EXOTIC NUCLEI RESEARCH AT LLNL

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This paper highlights some of the exotic nuclei studies at Lawrence Livermore National Laboratory (LLNL) within the Experimental Nuclear Physics (ENP) group. The work at LLNL concentrates on investigating nuclei at the extremes. The ENP group performs research to improve our understanding of nuclei, nuclear reactions, nuclear decay processes and nuclear astrophysics; an expertise utilized for important laboratory national security programs and for world-class peer-reviewed basic research.

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Introduction

On the wonderful occasion of EXON 2012 in the exotic far-Eastern Russian city of Vladivostok, it is fitting to discuss the properties of exotic nuclei and the methods for investigating these nuclei. The exotic nuclei research effort at LLNL is centered on investigating nuclei at the extremes—in particular, extremes of spin, isospin, neutron richness, excitation energy, decay and detectability, mass, and stability. Clearly, many of these areas are interrelated. The work at LLNL is aimed to support the U.S. nuclear physics goals as indicated in the Nuclear Science Long Range Plan [1], namely to develop a comprehensive and unified description of nuclei, which requires nuclear data on exotic nuclei, to make use of existing and future facilities (such as the Facility for Rare Isotope Beams (FRIB) currently under construction at Michigan State University) and to investigate neutrino properties and fundamental symmetries.

While research within the ENP group spans the chart of nuclides, this paper will focus on three specific areas of research:

1) the study of exotic neutron-rich nuclei such as ^{29}Na and ^{11}Be at the TRIUMF ISAC-II radioactive ion beam facility;

2) the study of exotic decay modes, namely the search for neutrinoless double-beta decay in ^{130}Te;

3) the study of superheavy elements (SHE) in collaboration with Dubna to investigate the nuclear decay properties and chemical properties of the heaviest elements.

Investigating the extremes of isospin – Nuclear structure

The magic numbers described by the shell model are not a universal quantity in nuclei. Magic numbers are a result of interactions between nucleons in the nucleus and should be expected to change with differing numbers of nucleons in a nucleus. Thus, experimental data for nuclei with extreme *N/Z* ratios are crucial to differentiate between models used to describe nuclear matter.

We are involved in investigating shell-structure effects when one adds additional neutrons to the nucleus – in other words the evolution of shell structure with *N/Z*. This work utilized radioactive ion beams from TRIUMF ISAC-II [2] and the TIGRESS/BAMBINO detector setup [3] as shown in Fig.1.

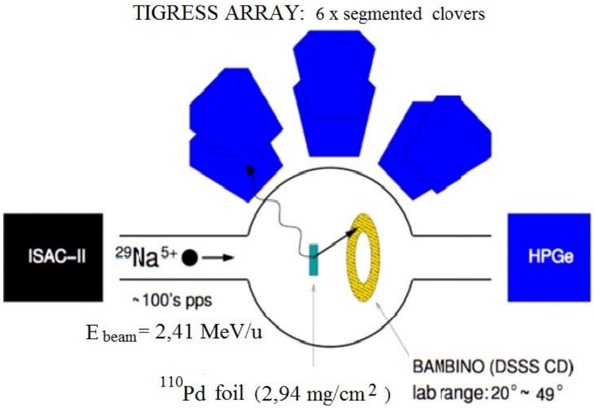

Fig.1 Schematic of the experimental setup for the ^{29}Na Coulomb excitation experiment. Note that the beam intensity was approximately 500 particles/sec.

The low-lying nuclear states in ^{29}Na were investigated using Coulomb excitation of a 70-MeV beam of ^{29}Na impinging on a ^{110}Pd target. The HPGe clover detectors of TIGRESS detected deexcitation gamma rays in coincidence with scattered particles which were detected in the segmented silicon detectors of BAMBINO. The observed gamma-ray spectrum is shown in Fig. 2.

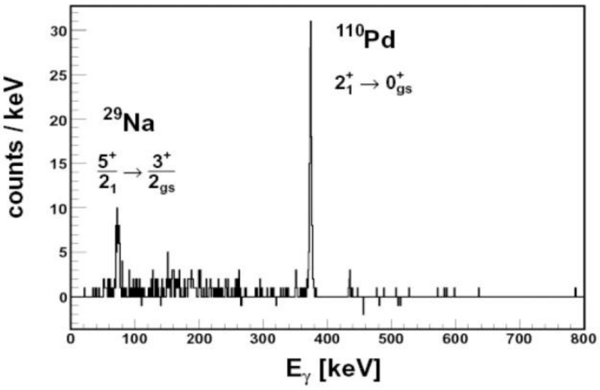

Fig.2 Particle- γ-ray coincident, background subtracted γ-ray energy spectrum following ~70 h beam on ^{110}Pd target showing the observed Coulomb excitation of the beam (^{29}Na) at 72 keV and target (^{110}Pd) at 374 keV.

The reduced transition matrix element for the transition from the first excited state to the ground state in ^{29}Na was measured to be 0.237(21) *e*b (corresponding *B(E2)* ~ 18(3) W.u.) and indicates a significant admixture of both *sd* and *pf* components in the wave-function. Significant narrowing of the shell gap (50% reduction) was observed in ^{29}Na as compared to ^{28}Na as one approaches *pf* – *sd* shell inversion in ^{30}Na. More details about this experiment may be found in [4].

The same technique was used to study ^{11}Be by impinging a beam of ^{11}Be of several different beam energies on a ^{196}Pt target. Preliminary gamma-ray spectra are shown in Fig. 3 for a ^{11}Be beam energy of 23 MeV (~2 MeV/A). The Coulomb excitation of the target can clearly be observed in the spectrum with the peak labeled ^{196}Pt $2^+ \rightarrow 0^+$ transition at 355.7 keV. The $1/2^- \rightarrow 1/2^+$ transition in ^{11}Be is also observed with a broadened peak in the lab frame at 320 keV due to the projectile motion. From this data combined with the data at a beam energy of 19 MeV, a preliminary *B(E1)* of 0.102(2) e^2fm^2 can be deduced using a semi-classical model. More details of this experiment can be found in [5].

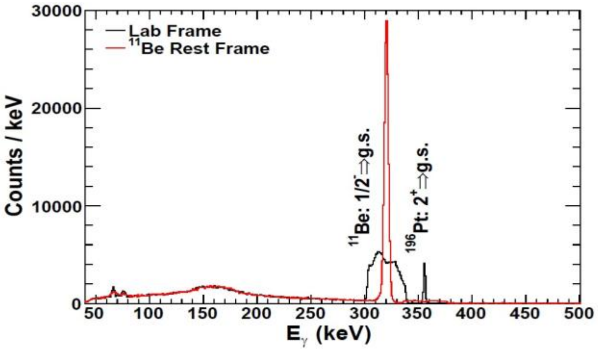

Fig.3 Preliminary background subtracted particle- γ-ray coincident spectra following a 23 MeV ^{11}Be beam on ^{196}Pt target showing the observed transition from the excited states populated by Coulomb excitation from the beam (^{11}Be) at 320 keV and target (^{196}Pt) at 355,7 keV in both the projectile frame and lab frames. The peaks at ~70 keV are x-ray lines from ^{196}Pt.

Investigating the extremes of decay and detectability – Neutrino physics

We are involved in experiments to understand fundamental properties of the neutrino utilizing detection of rare decay processes in ultra-low background counting experiments. In order to answer questions of whether the neutrino mass scale has inverted or normal hierarchy, whether neutrinos are Majorana particles (ie., neutrinos are their own anti-particles, differing from antineutrinos only by helicity—see Fig. 4), and whether lepton number conservation is violated, searches for neutrinoless double-beta decay in ^{130}Te at the CUORICINO array of TeO_2 bolometers have been performed [6] at the Labortori Nazionali del Gran Sasso (LNGS) in Italy. In two-neutrino double beta decay, because the neutrinos carry away energy, the beta-decay spectrum is a broad distribution of electron energies extending up to the Q value for the decay, the maximum sum electron energy. In neutrinoless double-beta decay, all of the energy is imparted to the two electrons resulting in a peak at the Q value. The shapes of these spectra are shown in Fig. 5.

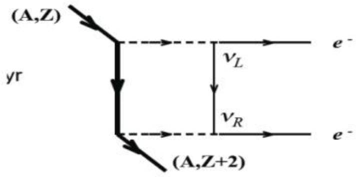

Fig.4 Feynman diagram showing the neutrinoless double-beta decay process.

No evidence for this rare decay mode is observed in these experiments and a half-life limit $T_{1/2}(^{130}\text{Te}) \geq 2.8 \times 10^{24}$ y (at 90% confidence level) was set [7].

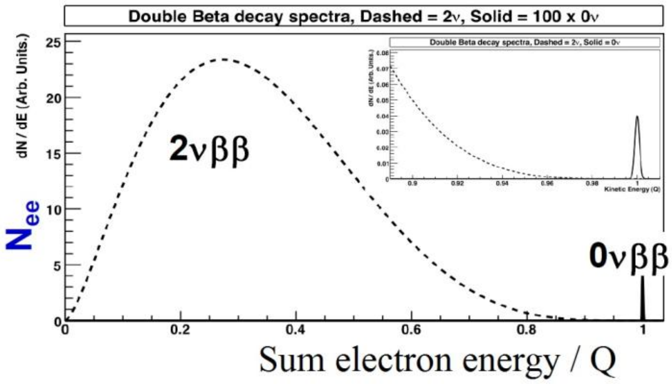

Fig.5 Expected electron spectrum for two-neutrino double-beta decay and neutrinoless double-beta decay. The relative sizes of these spectra were chosen to display their shapes – no peak at the Q value has yet been observed.

In order to increase the sensitivity of the experiment, approximately 20 times more TeO_2 bolometers are being assembled into the CUORE array in Italy. On the way to CUORE, the first tower of TeO_2 bolometers called CUORE-0 has been assembled in order to debug assembly procedures and to employ background reduction techniques useful for the full array.

Thus, detection of the electrons with high efficiency and good resolution in ultra-low background counting conditions is essential. The experimental sensitivity is given by: $S_{0\nu} \propto (MT/\Gamma b)^{1/2}$; where M is the source mass, T is the live counting time, Γ is the energy resolution of the detector, and b is the background level. Obviously, one wants a large source of decaying nuclei, hence the ¾-ton CUORE experiment. Long count times are required—with the expected improvements to the CUORE-0 tower over CUORICINO, one still expects to count for ~6 months in order to surpass the CUORICINO half-life limit stated above. Detection of a peak relies on as good a detector resolution as possible and one also wants to minimize background radioactivity.

Research at LLNL has addressed all aspects of the experimental sensitivity. Measurement of ^{130}Te, ^{128}Te, and ^{120}Te masses, using a Penning trap [8] have significantly improved the Q-values for neutrinoless double-beta decay in ^{130}Te and neutrinoless EC-β^+ decay in ^{120}Te, enabling the energy regions for searches to be narrowed and pinpointed [7,9]. LLNL was responsible for the US TeO_2 crystal production and took great care to ensure that backgrounds were minimized during fabrication [10]. Large area plastic scintillators were used to identify muon-induced backgrounds in operating CUORICINO bolometers at LNGS. This background was demonstrated to be negligible [11]. Additionally, techniques for reproducibly assembling the bolometers to improve reliability, reproducibility and performance of the crystals were developed at LLNL and used in the CUORE-0 assembly.

The CUORE-0 tower (see Fig. 6) was installed in the cryostat at LNGS in August 2012, was cooled down, and is beginning operation as a neutrinoless double-beta decay detector. The first pulse from the detector was obtained on August 24, 2012 (see Fig. 7) and the coming months of operation will not only begin a more sensitive search for this rare decay mode, but also include evaluation of all of the new techniques used to minimize backgrounds and improve performance of the bolometers, which will in turn provide more realistic estimates of the physics reach of the full CUORE detector.

Fig.6 CUORE-0 tower assembled prior to installation in the cryostat.

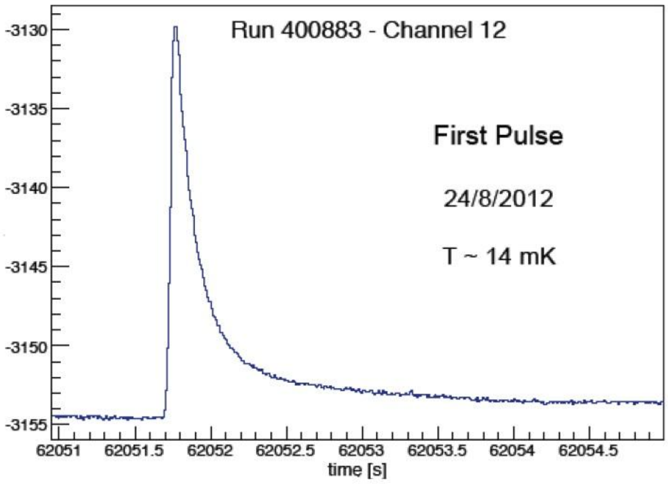

Fig.7 First pulse from the CUORE-0 tower.

Investigating the extremes of mass – Superheavy elements

One of the most productive collaborations over the last 25 years has been the Dubna/LLNL collaboration to investigate the nuclear and chemical properties of the heaviest elements. The Livermore Heavy Element group has a long and accomplished history of fundamental nuclear research, with spectroscopic, chemical, and decay studies dating back to the 1950s. In the 1980s, two fission modes were discovered which competed in the spontaneous fission of several heavy actinide nuclides. This "bimodal fission" decay challenged nuclear theory and resulted in fundamental changes in the way the fission barrier was modeled [12,13]. A collaboration between scientists at the Joint Institute for Nuclear Research (JINR) in Dubna, Russia and scientists at LLNL was established in 1989. In the early 1990s, this collaborative work resulted in the confirmation of a recently predicted region of nuclei that owe their extra stability to the nuclear shapes, the effect being strongest for nuclei near neutron number 162 and proton number 108 [14-16]. In late 1998 and 1999, again in collaboration with our Russian colleagues, we performed experiments that resulted in the first observation of an "Island of Stability" of superheavy elements [17-19]. Nuclei on this island, long predicted by theory to be centered around neutron number 184 and proton number 114, have been the subject of many experimental searches over the last 30 years. They owe their unusual stability to their proximity to nuclei with filled major nucleon shells, resulting in a spherical nuclear shape. This is the same effect that imparts the extra stability associated with nuclei in the lead region and doubly magic ^{208}Pb in particular. The collaborative work since 1998, described in a review article [20], has resulted in the discovery of elements 113, 114, 115, 116, 117 and 118, and over 43 new isotopes in about 140 decay chains.

We continue to investigate the region of the chart of nuclides near the “Island of Stability” with our colleagues at JINR in Dubna. An experiment was performed to attempt to synthesize element 120 using the ^{58}Fe + ^{244}Pu reaction – an exciting attempt to continue hot-fusion reactions utilizing beams other than ^{48}Ca. The results of this particular experiment set a cross-section limit for the production of element 120 and are discussed in more detail in [21]. We also performed a ^{48}Ca + ^{226}Ra experiment to produce Hs isotopes and several candidate decay chains were observed [22].

Indeed, there has been exciting progress in the study of the properties of the heaviest elements, and several other experiments are noteworthy of mention. Nuclear spectroscopic studies of ^{254}No and ^{256}Rf isotopes have for the first time identified states built on the single-particle levels from above the Z=114 shell gap in spherical nuclei [23-25]. Additionally, the Dubna/LLNL element 112 and 114 results have been reproduced by GSI [26], PSI/Dubna [27], and LBNL [28]. Element 116 has been produced also at GSI in Darmstadt [29]. The confirmatory experiments contributed to final acceptance of elements 114 and 116 by the IUPAC in June 2011 [30] and the naming of these elements flerovium (Fl) and livermorium (Lv), respectively [31].

A Dubna/LLNL/ORNL collaboration produced two isotopes of element 117 in 2010 using the ^{48}Ca + ^{249}Bk reaction as described in [32]. The ^{249}Bk is produced in the ORNL High Flux Isotope Reactor (HFIR) and is chemically purified at ORNL. This experiment required massive international coordination because ^{249}Bk has a half-life of only 330 d. The collaboration has concentrated experiments in 2011 and 2012 on ^{48}Ca + ^{243}Am and ^{48}Ca + ^{249}Bk reactions, producing many more odd-Z decay chains [33, 34].

Conclusions

Many of the research areas discussed in this paper are interconnected. Several areas of research were discussed in greater detail (see Fig. 8).

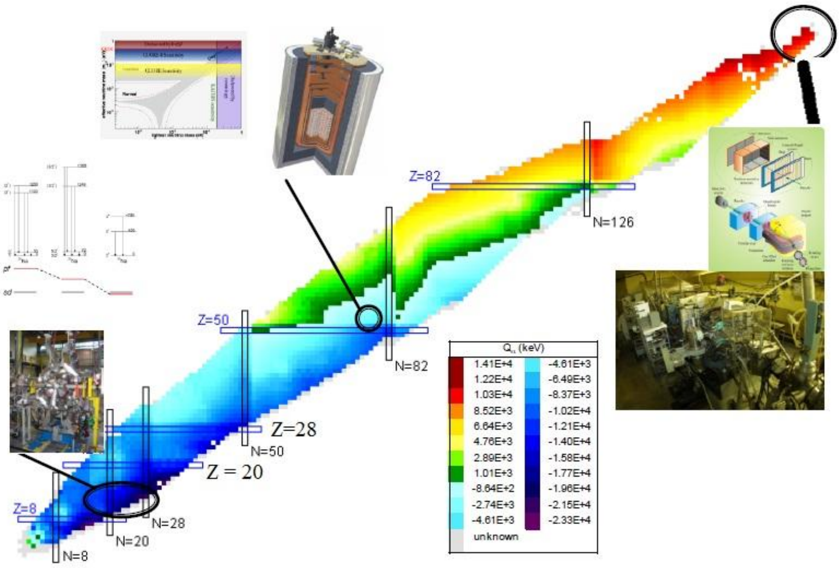

Fig.8 Chart of nuclides highlighting some of the exotic nuclei studied by the ENP group at LLNL in collaborations. More details of these experiments are given in the text.

All are focused on elucidating a better understanding of nuclei and nuclear reactions – an organization of our knowledge regarding the nucleus of a chemical element. Mendeleev's efforts to organize the chemical elements, and hence derive a basic understanding of nature, continues today with our work on the chemistry and physics of new heavy elements, with our work to develop a complete fundamental description of nuclei by studying exotic nuclei and nuclei in exotic environments, and with our work to understand the basic properties of the neutrino.

Acknowledgements

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