shape response to a particles.

The next step in this successful program of β-decay angular correlation measurements is to improve upon the ^{8}Li result summarized in Ref. [1] by an additional factor of 3. With the upgrades to the ion production and transportation, we can now collect 10× higher statistics than in Ref. [1]. In FY16, we will collect high-statistics data needed to determine the β-n angular correlation coefficient, $a_{\beta n}$, with an absolute precision of ~0.001. This result, which will be the most precise measurement of $a_{\beta n}$ performed in any nuclear decay, will increase our sensitivity to tensor currents and will open up the opportunity to measure the β-energy and excitation-energy dependence of the β-n and β-α angular correlations. Reaching this precision depends on significant further reduction in systematic effects by (1) adding notch filters to the signal processing for the DSSSDs to eliminate *rf* pickup that currently compromises the performance of ~35% of the detector strips to increase the number of useable β–α–α coincidences by over a factor of 2 and improve the symmetry of the detector array, (2) minimizing the β scattering from trap material (electrodes, *rf* shielding, etc.) by minimizing the material and geometry used for the electrodes and detector shielding, (3) directly measuring the β-particle energy using the recently-installed plastic scintillator detectors to overconstrain the kinematics and allow additional checks of systematic effects, and (4) improved precision on recoil-order terms through both higher statistics data collected with trapped ^{8}Li ions and *ab initio* nuclear-theory calculations [2]. This work will serve as the Ph.D. thesis for Mary Burkey, a graduate student at the University of Chicago. The high-statistics ^{8}Li data will allow a detailed calibration of the plastic scintillator detectors. These detectors will also be used for studies of fission-product β-energy spectra at CARIBU, which will serve as the Ph.D. thesis for Elizabeth Heckmaier, a graduate student at the University of California at Irvine. We will also publish the results from our ^{8}B β-decay studies, including implications for weak tensor currents, recoil-order corrections, and the solar neutrino spectrum.

For the β-delayed neutron spectroscopy effort, we have been working to finish the analysis of data collected for ^{137,138,140}I, ^{144,145}Cs, and ^{134,135,136}Sb collected at CARIBU. These results will be published in 3 journal articles and will serve as the PhD theses for Agnieszka Czeszumska of the University of California at Berkeley and for Kevin Siegl and Sabrina Strauss, both at the University of Notre Dame. Detailed simulations are being developed to guide the design of the next-generation ion trap that will be used for β-delayed neutron spectroscopy at CARIBU. The design of this new system has trap electrodes that come within 7 mm of the trap center and therefore allow ion confinement with lower voltage RF fields. The impact of the electric fields, which impart some energy to the low-energy recoil ions, is therefore reduced. This provides a better separation between the recoils resulting from neutron emission and all the other β-decay recoils, allowing the neutron spectrum to be measured to energies as low as 25-50 keV at which point the neutron and lepton recoils are comparable. The ion trap itself has a more complex longitudinal segmentation to provide more efficient capture and minimize transverse losses that contribute to the background. The ion trap will be surrounded by an array of plastic scintillator DE-E telescopes, position-sensitive microchannel plate detectors, and HPGe detectors for β-particle, recoil-ion, and γ-ray spectroscopy, respectively. This ion trap will be surrounded by 8 β detectors, 4 MCP detectors, and 4 "clover"-type HPGe detectors for a solid angle coverage of 25% of 4π for the recoil and γ-ray detectors and 15% for the b detectors. This will result in a β-recoil ion coincidence efficiency of over 2%. These improvements are outlined in Ref. [3]. This new ion trap and detector array will be used to collect data for $^{134,135,136}Sn$ of importance to *r*-process nucleosynthesis near mass A~130.

This overall effort involves a large number of graduate students and postdocs from the University of California at Berkeley, the University of Notre Dame, McGill University, and the University of Manitoba who actively participate in these precise β-decay studies using trapped ions. The collaboration will be expanding to include Louisiana State University and the Colorado School of Mines.

In addition, we finished up our analysis and published results summarizing a detailed study of the cosmogenic-neutron activation of TeO_2 and the implications for neutrinoless double-beta decay experiments such as the Cryogenic Underground Observatory for Rare Events (CUORE) and the Sudbury Neutrino Observatory Plus (SNO+) which are studying the decay of ^{130}Te.

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Metrics

Publications

1. M.G. Sternberg *et al.*, "Limit on tensor currents from ^{8}Li beta decay", accepted for publication in Physical Review Letters (2015).
2. K. Alfonso *et al.*, "Search for neutrinoless double-beta decay of ^{130}Te with CUORE-0", Physical Review Letters **115**, 102502 (2015).

3. B.S. Wang *et al.*, “Cosmogenic-neutron activation of TeO_2 and implications for neutroless double-beta decay experiments”, Physical Review C **92** 024620 (2015).
4. D.R. Artusa *et al.*, “Searching for neutrinoless double-beta decay of ^{130}Te with CUORE”, Advances in High Energy Physics 879871 (2015).
5. D.R. Artusa *et al.*, “Exploring the neutrinoless double beta decay in the inverted neutrino hierarchy with bolometric detectors”, European Physical Journal C **74**, 3096 (2014).

Talks

1. International Symposium on Symmetries in Subatomic Physics, Victoria, BC (June 2015)
2. Workshop on “The Status of Reactor Antineutrino Flux Modelling”, Nantes, France (January 2015)
3. 4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, Waikoloa, HI (October 2014)

Synergistic Activities

1. Presented at DOE/SC Science and Technology Review of ATLAS/CARIBU facilities at ANL (2015)
2. Helped draft the Long Range Plan for the ATLAS and CARIBU facilities at ANL (2014)

EVOLUTION OF SHELL STRUCTURE AND COLLECTIVITY IN NEUTRON-RICH NUCLEI

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Accomplishments

Most effort and resource for FY15 was devoted to the CHICO2 campaign together with GRETINA at ANL/ATLAS. We have fielded 10 experiments during the period between May 2014 and May 2015; seven with radioactive beams from CARIBU and three with stable beams. LLNL was responsible for maintaining the operation of CHICO2 [1], which is an upgrade version of CHICO [2] for the charged-particle detection, with improved position resolution matching to that of GRETINA. This year-long campaign involved 82 researchers including postdoctors and students, from 27 institutions worldwide. All but one of fielded experiments use the sub-barrier Coulomb excitation method to explore the collective aspects of nuclear structure physics, such as (1) the octuople collectivity in ^{144}Ba and ^{146}Ba (LLNL/ANL), (2) the shape coexistence in ^{72}Ge and ^{76}Ge (ANL) as well as ^{100}Zr (CEA Saclay), (3) the triaxiality in ^{106}Mo and ^{110}Ru (ORNL/CEA Saclay), and (4) the quadrupole collectivity in ^{98}Zr (Darmstadt) and ^{98m}Y (ANL/LLNL). Lead institutes are listed in the parenthesis. Physics interpretations for those measurements rely on the electromagnetic properties derived from the analyses using the semiclassical Coulomb excitation-deexcitation code, Gosia [3]. One experiment utilized the deep-inelastic reaction to study the single-particle structure in ^{71}Zn (ANL). The narrative below focuses only on the research effort led by LLNL.

1. Evolution of the octupole collectivity in ^{144,146}Ba

The dominant collective mode of motion exhibited in nuclei is resulting from reflection-symmetric shapes that arise from the quadrupole degree of freedom. However, nuclei with the proton number near 34, 56, 88, and the neutron number near 34, 56, 88, 134, can assume reflect-asymmetric shapes that arise from the octupole degree freedom [4]. The even-odd staggering of the positive and negative parity yrast bands in even-even nuclei, parity doublets in odd mass nuclei, and the enhanced E1 strength due to a displacement between the center of charge and mass are among the identifiable phenomena associate with the reflect-asymmetric shapes. Nevertheless, the only observable that provides the unambiguous evidence for the enhanced octupole collectivity is the measurement of E3 strength since the enhanced E1 is sensitive to the shell corrections [5]. In most cases, the E3 strengths can only be measured by using the sub-barrier Coulomb excitation method.

The neutron-rich Ba isotopes (Z = 56, N ~ 88) are among the ideal candidates to study the evolution of octupole collectivity in nuclei and can be accessed conveniently using the spontaneous fission sources [6-11]. The characteristics of octupole collectivity has been observed in ^{144}Ba ($T_{1/2}$ = 11.5 s) and ^{146}Ba ($T_{1/2}$ = 2.22 s), for example, the measured even-odd staggering of positive and negative parity bands as well as the enhanced E1 transitions. However, the measured E1 in ^{146}Ba is an order of magnitude lower than that in ^{144}Ba. The less-enhanced E1 in ^{146}Ba can be possibly attributed to significant shell corrections [5]. The study of the E3 strengths is the only way to resolve this anomaly. The recently completed CARIBU facility at ANL is the ideal place to study of the evolution of octupole collectivity in neutron-rich Ba isotopes, produced in the spontaneous fission of ^{252}Cf. A propose to measure the E3 strengths in ^{144}Ba using the sub-barrier Coulomb excitation method was approved and fielded at the CARIBU facility in FY13 with limited success. The ^{144}Ba experiment was fielded again over a period of 3 weeks in May and June 2014 using GRETINA/CHICO2 with the beam intensity of ~

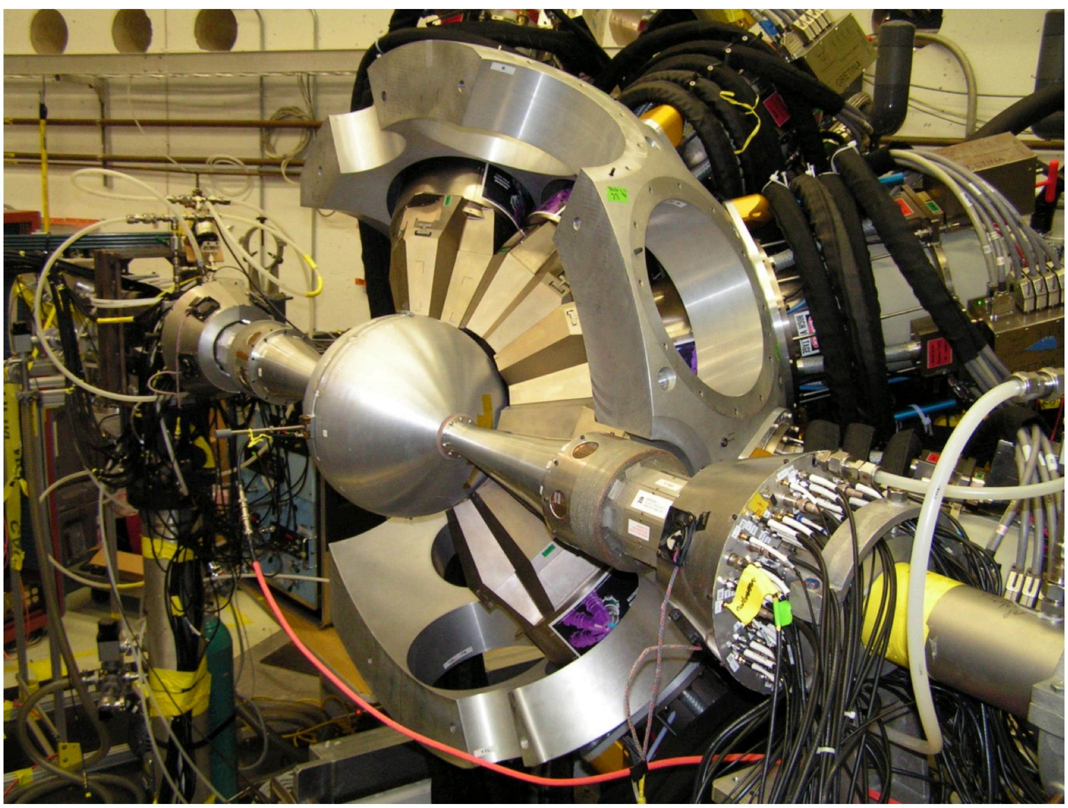

Fig. 1 GRETINA/CHICO2 setup at ANL. GRETINA has 7 detectors installed.

8,000 pps on a ^{208}Pb target of 1 mg/cm^2. The setup of GRETINA/CHICO2 is shown in Fig. 1. The analysis is complete now and the determined E3 matrix element, M(E3, $3^- \rightarrow 0^+$) = 0.65(+0.17/–0.23) eb$^{3/2}$, is factors of 2.5 to 5.3 larger than theoretic predictions [12] and provides a strong evidence of octupole deformation in ^{144}Ba. From the measured E2 and E3 matrix elements, an average shape of ^{144}Ba nucleus is given in Fig. 2 assuming a rigid rotor with a homogenous charge distribution. The pear shape is evident. This work has been presented at ANL in Feb. 2015 and at the Gordon Conference in June 2015. A manuscript to report this measurement is in preparation and will be submitted to Phys. Rev. Lett. for publication.

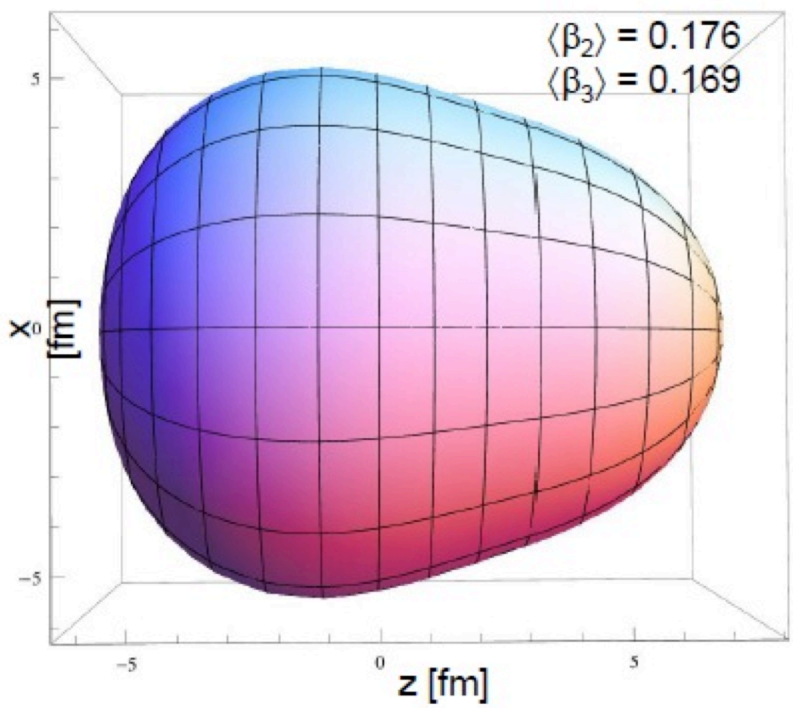

Fig. 2 Shape of the ^{144}Ba nucleus from the measured E2 and E3 matrix elements assuming a rigid rotor with homogeneous charge distribution.

The same setup was used for ^{146}Ba, where the experiment with beam intensity of ~ 3,000 pps at 650 MeV on a ^{208}Pb target of 1 mg/cm^2 was fielded over a period of two weeks in Feb – March, 2015. The resulting Doppler-shift corrected γ-ray spectrum is shown in Fig. 3. and the determination the E3 strengths using Gosia is in progress. We expect to finish the data analysis and publish the results in FY16.

2. CHICO2, a pixelated parallel-plate avalanche counter

CHICO2 is an upgrade version of CHICO (Compact Heavy Ion COunter) [2] with improved position resolution. CHICO was designed specifically for Gammasphere as auxiliary detector for the charged-particle detection. The design and fabrication work were carried out at University of Rochester under NSF funding. A total of 26 Gammasphere/CHICO experiments were

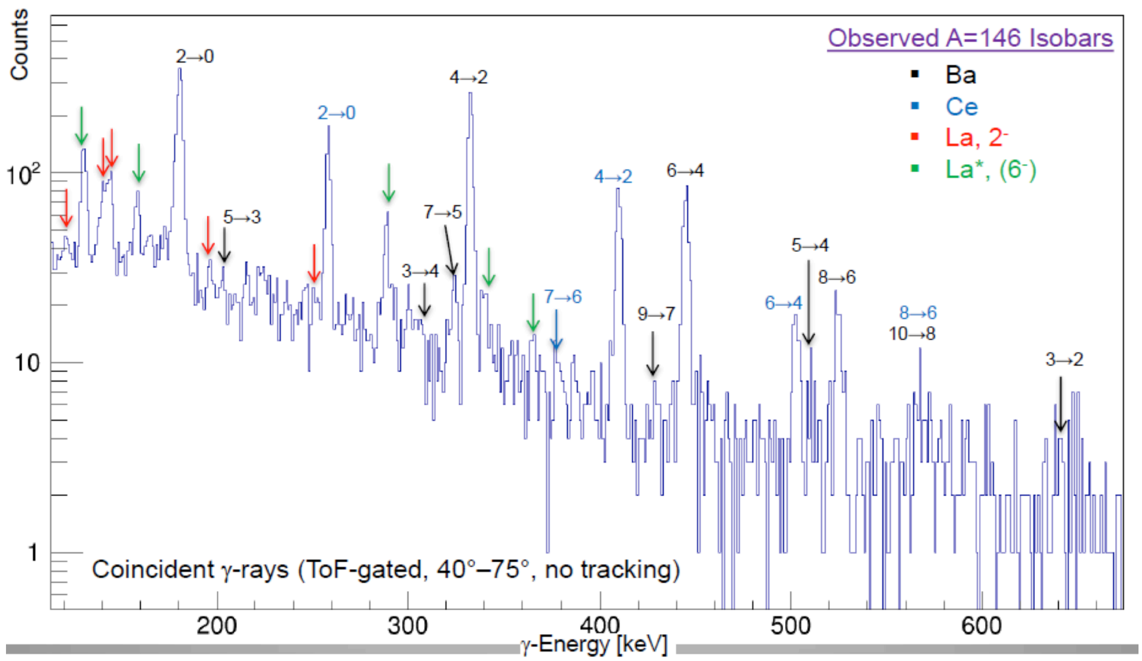

Fig. 3 Doppler-shift corrected γ-ray spectrum of ^{146}Ba using GRETINA/CHICO2 at ANL.

successfully fielded between 1996 and 2008 using various experimental techniques such as the sub-barrier Coulomb excitation, quasi-elastic or deep-inelastic reactions, and fission. These measurements addressed issues related to the evolution of nuclear collectivity, such as the shape transition and shape coexisting phenomenon in nuclei. It resulted in 37 publications and 5 Ph.D. theses with 58 researchers involved from 17 institutions worldwide.

CHICO consists of two mirror-image hemispheres with solid-angle coverage of 69% of 4π and each hemisphere holds 10 individual parallel-plate position-sensitive avalanche counters (PPAC). CHICO has a minimum mass for the construction material and can be operated stably at high counting rates without significant radiation damage. The position is read out in spherical coordinates; the polar angle, θ, is determined from the pixelation on the cathode plate using the delay-line readout technique and the azimuth angle, φ, is determined from the geometric location of segmented anode plates. For a given experiment, the event is uniquely identified by the measured quasi-two-body kinematics. It has two advantages; one is to allow precision Doppler-shift corrections for the coincident γ rays observed by Gammasphere. The resulting γ-ray energy resolution is about 1%, which is limited by the Ge detector size of Gammasphere. Secondly, it provides a signature to distinguish contaminants from the primary beam species. This is important for experiments with radioactive beams, where contaminants sometime are the dominant components of the delivered beam. It is illustrated in Fig. 4, where the measured two-body kinematics for a 650 MeV ^{144}Ba primary beam on a ^{208}Pb target of 1 mg/cm^2 cab be used to differentiate the beam contaminants other than the isobars, which include ^{36}Ar, ^{108}Cd, ^{113}Cd, ^{134}Xe, ^{180}Hf.

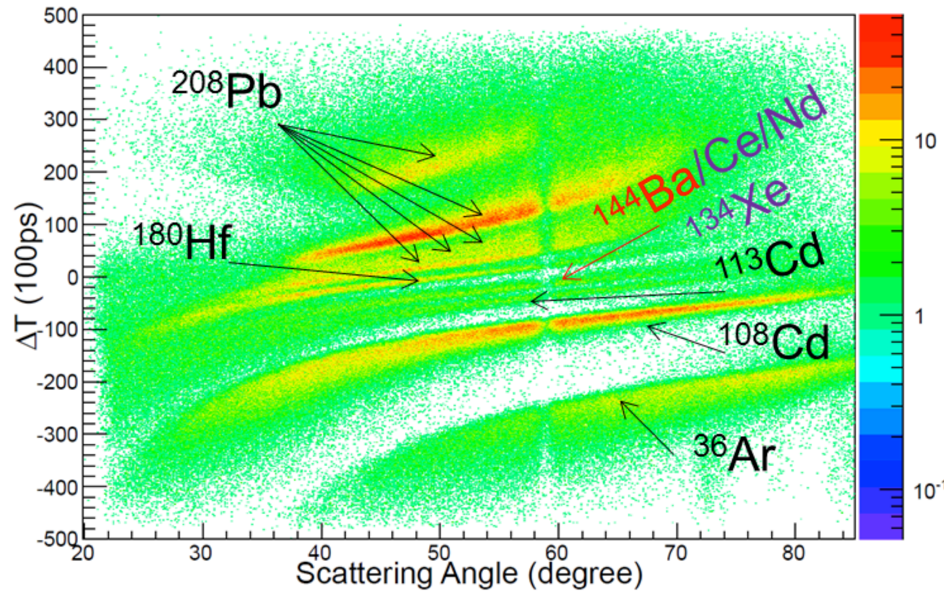

Fig. 4 The time-of-flight difference vs the scattering angle between two particle detected in kinematic coincidence by CHICO2 with at least one γ ray detected by GRETINA.

With the advent of the modern gamma-ray energy tracking arrays such as GRETA/GRETINA, the γ-ray energy resolution can be improved by a factor 2 to 3 by developing an auxiliary detector system with matching position resolution. A proposal to upgrade CHICO to CHICO2 by improving the position resolution, in particular the ϕ resolution from ~ 9^o to ~ 1^o, was submitted to DOE and approved in FY10. This improvement was made possible by adding pixels in the ϕ coordinate to the existing ones in θ coordinate on the cathode plate, resulting in a total of 1,478 pixels for each PPAC. The position determination is not from the location of each pixel, instead, it relies on the delay-line readout technique that lowers the output channels from 1,478 to 4.

In addition to the improved position resolution in this upgrade, new generation fast amplifier as well as a new VME based data acquisition system, was developed. CHICO2 was successfully integrated into Gammasphere in FY13 and GRETINA in FY14 with an achieved position resolution (FWHM) of 1.6^o in θ and 2.5^o in ϕ, limited by the target thickness (> 0.5 mg/cm^2) and the beam spot (> 3 mm). It has been operated successfully together with GRETINA for 10 experiments at ANL in FY14 and FY15.

3. Summary

We have completed a very successfully year-long CHICO2 campaign at ANL/ATLAS together with GRETINA. A total of 10 experiments were fielded; seven with the radioactive beams from CARIBU and three with stable beams with 82 researchers involved from 27 institutions worldwide. We provided valuable service to a substantial fraction of the low-energy nuclear physics community with very limited resource. CHICO2 performed flawlessly during this long campaign with achieved position resolution matching to that of GRETINA, which greatly enhances the sensitivity in the study of nuclear γ-ray spectroscopy. This can be demonstrated in our results on ^{144}Ba and ^{146}Ba where the octupole deformation is evident from the measured B(E3; $3^- \rightarrow 0^+$) strengths that significantly greater than the theoretical predictions. We anticipate that CHICO2 will continue to be a viable charged-particle detector for the research need of the low-energy nuclear physics community in addition to ours.

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