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Research at the University of Kentucky Accelerator Laboratory

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Abstract

The Department of Physics and Astronomy at the University of Kentucky operates a 7-MV CN Van de Graaff accelerator that produces primary beams of protons, deuterons, and helium ions. An in-terminal pulsing and bunching system operates at 1.875 MHz and is capable of providing 1 ns beam bunches at an average current of several microamperes. Nearly all ongoing research programs involve secondary pulsed neutrons produced with gas cells containing deuterium or tritium, as well as with a variety of solid targets. Most experiments are performed at a target station positioned over a deep pit, so as to reduce the background created by backscattered neutrons. Recent experiments will be described; these include: measurements of *n-p* scattering total cross sections from E_n = 90 to 1800 keV to determine the *n-p* effective range parameter; the response of the plastic scintillator BC-418 below 1 MeV to low-energy recoil protons; *n-p* radiative capture cross sections important for our understanding of nucleosynthesis approximately 2 minutes after the occurrence of the Big Bang; γ-ray spectroscopy following inelastic neutron scattering to study nuclear structure relevant to double-β decay and to understand the role of phonon-coupled excitations in weakly deformed nuclei; and measurements of neutron elastic and inelastic scattering cross sections for nuclei that are important for energy production and for our global understanding of the interaction of neutrons with matter.

Peer-review under responsibility of the Scientific Committee of the Conference on the Application of Accelerators in Research and Industry

Keywords: Neutron-proton total cross sections; $p(n,d\gamma)$ radiative capture cross sections; neutron production; neutron detection; γ-ray spectroscopy; neutron elastic scattering cross sections; neutron inelastic scattering cross sections

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1. Introduction

The 7 MV modified Model CN Van de Graaff accelerator located at the University of Kentucky Accelerator Laboratory (UKAL) has been used extensively since its installation by High Voltage Engineering in 1963 for the investigation of important questions in nuclear astrophysics, nuclear structure, neutron scattering, and applied nuclear science. The laboratory is a founding member of the Association for Research at University Nuclear Accelerators (ARUNA) and has long been used to provide graduate and undergraduate students the facilities for their initiation into nuclear science, as well as for postdoctoral scholars to gain experience with neutron-induced reactions and scattering. UKAL is also used for the testing and development of novel neutron detectors and particle-detection techniques.

Recent investigations at UKAL have focused on the measurements of neutron-proton (*n*-*p*) scattering and radiative capture cross sections below 2 MeV where existing measurements are not only sparse, but inconsistencies exist between different measurements and with existing model calculations, and because of their importance to our understanding of the nucleon-nucleon interaction and in models of Big Bang nucleosynthesis (Daub (2012)). Other areas of experimental emphasis at UKAL include nuclear structure studies of collective modes of excitation in nuclei, which take advantage of using fast neutrons to study low-spin, non-yrast states through γ-ray spectroscopy following inelastic neutron scattering, and measurements of neutron elastic and inelastic scattering cross sections on materials important for fission reactor applications and our global understanding of how neutrons interact with matter. These research programs are conducted in collaboration with researchers from MIT (e.g., Daub et al., (2013)), LANL (e.g., Henzl et al., (2010)), the United States Naval Academy (e.g., Vanhoy et al., (2015)), the University of Dallas (e.g., Hicks et al., (2017)), Georgia Institute of Technology (e.g., Peters et al., (2016)), and the University of Guelph (e.g., Bildstein et al., (2013)), as well as with other institutions. Neutron detection innovations that have recently taken advantage of the UKAL neutron production facilities include measurements of the response of BC-418 plastic scintillator by detecting low-energy neutrons scattered by an active scintillator target. The UKAL facilities and overview of some current research efforts are given below.

2. Experimental Apparatus

2.1. The UKAL accelerator

The accelerator at UKAL operates with a tank gas of N_2:CO_2 in a 4:1 admixture, and it is capable of producing DC or pulsed beams of ^{1}H, ^{2}H, ^{3}He, and ^{4}He ions with a maximum energy of 7 MeV. Beams are pulsed at a frequency of 1.875 MHz and can be bunched such that each pulse has a FWHM of ~1 ns. While much of the accelerator, as shown in Fig. 1 (a), and the control panel, as seen in Fig. 1 (b), are from the original installation, upgrades were completed in 1988 and 1991 that include a new stainless steel accelerator tube, post-acceleration electrostatic focusing capabilities, and an in-terminal buncher from National Electrostatics Corporation.

(a) (b)

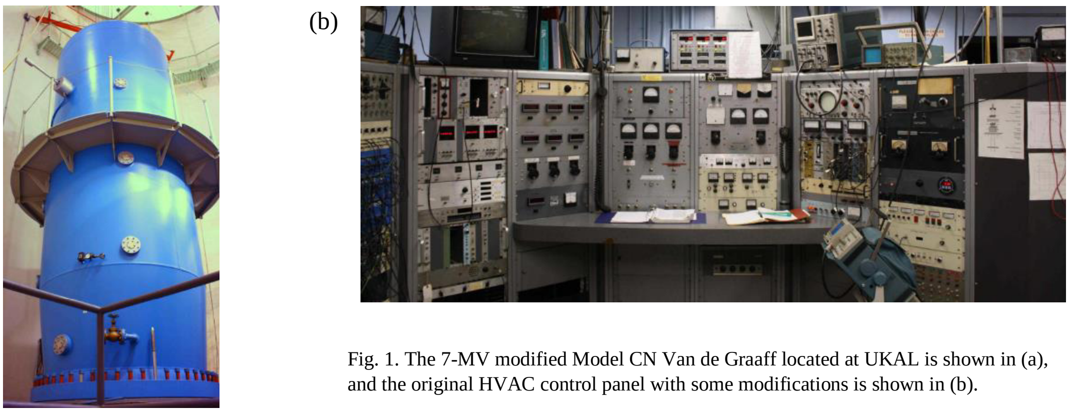

Fig. 1. The 7-MV modified Model CN Van de Graaff located at UKAL is shown in (a), and the original HVAC control panel with some modifications is shown in (b).

2.2. Neutron Production and Detection Facilities at UKAL

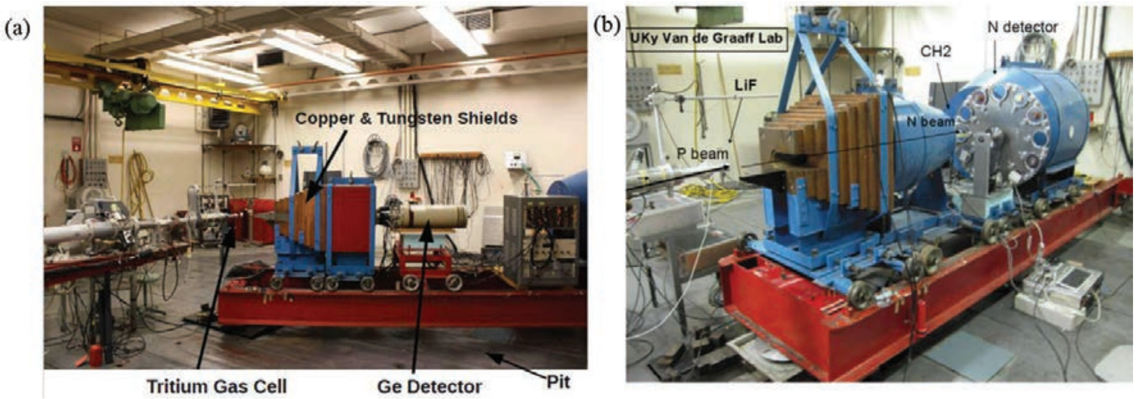

Fig. 2. The apparatus shown in Fig. 2(a) is used for most nuclear structure studies at UKAL, which utilizes primarily the $^3H(p,n)^3He$ reaction for neutron production. The setup shown in Fig. 2(b) is used for neutron transmission studies, with neutrons produced using the $^3Li(p,n)^3Be$ reaction. Various targets are rotated into the beamline for the transmission studies by remote control.

Two views of the shielding and detector goniometer located in the neutron scattering hall are shown in Fig. 2. The standard γ-ray detector configuration is shown in Fig. 2(a), while the neutron collimation and target wheel used in the neutron transmission measurements is shown in Fig. 2(b). A third detector configuration is used for radiative capture cross section measurements and is shown schematically in Fig. 3. In the former, the $^3H(p,n)^3He$ reaction is typically used as the neutron source with the tritium gas cell located at the end of the beam line (≈1 atm or less of tritium gas; ΔE≈100 keV). In the latter the $^7Li(p,n)^7Be$ reaction is used as the neutron source (20 kÅ LiF target; ΔE≈50 keV). A schematic diagram of the experimental configuration for the *n-p* total cross section measurements and time-of-flight (TOF) spectra, with and without pulse-shape discrimination (PSD), for protons incident on the LiF target are shown in Figs. 4(a) and 4(b), respectively. Four CH_2 and three carbon samples were used in the *n-p* scattering studies. For γ-ray detection and neutron scattering measurements enriched isotopic samples containing approximately 0.1 to 1.0 mole of material are typically used with the neutron source-detector configuration used in Fig. 2(a). A deuterated benzene liquid scintillation detector is positioned in the larger shielding apparatus shown in Fig. 2(b) with flight paths typically of 1.5 to 4.0 m for neutron elastic and inelastic scattering cross section measurements.

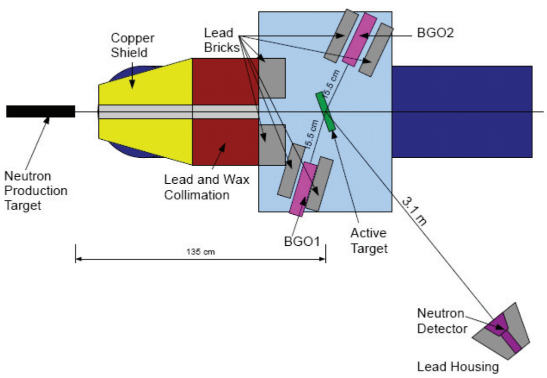

Fig 3: Schematic of the experimental setup used for radiative capture cross section measurements at UKAL.

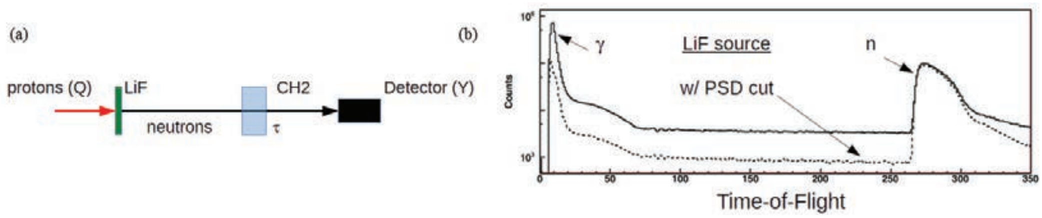

Fig. 4 (a) A schematic representation of the experimental configuration for measuring the *n-p* total cross sections and (b) an experimental TOF spectrum, with and without PSD, for the neutron transmission measurements.

3. Results

3.1. n-p Total Cross Sections from 100 keV to 1 MeV

The *n-p* interaction is important for our understanding of the strong nuclear force and the strength of the fundamental nucleon-nucleon (N-N) interaction, which plays an important role in nuclear models and for calculations that include binding energies, nuclear structure, and neutrino detection, to name just a few examples. Below 500 keV, the data that existed prior to 2012 were sparse and showed large inconsistences, especially between 100 and 500 keV, according to an evaluation of the National Nuclear Data Center compilation by Daub (2012). As part of his thesis, Daub (2012) completed measurements of the *n-p* total cross sections at UKAL for incident energies from 100-800 keV using the apparatus shown in Fig. 3 with a BC-501A deuterated liquid scintillator detector. The cross sections were determined using Eq. 1:

$$\sigma_{np} = \frac{1}{\tau}\ln\left(\frac{(Y/Q)^{out}}{(Y/Q)^{CH_2}}\right) - \frac{\sigma_C}{2} \quad (1)$$

where σ_{np} is the *n-p* scattering total cross section, *Y* is the detector yield, *Q* is the number of incident protons, σ_c is the neutron scattering total cross for C, and *out* refers to the sample (*CH_2*) out of the neutron flux. While Daub's results extended the measurements extensively, they were found to be consistently 1-3% larger than ENDF evaluations. Yang (2015) re-measured these *n-p* total cross sections and extended the incident neutron energy to 90 keV after detector and data acquisition systems were enhanced. The *n-p* total cross sections reported by Yang (2015) are shown in Fig. 5; the agreement with ENDF evaluations is excellent. These data were used to determine effective range theory parameters, which agreed with the earlier results of Hackenburg (2006).

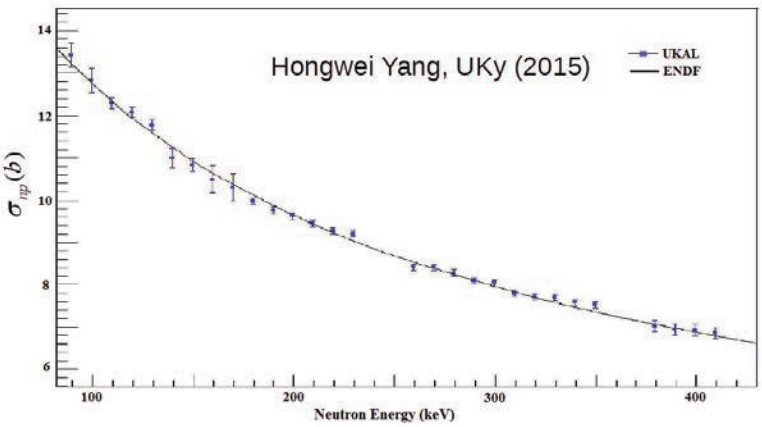

Fig. 5: *n-p* total cross sections measured at UKAL with the improved detector and data acquisition system. No systematic disagreement is seen between these data and the ENDF evaluation.

3.2 The Light Response of BC-418 Plastic Scintillator to Low-Energy Protons

The ability to control the incident neutron energy makes the facilities at UKAL ideal for testing the response of neutron detectors and new detection techniques, and several groups have utilized the facility for this purpose. For example, the light-yield response of a 50 mm × 50 mm × 2 mm BC-418 plastic scintillator as a function of recoiling proton energy was measured for E_p = 100 keV to 1 MeV using elastically scattered neutrons produced via the ^{3}Li(p,n)^{3}Be reaction on thin LiF targets to control the energy spread of the incident neutrons. The BC-418 detector was used as an active target placed 30 cm downstream of the neutron production target. The recoil-proton energy was determined by detecting the scattered neutron in coincidence with an event in the active target and using the time-of-flight determined neutron energy and elastic scattering kinematics. A schematic of the particles involved in the scattering process is shown in Fig. 6(a) and the active target, neutron detector, and the shielding apparatus are shown in Fig. 6(b). The results of these detector studies, which extended the measurements to 100 keV, were published by Daub *et al.* (2013); the BC-418 detector response function is now available from 100 keV to nearly 10 MeV.

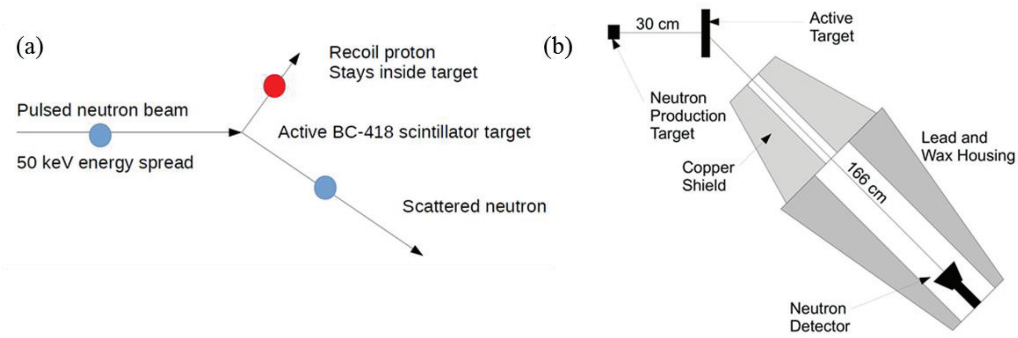

Figure 6: (a) Schematic of kinematics of reaction used in tests of the response function of BC-418 liquid scintillator, and (b) the detectors and shielding apparatus used in the detector tests.

3.3 Feasibility Studies of n-p Radiative Capture Cross Section Measurements at UKAL

At approximately two minutes after the Big Bang the mean background photon energy had dropped sufficiently for deuterium nuclei created by radiative n-p capture to survive against the competing photodisintegration process. Subsequent reactions involving these primordial deuterons then created the set of light Big Bang Nucleosynthesis (BBN) nuclei. Model calculations show that the resulting distribution of nuclear abundances is most sensitive to the neutron-proton radiative capture cross section in the region of neutron energy near 500 keV.

In order to increase the capture data set at this low energy we have studied the feasibility of measuring the n-p capture cross section using a pulsed-neutron beam and an active-scintillator target at the UKAL. γ rays are detected in coincidence with recoil deuterons in the target, thereby reducing the backgrounds observed in the singles γ-energy spectra. To date we have used multiple BGO detectors for photon detection, but in order to provide tighter constraints against potential backgrounds we will collect additional data using an anti-coincidence shielded Ge detector.

3.4 Nuclear Structure Studies at UKAL

The long-standing nuclear structure program at UKAL focuses on obtaining information on nuclear levels, e.g., lifetimes, spins, and multipole-mixing ratios, utilizing γ-ray spectroscopy following inelastic neutron scattering. While these studies are limited to stable nuclei, the structure information obtained is often inaccessible by other reactions; furthermore, these studies complement those done elsewhere on nuclei under extreme conditions in temperature, angular momentum, and far from the line of stability. The most recent investigations have focused on nuclear structure relevant to neutrinoless double-β decay, the role of phonon-coupled oscillations in weakly deformed nuclei, and low-spin excitations in transitional nuclei.

Neutrinoless double-β decay, 0νββ, is a lepton-number-violating nuclear process and will occur only if neutrinos have mass and are Majorana particles; that is, they are their own antiparticles. One of the candidates under investigation for neutrinoless double-beta decay is ^{136}Xe. Detailed knowledge of the nuclear structure is necessary for calculation of the nuclear matrix elements used to determine the Majorana mass of the neutrino (if the process is observed) and is currently under study at UKAL. In large-scale experiments like those currently underway in EXO-200 collaboration (Auger (2012)), an understanding of the background in the region of interest is also crucial. In our measurements γ-ray cross sections were determined for possible neutron-induced interferences within the liquid xenon employed in the detector systems (Peters, (2016)). An example summed γ-ray spectrum for ^{136}Xe used to assess these interferences is shown in Fig. 7. The A=76 nuclei, ^{76}Ge and ^{76}Se, are also of interest in 0νββ searches; their structure has been studied at UKAL by Crider *et al.* (2015) and Mukhopadhyay *et al.* (2017) resulting in new information on the low-lying level scheme, level lifetimes useful for transition rate information for comparison to model calculations, and for background information for the actual 0νββ searches.

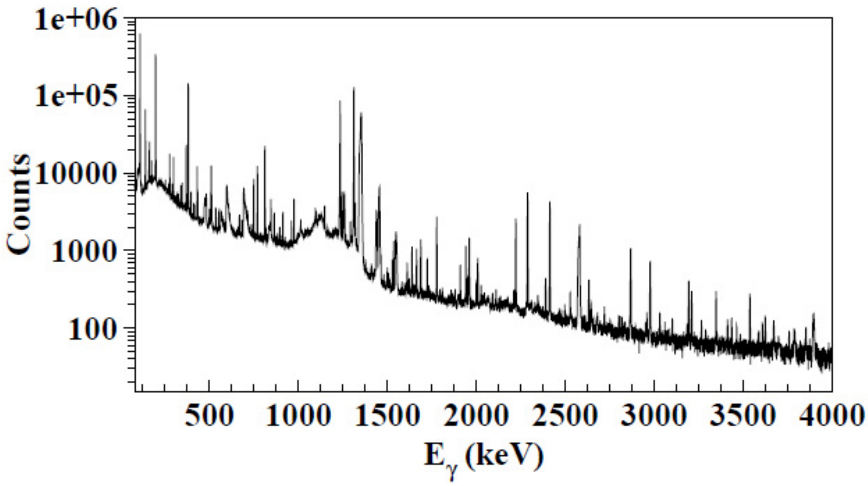

Fig. 7: Summed (n,n′γ) excitation function spectrum for ^{136}Xe for incident neutron energies from 2.5 to 4.5 MeV in 0.25 MeV increments using a solid $^{136}XeF_2$ scattering sample.

The validity of vibrational modes of excitation in nuclei is a topic of long-term interest at UKAL. Recent investigations of ^{106}Pd and ^{106}Cd have resulted in a comprehensive picture of *E*2 strength in these nuclei that have long been considered to have vibrational structure. Additionally, shape coexistence and configuration mixing in nuclei are identified in a model-independent way through the observation of *E*0 transitions and large $\rho^2(E0)$ values that quantify the extent of the mixing. Previously shape coexistence has been observed in several of the N = 60 isotones; work at UKAL has extended this description to ^{106}Pd through the measurement of lifetimes, multipole-mixing ratios, and γ-ray intensities for excited 0^+ levels, which when combined with *E*0 transitions identified in internal conversion measurements by Colvin *et al.* (1987) have been used to extract $\rho^2(E0)$ values. The large $\rho^2(E0)$ values have provided the evidence to extend shape coexistence to ^{106}Pd (Peters et al., 2016).

Transitional behavior in nuclei has long been a topic of interest in nuclear structure studies, but it is often difficult to describe in terms of nuclear models. Iachello (2000) proposed that nuclei may exhibit phase transitions analogous to what is observed in matter. The stable Xe isotopes span a region of nuclei that exhibits a transition from γ-soft rotors in the neutron mid-shell to more spherical nuclear behavior near the closed neutron shell at N = 82. The (n,n′γ) reaction has been used at UKAL to probe the structure of ^{130,132}Xe. The information obtained, especially for 0^+ states, provided the framework for comparisons with the E(5) critical-point symmetry. In neither case are the expectations of the E(5) symmetry fully realized; decays that are forbidden in the E(5) description are observed in both nuclei. Moreover, it appears that none of the Xe isotopes are clear-cut representations of an E(5) critical-point nucleus.

The (n,n′γ) reaction with its statistical excitation of low-spin states and ability to excite nuclear levels near their threshold has proven to be a very powerful way to study the structure of nuclei. At UKAL, this value is magnified by the quasi-monoenergetic nature of the pulsed neutron beam and the ability to use the Doppler-shift attenuation method to measure nuclear lifetimes in the femtosecond regime. The studies presented offer just a brief overview of the nuclear structure that can be studied at UKAL.

3.5 Neutron Elastic and Inelastic Scattering Cross Sections

Neutron elastic and inelastic scattering total and differential cross sections are important for both applied nuclear science through their importance in fission reactor applications, and for attaining a global and data driven description of how neutrons interact with matter. For several years the neutron cross-section measurements at UKAL with collaborators from the U. S. Naval Academy and the University of Dallas have focused on measuring neutron scattering from Na and Fe targets because of the importance of these materials in reactor coolants and structural materials, respectively, in both existing and next-generation nuclear reactors. Neutron elastic and inelastic scattering differential cross sections on ^{23}Na were measured at thirteen energies in the incident neutron energy range of 1.5-4.0 MeV (Vanhoy et al., 2015). Similar measurements were made on ^{54,56}Fe for E_n = 1.5 - 6.0 MeV; a TOF spectrum from these measurements is shown in Fig. 8. Neutron total inelastic cross sections were determined for many of the unresolved levels in Fig. 8 from γ-ray production cross sections measured following the (n,n′γ) reaction. These data have all been submitted to data evaluators for global data modeling.

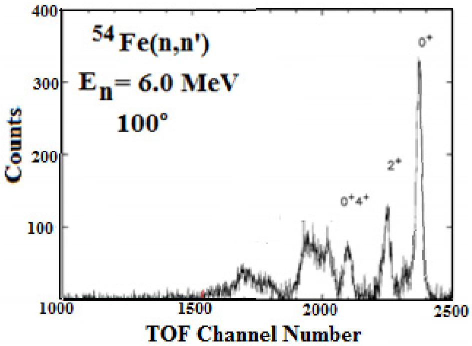

Fig. 8: Time-of-flight spectrum from ^{54}Fe neutron scattering measurements. The elastic scattering peak is rightmost in the spectrum as time increases from right to left. The lowest levels are clearly observed, but above the first few levels, the individual states cannot be resolved.

Currently, the focus of the neutron scattering group is to resolve discrepancies of over 30% in existing ^{12}C inelastic scattering cross sections near E_n = 6.0 MeV and to extend the measurements on ^{56}Fe to lower incident neutron energies were data evaluators have expressed a need for new measurements.

4. Conclusions

The University of Kentucky Accelerator Laboratory offers users the ability to use quasi-monoenergetic neutrons to study a broad range of phenomena and to answer questions of fundamental importance in nuclear physics. The laboratory also serves as a valuable facility to educate graduate and undergraduate students, as well as to offer postdoctoral fellows the ability to learn neutron production and detection techniques. The effective range of the *n-p* interaction, nuclear structure important for 0νββ decay studies and for our understanding of collective modes of excitation in stable nuclei, neutron cross sections for energy production applications and to improve our global understanding of how neutrons interact with matter, *n-p* radiative capture cross sections for use in Big Bang nucleosynthesis models, as well as neutron detector behavior for low-energy proton detection, are just a few examples of the nuclear physics studies which have either recently been completed or are currently underway at the facility. UKAL welcomes national and international collaborators and has had long-running collaborations with nuclear scientists from the U. S. Naval Academy, the University of Dallas, the University of Guelph, Georgia Institute of Technology, the University of Cologne, and the Massachusetts Institute of Technology.

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