Initiation of a Nuclear Research Program at Fisk University in Cooperation with the Nuclear Physics Group at Vanderbilt University

Final Technical Report

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ABSTRACT

Carrying a spirit of a long history of cooperation in physics education and research between Fisk University and Vanderbilt University, the Nuclear Research Program (NRP) in the Department of Physics at Fisk University was proposed in 1996 in cooperation with the Nuclear Physics Group at Vanderbilt University. An initial NRP program was commissioned in 1997 with the financial support from DOE. The program offers a great opportunity for students and faculty at Fisk University to directly access experimental nuclear data and analyzing facilities within the Nuclear Physics Group at Vanderbilt University for a quick start.

During the program Fisk faculty and students (along with the colleagues at Vanderbilt University) have achieved progress in a few areas. We have a) established an in-house nuclear data processing and analysis program at Fisk University, b) conducted hands-on nuclear physics experiments for a Fisk undergraduate student at Vanderbilt University, c) participated in the UNIRIB research with radioactive ion beam and Recoil Mass Spectrometer at Oak Ridge National Laboratory, and d) studied ^{252}Cf spontaneous fission and in-beam nuclear reactions for exotic nuclei . Additionally, this work has produced publication in conference proceedings as well as refereed journals. [2-7]

DISCLAIMER

Introduction

The new generation nuclear radiation detection array such as GAMMASPERE and new generation Recoil Mass Spectrometer (RMS) and new Radioactive Ion Beam (RIB) facilities have pushed the study of nuclear structure to a few new frontiers. Studied of nuclear structures of exotic nuclei far from the beta stability line and on and near the N = Z line are now possible using those new facilities. The studies are of particular interests in understanding the high spin states, super-deformation, cluster decay and many other nuclear properties, which are not readily accessible with other existing facilities.

Upon many years of research, Vanderbilt Nuclear Physics Group has established itself to be one of the world's leading research groups in experimental nuclear structure studies. In cooperation with the Vanderbilt Nuclear Physics Group, Fisk University has initiated a Nuclear Research Program (NRP) with the support from DOE. The program took the advantage of existing experimental data and the necessary data analysis facilities and programs through Vanderbilt, which would be costly to develop and maintain, for faster and more economical development of a nuclear research program at Fisk. In addition, an established nuclear research program at Fisk could offer the opportunity for M.A. degree students at Fisk to move directly into a Ph.D. program at Vanderbilt and maintain ties with Fisk that would be particularly attractive to African-American students.

Establishment of an in-house Nuclear Data Processing and Analyzing Program at Fisk University

Desktop computers were purchased with the funds from DOE for hosting double and triple gamma coincidence nuclear data matrixes and its analysis programs. Nuclear-data-process and analysis software were obtained from Vanderbilt Nuclear Physics Group and Dr. Radford at Oak Ridge National Laboratory (ORNL). The computer operation system, Linux, was from Redhat. The program, after initial system installation, configuration and networking, and software debugging, has been established and synchronized with the related data at Vanderbilt Nuclear Physics Group. Software of Isotope Explorer and the Nuclear Structure DataBase from National Nuclear Data Center (NNDC) and other referential and educational programs for nuclear structure study were also installed.

Preliminary investigation of $^{94-100}$Sr and their spontaneous fission partners (mainly, Nd isotopes) has been conducted using the program. Triple coincident gamma rays from neutron-rich strontium (Sr) isotopes created in a spontaneous fission (SF) of ^{252}Cf were used in the study. We have explored and re-evaluated existing nuclear structure data for Sr isotopes and their fission partners with the SF gamma coincident data [1].

Particularly, ^{98}Sr has been re-evaluated extensively with new SF data. Two new gamma transitions, 799.0 keV, and 872.0 keV, were found in coincident with the existing E2 ground state band and tentatively added to the band. Modification of energies of two gamma rays, 144.2 keV and 656.2 keV from an earlier unpublished study (Zhu, S.J., private communication), have been suggested to be 144.9 keV and 663.5 keV, respectively. There are over a dozen gamma rays that are found in coincident with the existing gamma transitions in ^{98}Sr, which are still under investigation (to be published).

Student Training

Students were involved in the establishment of the nuclear research program at Fisk. Lectures on the basics of nuclear physics and the structure of experimental data were given to undergraduate students who participated in the program. Hands-on nuclear physics experiments of gamma ray detection and gamma-gamma coincident measurements were conducted by Fisk faculty and students at Vanderbilt University in order to help the students better understand the physics behind the experimental nuclear data. Students also took afield-trip to ORNL to get more first hand experiences of nuclear research. Moreover, students who in the program enhanced their knowledge of computer systems and programming.

Spontaneous Fission(SF) Study [2,3,5,6,7]

The fragments immediately following spontaneous (and induced) fission contains a rich source of highly excited neutron-rich nuclei – most of which are not accessible by other techniques. Studies of the prompt gamma rays from excited levels of the residual nuclei from SF offer new insights about the structure of the neutron-rich nuclei. New characteristics of nuclear structures, such as superdeformation, hyperdeformation, octupole deformation, triaxial, large oblate ground states, high spin states, and interwined bands, etc. were discovered.

With the construction of large detector arrays, such as the GAMMASPHERE, very large gamma-gamma and triple gamma-gamma-gamma coincidence data sets from spontaneous fission were collected which offer a powerful tool for sorting out useful information. In spontaneous fission of heavy nuclei such as ^{252}Cf, over 100 isotopes are produced and each may have 10 or more gamma rays associated with the radioactive decay chains which follow. Gamma-gamma coincidence, especially the triple gamma coincidence has significantly speeded up the data analysis. Those coincidence events have revealed many new characteristics in nuclear structure as mentioned above in addition to some new (or rare) fission features such as zero neutron emission, cluster radioactivity and ternary decay.

A region of stable octupole deformation was predicted to occur with its center around the reinforcing shell gaps for $\beta_3 \sim 0.15$ at Z = 56, N = 88; ${}^{145}_{56}Ba_{89}$ was predicted to be a prime candidate for stable octupole deformation. Evidence for stable octupole deformation was found in ^{144}Ba, ^{146}Ce and expanded to include odd-A ^{143}Ba and other neighboring isotopes but was not observed in ^{145}Ba. Recently we found evidence for the rotational enhancement of stable octupole deformation in $^{145,147}La$. In a reinvestigation of ^{145}Ba in spontaneous fission of ^{252}Cf, two new bands were discovered that are connected by enhanced, interwined E1 transitions to two different previously known bands in ^{145}Ba. These new data support the predicted presence of octupole deformation in ^{145}Ba, which is rotation-enhanced above about spin 19/2. In both ^{145}La and ^{145}Ba, the low spin ground bands are built on a symmetric rotor shape and at intermediate spins there are shifts to the yrast bands having asymmetric octupole shapes. These are the first examples of this type shape coexistence that was earlier predicted could occur in an odd-A nucleus depending on the single particle orbitals. A new side band with equal and constant dynamic and kinetic moments of inertia equal to the rigid body value, as found in superdeformation bands, was discovered in ^{145}Ba. In addition, the following fragment pairs are observed to be correlated with ^{10}Be from coincidence spectra based on missing N and Z for the pairs: ^{96}Sr – ^{144,146}Ba, ^{98,99}Y – ^{142,143}Cs, and ^{106,108}Mo – ^{134}Te. In spectra with double gates on one transition in each of these correlated pairs, possible weak peaks are seen with energies just below the 3368 keV transition in ^{10}Be. These energy-shifted lines with no Doppler broadening may be interpreted as evidence that ^{10}Be-correlated pairs in spontaneous fission form a triple nuclear molecule that lives for the order of 10^{-12} s.

UNIRIB Research with Radioactive Ion Beam and Recoil Mass Spectrometer

As spontaneous fission reveals rich sources for studies of neutron-rich nuclei, UNIRIB research with radioactive ion beam and Recoil Mass Spectrometer at Holifield Radioactive Ion Beam Facility (HRIBF), Oak Ridge National Laboratory, offer great opportunities for studies of nuclei along the N = Z line and near and beyond the proton drip-line. Recent theoretical calculations have predicted a surprising richness of different superdeformed, both prolate and oblate, and hyperdeformed and octupole-deformed shapes about the N = Z line between Z = 28 and 50. These different deformations can be related to the reinforcement of the protons and neutrons which have shell gaps in their single-particle levels for the same deformation since N =Z. Moreover, because the N = Z nuclei involve the protons and neutrons filling the same orbitals, these nuclei provide the best opportunity to probe the fundamental proton-neutron interaction. Thus, these very neutron-deficient nuclei provide fertile testing grounds for discriminating theoretical models which otherwise are usually based on the nuclear structures observed closer to the beta stability valley.

The nuclear research program at Fisk has involved in the research of neutron-deficient nuclei at HRIBF[4]. The proton emission from rare earth nuclei near and beyond the proton drip line were produced by means of fusion-evaporation reactions and studied with the Recoil Mass Spectrometer and Double-sided Silicon Strip Detectors at ORNL.

Proton emission from ^{150}Lu was studied by using a double-sided silicon strip detector placed at the focal plane of the HRIBF's Recoil Mass Spectrometer. The ^{150}Lu nuclei were produced in the ^{96}Ru(^{58}Ni, p3n) reaction at a beam energy of 292 MeV. The half-life of the previously observed proton emitting state at 1.261 MeV was re-measured to be 49 ± 5 ms. A new proton emitting state in ^{150}Lu was observed with a transition energy of 1.295 ± 0.015 MeV and a half-life of 70^{+50}_{-40} μs. These values are consistent with a $\Delta l = 2$ character for the new proton transition.

Gamma rays decaying from the excited states of the proton-unbound Lu-151 were observed for the first time in the ^{96}Ru(^{58}Ni, p2n)^{151}Lu reaction. These gamma rays were identified by correlating prompt gamma radiations at the target position with ^{151}Lu proton radioactivity at the focal plane of a recoil mass separator. Systematic data on N = 80 isotopes suggest a possible isomeric level at high spin in ^{151}Lu. Our measurement was unable to observe such an isomer, but provided an upper limit on its half-life. The observed gamma rays in ^{151}Lu can be interpreted in terms of two possible level structures.

The possibility of observing experimental signature of T = 0, n-p interaction has attracted great attention recently as mentioned above. To observe such signatures, we need to have very strong and stable deformation in N = Z nuclei which has been found around the N~Z~40 reinforcing shell gaps. In pursuit of observing these signatures, we recently performed an experiment to identify gamma rays in N =Z =39, ^{78}Y, which is one of the most promising cases for observing the T = 0, n-p interaction. We have successfully identified two gamma rays in ^{78}Y from this experiment. The identification of these gamma rays was achieved by using the reaction ^{40}Ca(^{40}Ca, pn)^{78}Y at a beam energy of 120 MeV and an experimental setup consisting of an array of 11 Clover detectors (CLARION), the Recoil Mass Spectrometer and an ionization chamber at ORNL. The estimated cross-section of ^{78}Y is around 13 μb. To study in detail the level structure of ^{78}Y, more experiments with GAMMASPHERE are to be conducted.

Long term Implications

One expected outcome of the program was the establishment of an autonomous nuclear physics research at Fisk University. In order to establish such a program, it was necessary that the university commit itself to hiring full-time faculty in the department of physics. At the start of the program, the president of the university supported such action, however he died five months after taking office. For much of the active period of this grant, only acting presidents existed, and they were unwilling to make any long-term commitments of the university. With the financial commitment made by DOE, and little or no commitment made by the university toward the nuclear program, it was determined that we would not request funding for the third year of the grant, even though we had been productive in faculty-student participation and research results.

Presently, two nuclear-trained physicists are on the staff in the physics department at Fisk University and their primary research responsibilities are in materials science. They can clearly form the initial core of a nuclear group at Fisk. However, to establish a program as envisioned in the original proposal, a larger commitment in funding from DOE will be required. Without present funding, some nuclear work is continuing at a very low level. Since a new president has been named, it is anticipated that funding will be requested in the future to continue our efforts in nuclear physics. We have the potential to significantly influence minority participation in this area of physics research, given sufficient funding.

In summary, every aspect of the proposed activities has been accomplished. However, we have not established a strong long-term autonomous nuclear research program at Fisk University in cooperation with Vanderbilt due to funding limitations. The potential of the program has been demonstrated with minimal funding from DOE. We thank DOE for its efforts in assisting us in developing a nuclear physics capability at Fisk University and will seek future funding to realize a viable program for the future.

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