COLLINEAR LASER SPECTROSCOPY AND POLARIZED EXOTIC NUCLEI AT NSCL

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A facility for collinear laser spectroscopy and beam polarization of exotic nuclei is being developed at NSCL. The facility will make use of thermalized rare isotope beams available at NSCL from projectile fragmentation and in-flight separation with subsequent gas stopping. This system provides access to new and unexplored territory in the nuclear chart and will be implemented at the next generation rare isotope facility. Laser spectroscopy and β NMR/NQR techniques will be utilized to determine nuclear charge radii and nuclear ground state electromagnetic moments as well as for fundamental interaction tests.

Keywords: laser spectroscopy; optical pumping; cooled and bunched beams; β NMR; β NQR; mean square charge radii; electromagnetic moments; fundamental symmetries.

1. Introduction

Laser spectroscopy and optical pumping techniques have been extensively used in nuclear physics to determine the nuclear spins I, the magnetic dipole moments μ, the spectroscopic electric quadrupole moments Q, and the mean-square charge radii $\langle r^2 \rangle$ of nuclear ground states and isomers [1]. Atomic spectroscopy is also used in testing fundamental interactions, for example, through laser cooling and confinement of radioactive atoms [2].

Most of the laser spectroscopic data has been obtained at Isotope Separator On Line (ISOL) facilities [1], where rare isotopes are extracted from thick targets bombarded by light ions. Long chains of isotopes have been systematically investigated, taking advantage of the good quality low-energy beam ($\sim$ 60 keV) and the high beam intensities available for many nuclides of certain elements. The number of elements for which rare isotopes can be produced with the ISOL technique is limited when long release times from the targets lead to large decay losses. These limitations have been partly overcome by the Ion Guide at an Isotope Separator On Line (IGISOL) approach, where low-energy reaction products are stopped in a gas and converted into a low-energy ion beam [3].

On the other hand, projectile fragmentation reactions and in-flight separation routinely provide high-energy beams (>50 MeV/nucleon) for isotopes of all elements lighter than uranium. The technique is universal and reaches very far from stability since decay losses are negligible. The recent conversion of these fast beams into high-quality low-energy beams via gas stopping techniques [4,5] and advanced beam manipulation techniques [6,7] has opened the door for a new range of experiments with projectile fragments, complementing and extending studies previously only possible at ISOL-type facilities.

National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University was the first facility where fast rare isotope beams, produced in projectile-fragmentation, have been slowed to thermal energies with a gas stopping system [5] and used for precision experiments. An experimental program of high-precision mass measurements with a 9.4 Tesla Penning trap mass spectrometer is underway [8–10]. Extending these experimental opportunities is a logical next step. In addition to work with stopped beams, the re-acceleration of the thermalized rare isotope beams is under preparation [11].

The laser-spectroscopy activities at NSCL are expected to make a major contribution to the science program, since isotopes can be studied that are inaccessible or difficult to obtain anywhere else in the world. The activities will also set the ground work for even greater science opportunities to become available at the next-generation rare isotope facilities like the prospective Facility for Rare Isotope Beams (FRIB) in the US. NSCL has proposed the Isotope Science Facility (ISF) [12] to satisfy the technical and scientific goals of FRIB. ISF will make it possible to produce rare isotopes beams with the shortest half-lives at unprecedented intensities, using projectile-fragment reactions for rare isotope production and in-flight separation techniques.

One of examples of the extended science opportunities that will be started at NSCL and then continued at ISF is the measurement of mean-square charge-radii, $\langle r^2 \rangle$, of short-lived very exotic nuclides. As mentioned before, most of the laser spectroscopic data to date have been obtained at ISOL facilities. However, there still is very little information on $\langle r^2 \rangle$ of light- and medium-mass nuclei. Such shortcomings can be attributed to the

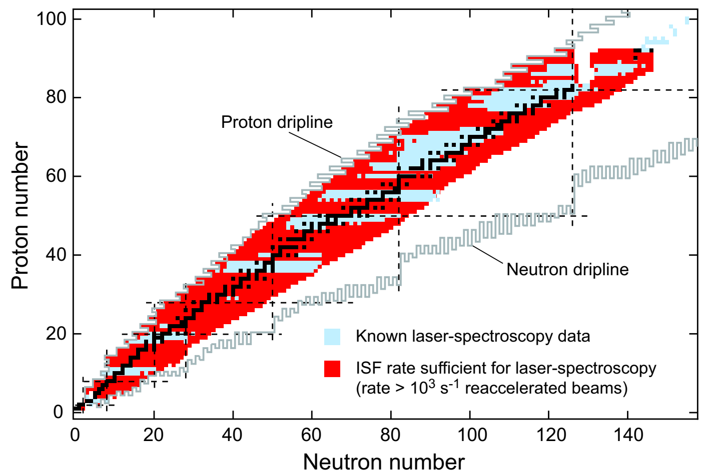

Fig. 1. Chart of nuclei depicting those isotopes studied via laser spectroscopy [1]. Previously studied cases and the reach of ISF are shown by light and dark gray squares, respectively. The solid squares are the stable nuclei. Taken from Ref. [12].

difficulty of production of short-lived metallic and refractory rare isotope beams. The increased production rate at ISF will allow laser spectroscopy to be extended to isotopes far from stability. Fig. 1 shows a comparison of present laser spectroscopy data [1] and the eventual reach of laser spectroscopy at ISF. It is clear that the present data are fairly limited and the beams available at ISF will cover long isotopic chains for all elements not only in neutron-rich but also neutron-deficient regions. The increased production rate at ISF also opens up opportunities to perform laser spectroscopic experiments to test fundamental interactions using thermalized beams from projectile fragmentation.

2. Laser Spectroscopy with Thermalized Beams at NSCL

An on-line laser spectroscopy and beam polarization facility is under development at NSCL, where the source of radioactive ions will be projectile fragments that are stopped in a gas stopping system [4,5,13]. After extraction and conversion into a low-energy continuous beam, the ions will be accelerated to ~ 30 keV for transport to the laser spectroscopy facility, which is shown schematically in Fig. 2. The low-energy beam will be slowed down electrostatically before entering a linear Radio Frequency Quadrupole (RFQ) ion trap [6] filled with helium as a buffer gas at low pressure. The linear trap will reduce the beam emittance and provide short ion bunches.

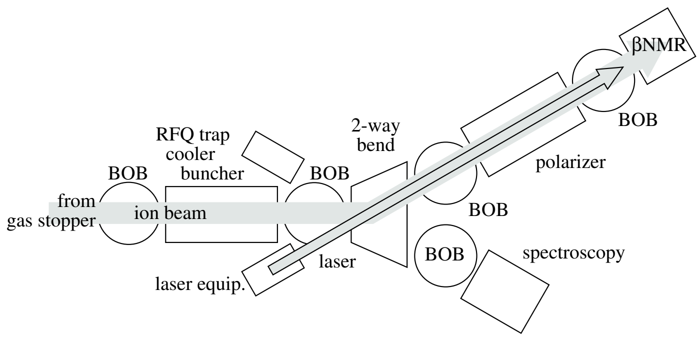

Fig. 2. Schematic of the planned laser spectroscopy and beam polarization facility at NSCL. Thermalized rare isotope beams are provided by the NSCL gas stopping system. After cooling and optional bunching in a linear RFQ ion trap, a high-quality low-energy beam (pulsed or continuous) will be transported to either a laser spectroscopy or polarization beam line, where laser light will be collinearly overlapped with the ion beam. Various techniques for laser spectroscopy (optical detection, ion detection) will be used as well as a beta-NMR and NQR setups for moment measurements.

The trap can be operated at cryogenic temperatures, a technique also pioneered at the NSCL [6,7], that is key to providing excellent beam quality. The cooled and bunched beam will then be transported to a laser spectroscopy or a laser polarizer beam line. The very short pulses with good emittance and low energy-spread will increase the detection sensitivity of laser spectroscopy experiments. For example, laser spectroscopy has been demonstrated with microsecond pulses at ion rates as low as $\sim 10^2$/s at JYFL [14,15]. The existing beam cooler for LEBIT at NSCL routinely provides ion pulse lengths below 100 ns [7] and similarly excellent beam timings properties are expected for the new beam cooler for the laser spectroscopy and beam polarization facility, all of which indicates that the sensitivity of laser spectroscopy will be drastically improved.

Nuclear magnetic/quadrupole resonance techniques based on detecting β decay (β-NMR/NQR) will be employed to beams whose nuclear spin ensemble has been polarized by optical pumping [16–18]. The β-NMR/NQR techniques can be applied to nuclei with production rates of $\sim 10^2$/s, assuming $\sim 10\%$ nuclear polarization, when the NMR signal is obtained by detecting the β-ray asymmetric angular distribution from polarized nuclei (see, for example Ref. [19]). The early science program at the laser spectroscopy and beam polarization facility at NSCL will examine nuclear-electromagnetic moments and charge radii of nuclei in the sd-shell and in the light fp-shell. Some examples are discussed in the following subsections.

2.1. *Mean-square charge radii*

Changes in the nuclear charge radius determined in isotopic shift measurements are very sensitive to nuclear deformation. Such measurements have been performed for many elements along long isotopic chains [1] and revealed interesting nuclear structure effects. Light and medium mass nuclei are largely unexplored, as seen in Fig. 1. The recent measurement of the $\langle r^2 \rangle$ of ^{11}Li [20] completed at ISAC/TRIUMF serves as an excellent example of the variation of the nuclear shape at the limit of stability, and the potential reach of such measurements to the limits of the nuclear chart.

At NSCL, $\langle r^2 \rangle$ measurements of light and medium mass nuclei, especially refractory elements, will be performed with a focus on nuclides inaccessible or difficult to extract at ISOL facilities. Techniques already developed for producing high-quality cooled and bunched beams will be key to reaching the sensitivity necessary to reach nuclides very far from stability.

2.2. *Electric quadrupole moments*

The deviation of nuclear shape from spherical symmetry can be directly observed in the electric quadrupole moment, Q. Nonzero values of Q for nuclei far from stability serve as indicators of new regions of deformation. Most of the data for Q was obtained by laser spectroscopy and the hyperfine structures provide direct information on the sign and magnitude of Q. However, the majority of these data have been collected for heavier nuclei, and the nuclear landscape below $Z = 50$ remains largely unexplored [1,21].

Very limited data are available for ground state Q of light nuclei, apart from systematic studies of a few isotopic chains; B [22] and Na [18,23] isotopes. Efforts to extend such studies of neutron-rich nuclei continue. For example, measurements of the ground state Q of neutron-rich magnesium and aluminum isotopes [24] will better define the limits of the island of inversion around ^{32}Mg. On the neutron-deficient side of the valley of stability, the nature of the proton-halo structure is one of the interesting areas to be addressed. Since the Q is defined by the proton distribution in the nucleus, Q is one of the most sensitive measures of a proton-halo structure. However, the available data are sparse. The strongest evidence for a proton halo structure is in the large Q of ^{8}B [25], but the proton-halo structure, and its relation to Q, is still to be clarified.

2.3. *Magnetic dipole moments*

The magnetic dipole moment, μ, is sensitive to the relative amplitudes of different orbital components of the nuclear wave function. The well known form of the electromagnetic operator makes μ an important observable for assessing nuclear structure models. This is especially true for mirror nuclei, which only differ in the exchange of proton and neutron numbers. For example, the expectation values of both spin and orbital angular momentum can be deduced from the known ground-state μ of both mirror partners [26]. The systematics of the spin expectation value, $\langle\sigma\rangle$, of the isospin $T = 1/2$ mirror nuclei in the *sd* shell have been well established in the *sd* shell. However, $\langle\sigma\rangle$ has only been deduced for 4 mirror partners with $T = 3/2$.

Two anomalous results of $\langle\sigma\rangle$ values have been reported. First, the deduced $\langle\sigma\rangle$ for the $T = 3/2$, ^{9}Li - ^{9}C mirror system [27,28] was found to be 50% larger than the extreme single-particle expectations. It still remains a challenge to nuclear-structure theories [28,29]. Data on $\langle\sigma\rangle$ for heavier $T = 3/2$ nuclei near the proton drip line may illuminate the underlying structure changes associated with loosely-bound valence protons. Secondly, the ground state μ of ^{57}Cu, which completed the $T = 1/2$, $A = 57$ mirror-moment measurements, gives a large and negative value for $\langle\sigma\rangle$ [30]. The result is also very different from extreme single-particle model expectations, and suggests a breaking of the ^{56}Ni doubly magic core. Extension of μ measurements of neutron-deficient nuclei beyond the *sd* shell will be critical to test the applicability of shell model interactions in medium-mass nuclei.

3. Examples of Scientific Opportunities with Laser Spectroscopy at a Next-Generation Facility like the ISF

The wide range of nuclei promised at ISF naturally will allow extension of measurements of $\langle r^2\rangle$ and ground-state nuclear-electromagnetic moments, as discussed in the previous sections, to nuclei at the nucleon driplines (see Fig. 1). At the same time, the overall increased production rates throughout the chart will open up possibilities to perform experiments to test fundamental symmetries, which generally require high statistics. Some of these opportunities are discussed in the following subsections.

3.1. *Test of parity and time reversal symmetries*

The CPT theorem requires invariance under the combined application of three independent operations, namely charge conjugation (C), parity inversion (P), and time-reversal (T). Direct evidence for CP violation in the decay of the neutral kaon [31], which is now implemented in the framework of the Standard Model (SM), led immediately to searches for possible T violation. CP violation is thought to have played a crucial role in producing the excess of matter over antimatter early in the history of the universe [32].

The SM does not violate CP symmetry strongly enough to account for this excess. To understand baryogenesis, the physical process of generation of nucleons in the early universe, we must first discover the additional CP violation and/or equivalently the T invariance, if it indeed exists.

One such effort is the determination of electric dipole moments (EDM) [33–35], which violate parity as well as time-reversal invariance. The sensitivity in observing EDMs can be enhanced by studying heavy rare isotopes. Due to relativistic effects, the measurable electron EDM in atomic systems is proportional to Z^3 [36]. Therefore, measurements on the heavier Z atoms are more sensitive to the EDM. Francium is a very good candidate because of its simple atomic structure. Hadronic EDMs observed in diamagnetic atoms can experience large enhancement factors (100-1000) if the nucleus is octupole-deformed [37,38]. Such deformations exist in rare isotopes of radon, radium, and francium.

New experiments with higher precision are required in a variety of atomic systems. They will help us to learn to what extent EDMs exist and may contribute to the understanding of the matter-antimatter asymmetry in our universe. Examples of rare isotopes considered for EDM studies are ^{211}Rn, ^{223,225}Ra, and ^{221}Fr, which will be available at ISF.

Complementary searches for CP violation can be performed in low energy β-decay experiments. Time-reversal violation tests via correlation experiments in β-decay require an odd number of spin and/or momentum vectors, which is odd in time-reversal operations. The results of the nuclear β-decay experiments on the neutron [39,40], ^{8}Li [41], ^{19}Ne [42–44], and ^{56}Co [45] are all consistent with T invariance and the SM.

A potentially more precise time reversal violation test can be performed in a β-γ-ray angular correlation experiment from spin-aligned nuclei [46,47]. This type of experiment has been performed in the case of ^{56}Co. However, it provides the poorest constraint on T-violating coefficients. One of the candidate of such experiment at ISF is ^{52}Co.

3.2. *Search for new interactions in weak nucleon current*

The SM describes the β-decay process in terms of an exchange of charged vector bosons between the hadronic and leptonic currents. Only vector and axial-vector type interactions are allowed in the SM. However, scalar and tensor type interactions could exist and, at present, are only ruled out at a level of about 10%. Finding such new interactions would provide a signature of new physics beyond the SM, possibly requiring the exchange of leptoquarks or new charged bosons.

The most stringent limit on scalar currents comes from a delayed proton-emission experiment on ^{32}Ar at ISOLDE [48] and an atom trap experiment with ^{38m}K at ISAC [49]. The most precise experiment searching for tensor currents was carried out with ^{6}He at Oak Ridge more than four decades ago [50]. All these experiments are still in agreement with SM predictions. In addition to the nuclei already considered, other interesting candidates, which can be produced at high rates at ISF, for electron-neutrino correlation studies in ion traps are ^{14}O, ^{26m}Al, ^{33}Cl, ^{35}Ar, ^{42}Sc, ^{46}V, ^{50}Mn, and ^{54}Co.

3.3. *Search for induced currents in weak interactions*

The SM predicts that β decays can be described by the vector-axial vector (V-A) form of the weak nucleon current. Even if scalar (S) and tensor (T) interactions in the fundamental weak quark-lepton interactions do not exist, currents can be induced by the strong interaction due to pion exchange in the nucleus [51]. In the vector current, two of the induced terms are the weak magnetism f_W and the induced scalar term f_S. In the framework of the CVC theorem, where the weak currents and the isovector part of electromagnetic current form an isospin triplet, f_W and f_S are exactly given. The f_S should be zero and, experimentally, has been determined to be small ($f_S < 0.0013$ [52]). Theory predicts a nonzero value for f_W, which is yet to be determined experimentally with good precision. In the case of the axial vector current, two terms may be induced, a pseudo-scalar term, f_P, and a tensor term, f_T. The f_P term can be determined in muon capture reactions. The f_T term is known as a Second Class Current (SCC) [53,54]. According to the SM, f_T should be zero. However, the small mass difference between proton and neutron (and hence up and down quarks) may result in a small but finite number, $f_T \sim 10^{-5}$/MeV [55]. The most stringent constraint $f_T < 2{\times}10^{-4}$/MeV, obtained from β-decay angular distribution from aligned ^{12}B and ^{12}N [56], does not reach that level.

One possibility for a precise determination of f_W in the vector current is a systematic and very precise measurement of the spectral shape, a, of the β-decay energy spectra observed in pure Gamow-Teller transitions, where a simple interpretation of the shape factor is possible. Because the effect of f_W on the a appears in the form of $\sim f_W E_\beta$, high-energy β decays are preferred. For example, the ^{24m}Na and ^{24m}Al $T = 1$ pair would be available with required beam rates at ISF, allowing the currently very small set of test cases to be extended. An ion trap based spectrometer similar to the WITCH facility [57] at ISOLDE would be a good choice for determining the shape of the β-decay energy spectrum with high precision and efficiency.

Measurement of the β decay angular distributions from spin-aligned mirror nuclei can be employed to search for f_T in the axial vector current. The results for both nuclei takes advantage of mirror symmetry and allows systematic effects to be minimized, which is essential to extract the very small effect of f_T. Polarized beams are required, and can be realized by laser optical pumping. A promising example is ^{13}O. The high β-decay energy and a pure GT transition make ^{13}O very sensitive to f_T. The polarized ^{13}O beam can be obtained by optical pumping, starting from a metastable atomic state [58]. The necessary measurement of the mirror partner ^{13}B is now in progress at Osaka University. Systematic studies of multiple mirror partners are needed to put a reliable limit on the induced tensor term.

4. Conclusion

A laser spectroscopy and nuclear polarization facility is being implemented at NSCL for experiments with thermalized projectile fragments. Highly-sensitive measurements will be possible by employing laser spectroscopy techniques on cooled and bunched beams and by using β-NMR/NQR techniques. Charge radii and electromagnetic moments of isotopes not accessible with ISOL techniques will be studied. The techniques developed will be beneficial for future studies at the next-generation facility FRIB, like ISF as proposed by MSU. The promised rare isotope beams produced by projectile fragmentation will open new opportunities to extend the limits of such studies towards the nucleon driplines and test fundamental symmetries.

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