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Laser assisted decay spectroscopy at the CRIS beam line at ISOLDE

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Abstract. A new collinear resonant ionization spectroscopy (Cris) beam line has recently been installed at Isolde, Cern utilising lasers to combine collinear laser spectroscopy and resonant ionization spectroscopy. The combined technique offers the ability to purify an ion beam that is heavily contaminated with radioactive isobars, including the ground state of an isotope from its isomer, allowing sensitive secondary experiments to be performed. A new programme aiming to use the Cris technique for the separation of nuclear isomeric states for decay spectroscopy will commence in 2011. A decay spectroscopy station, consisting of a rotating wheel implantation system for alpha decay spectroscopy, and three high purity germanium detectors around the implantation site for gamma-ray detection, has been developed for this purpose. This paper will report the current status of the laser assisted decay spectroscopy set-up for the Cris beam line.

1. Introduction

Many experiments in nuclear physics are unable to study rare isotopes due to the presence of large isobaric contaminations. Of particular interest are the low lying isomers of less than 40 keV that cannot easily be distinguished from their ground state. Mass measurements [1] of ^{80}Ga missed the long lived isomer that was discovered with collinear laser spectroscopy [2]. Gamma ray spectroscopy provides higher resolution, but cannot distinguish between ground and isomeric states that both decay, such as ^{80}Ga, or those that are too long lived. Furthermore, the resolution may be insufficient to distinguish the states, for example in ^{73}Ga where the 3/2 and 1/2 ground state doublet are within <1 keV of each other [3]. Initial decay spectroscopy of ^{202}Fr and ^{204}Fr could not differentiate the alpha decay of the isomeric states from those of the ground

state [4]. However, later measurements [5] revealed the low lying structure of these isotopes, but the tentative spin-parity assignments of these isomers are based on feeding patterns in $\beta+$/EC decay and on systematics. The predicted isomer in ^{229}Th (with an energy of 5.5 eV [6]) has been inferred [7, 8] and is under investigation [9], but its existence has yet to be proven conclusively.

Isomer identification has already been achieved with in-source laser spectroscopy [10], for example ^{68,70}Cu. Following this selection, secondary experiments such as Coulomb excitation [11] and mass measurements [12] have been performed on these isomeric beams. However, these experiments suffered from the isobaric contamination of surface ionized gallium, as well as significant ground state contamination due to the Doppler broadening of the hyperfine resonances of each isomer [13].

The new collinear resonant ionization spectroscopy experiment at ISOLDE has been developed for hyperfine structure measurements [14]. Laser radiation is used to step-wise excite and ionize an atomic beam using its characteristic hyperfine structure. In addition to hyperfine measurements, this technique offers the ability to purify an ion beam that is heavily contaminated with radioactive isobars, including the ground state of an isotope from its isomer [15], allowing sensitive secondary experiments to be performed. A decay spectroscopy station is due to be installed at the end of the CRIS beam line to take advantage of the selectivity of collinear laser spectroscopy to perform decay measurements on these rare isotopes.

2. Collinear resonant ionization spectroscopy for decay studies

The status of radioactive ion beam experiments is such that high resolution laser spectroscopy measurements cannot, in general, currently be performed on short-lived isotopes with yields less than 10^2 ions per second. The CRIS technique [16] provides a combination of high detection efficiency, high resolution and ultra-low background, allowing measurements to be performed on isotopes with yields down to 1 ion per second.

The collinear geometry of the set-up gives a reduction in thermal Doppler broadening by a factor of $\approx 10^3$, thus the selectivity of the state of interest is greatly increased. As shown in Equation 1, the product of the velocity and velocity spread remains constant under acceleration. By collinearly overlapping the accelerated ion beam with the laser, a narrower velocity distribution of the ion beam is probed by the laser, decreasing the Doppler broadened line width of the hyperfine transition to below its natural width in most cases.

$$\Delta E = \delta(\frac{1}{2}mv^2) \approx mv\delta v = constant \tag{1}$$

This is apparent in Figure 1(a). The simulated plot shows the hyperfine spectrum of ^{80g,m}Ga obtained using in-source and collinear laser spectroscopy. The narrower line widths of the hyperfine transitions produced by the collinear geometry lead to a greater degree of selectivity between the ground state and isomeric state of the isotope.

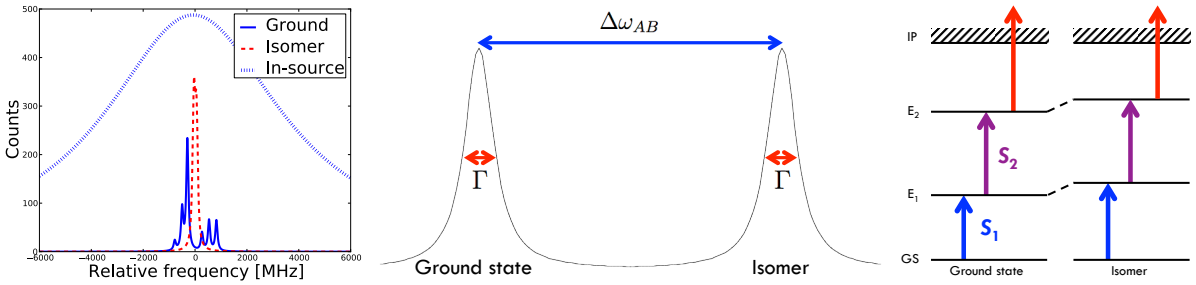
For resonant ionization spectroscopy, the maximum selectivity S is given by Equation 2:

$$S = \left(\frac{\Delta\omega_{AB}}{\Gamma}\right)^2 = \prod S_n \tag{2}$$

where Γ is the radiation line width and $\Delta\omega_{AB}$ is the difference in frequency between the two absorption lines due to the isomer shift, schematically shown in Figure 1(b). Additional selectivity can be gained due to the kinematic shift of the isotopes caused by the collinear geometry. The total selectivity of a resonant ionization process is given by the product of the individual selectivities. Thus increasing the number of resonant transitions in the ionization scheme will greatly increase the selectivity of the process [13], as can be seen in Figure 1(c).

Techniques such as mass spectrometry do not have the energy resolution to distinguish between two low lying states, or they saturate due to the abundance of the ground state

compared to the isomeric state, making measurements of nuclear parameters problematic. With the combination of collinear laser spectroscopy and resonant ionization available at CRIS, decay spectroscopy can be performed on pure isomeric states, with a suppression of the ground state by a factor of at least 10^4 per resonant transition. Indeed, by using a three step ionization scheme (instead of two) the suppression would increase to 10^8.



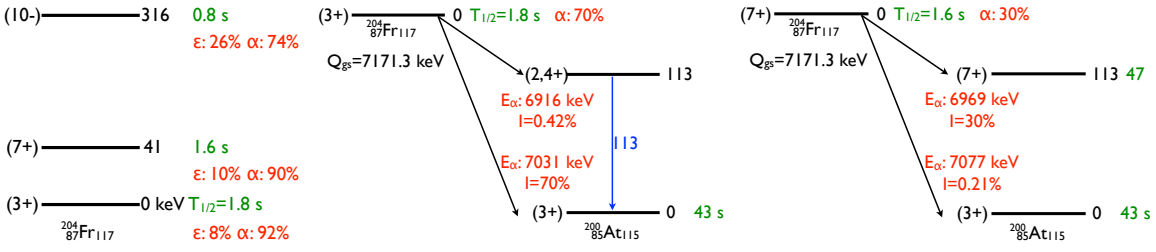
(a) (b) (c)

Figure 1. [Colour online] (a) A simulated scan of the hyperfine structure of ^{80g,m}Ga that would be obtained using in-source [dashed blue] and collinear [solid blue and dashed red] laser spectroscopy. A Doppler broadened line width of 100 MHz is assumed, with the data for ^{80g,m}Ga taken from [3]. (b) The difference in frequency $\Delta\omega_{AB}$ between two absorption lines, due to the isomer shift. (c) The number of resonant transitions increases the selectivity of the process.

3. Nuclear measurements with laser and decay spectroscopy

Laser spectroscopy of an isotope's hyperfine structure provides model independent measurements of nuclear observables: nuclear spin, magnetic dipole and electric quadrupole moments, and the change in mean square charge radii between isotopes. Using the selectivity of resonant ionization, isobaric contaminants are suppressed, allowing decay spectroscopy to be performed. Decay spectroscopy provides complementary information on the nuclear level structure of the daughter nucleus. The combination of the two complementary techniques present at the CRIS beam line allows a wealth of information to be obtained on the isotope under investigation.

As a proof of principle for the CRIS technique, the first case to be looked at is the low lying isomer in ^{204}Fr. Here, the ground and isomeric state are within 41 keV of each other, as shown in Figure 2(a). The decay schemes of these two states can be seen in Figure 2(b) and (c).



(a) (b) (c)

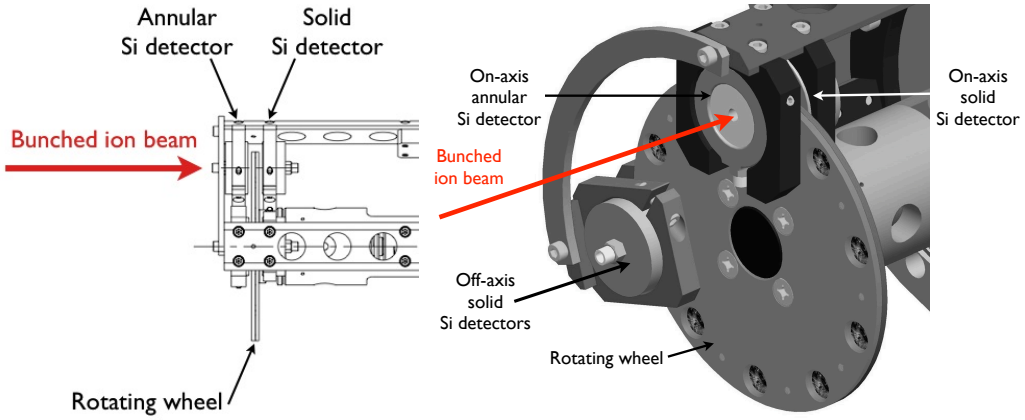
Figure 2. (a) Level scheme of ^{204}Fr [17]. (b) Decay scheme of ^{204g}Fr and (c) ^{204m1}Fr [5, 18].

This region of the Segrè Chart has garnered considerable attention, with experimental campaigns into β-delayed fission of ^{200,202}Fr having already been undertaken [19]. This uncommon fission process is thought to play an important part in the astrophysical r-process.

The different spins and moments result in hyperfine structures that will significantly differ in magnitude, allowing the isomers and ground state to be distinguished. The provisional assignments of the 3^+ ground state and 7^+, 10^- isomeric states will result in different hyperfine spectra. In addition, the three states will display spectra with an isomer shift due to their different distribution of charge. Predictions for magnetic moments based on systematic measurements in the region can give insight into where the hyperfine resonances will occur.

By locking the laser onto resonance with a characteristic hyperfine transition, decay spectroscopy measurements can be conducted on pure beams, allowing the energies of the alpha particles and gamma rays emitted, and the lifetime of the states, to be unambiguously determined. From hyperfine structure measurements, unequivocal values for the spin of the states will be determined, furthering the work previously done in this area [5].

4. Decay spectroscopy station



(a) Side view of the windmill (b) Front view of the windmill

Figure 3. [Colour online] Technical drawings of the rotating wheel and silicon detectors of the decay spectroscopy station 'windmill'.

The decay spectroscopy station consists of a rotating wheel implantation system, as shown in Figure 3. It is based on the design from KU Leuven [20, 21], which has already provided results with a number of successful experiments [22, 23]. The wheel holds ten thin carbon foils, with a thickness of 800 nm into which the laser ionized bunch is implanted. The system is installed in a stainless steel chamber in order to maintain the ultra-high vacuum necessary to perform resonant ionization and to decrease the background. Two Canberra PIPS silicon detectors for alpha decay detection are situated on either side of the implanted carbon foil, as shown in Figure 3. One solid detector (Series A) sits behind the carbon foil, and an annular detector (Series AN) is placed in front, both 300 μm in thickness. The ion beam is directed through the 4 mm aperture of the annular detector, allowing for backwards recoil particle detection. In addition to the on-axis detectors, two solid PIPS silicon detectors will be placed off-axis. This will allow for measurements on longer lived decay products to be performed by rotating the implanted foil from the on-axis to off-axis detector position. There is the possibility of placing up to three high-purity germanium detectors around the implantation site for gamma-ray detection.

Pure beams of the desired isotope or isomer will be deflected to the decay station, where alpha and gamma decays can be detected. Additionally, alpha-gamma coincidences can be used to identify a radioactive decay, and reduce the background gamma rays associated with the dumped beam.

Measurements of the attenuation of the steel chamber and the steel windmill were carried out using a 70% GC7020 Canberra High purity germanium detector. The percentage of the gamma rays attenuated by the steel wall of the decay spectroscopy station chamber is shown in Figure 4. This was calculated by measuring the gamma rays of several sources (^{241}Am, ^{152}Eu and ^{60}Co) at a given distance, first with the source inside the steel chamber and then in free space. As can be seen in Figure 4, more than 92% of the 59 keV gamma rays were attenuated by the steel walls, and 52% of the 123 keV gamma rays. At energies higher than 591 keV, no more than 18% of the gamma rays are stopped by the steel.

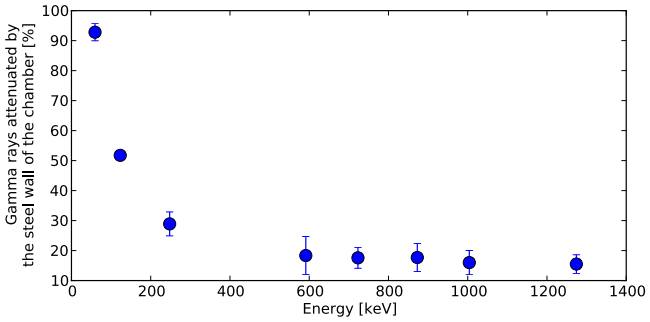
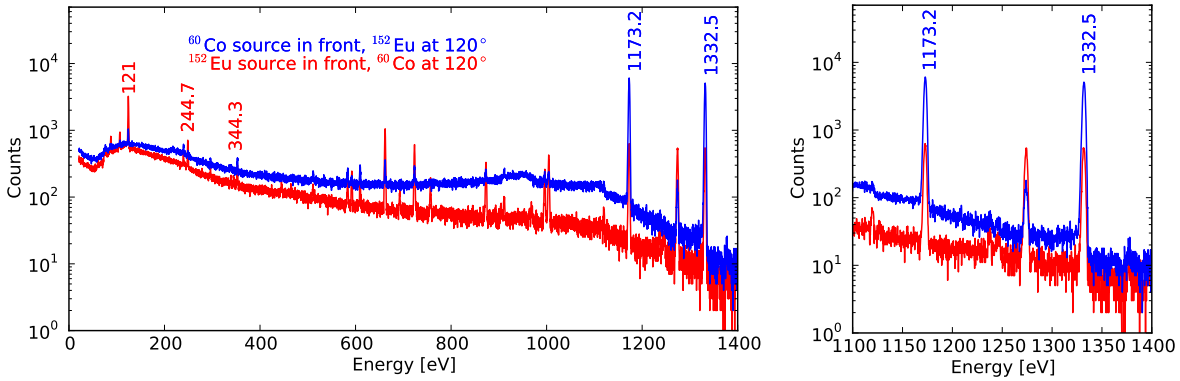


Figure 4. The percentage of gamma rays attenuated by the steel wall of the decay spectroscopy station chamber. Lower energy gamma rays are almost completely stopped by the steel chamber wall, but higher energy rays are only partially attenuated.



(a) Gamma spectrum (b) The ^{60}Co lines

Figure 5. [Colour online] The attenuation of the gamma rays due to the steel windmill. The blue spectrum shows a ^{60}Co source in front of the germanium detector and a ^{152}Eu source at 120° to it. The red spectrum shows the ^{152}Eu source in front, and ^{60}Co at 120°.

The attenuation of the gamma rays by the steel windmill itself was investigated. Two sources, ^{60}Co and ^{152}Eu, were attached to the rotating windmill, with 120° separating the two sources, and a gamma spectrum was taken at the two different positions. The blue spectrum shows the ^{60}Co source directly in front of the germanium detector and the ^{152}Eu source at 120° to it. In contrast, the red spectrum shows the ^{152}Eu source in front of the detector and the ^{60}Co at 120° to it. From Figure 5(b), it can be seen that the characteristic ^{60}Co lines are significantly decreased when the ^{60}Co source is rotated away from the germanium detector, indicating that the steel windmill attenuates the gamma rays that are produced off-axis by a factor of 10.

Energy resolution tests were performed on the solid Canberra PIPS silicon detector. A 4 kBq quadruple-alpha source, containing the radioactive isotopes ^{148}Gd, ^{239}Pu, ^{241}Am and ^{244}Cm

was used, attached in the position of a carbon foil. At 5.485 MeV, the energy resolution was determined to be 17.77 ± 0.18 keV, agreeing favourably with the manufacturer's resolution of 18 keV. Figure 6 shows the alpha spectrum obtained from these tests on the solid silicon detector.

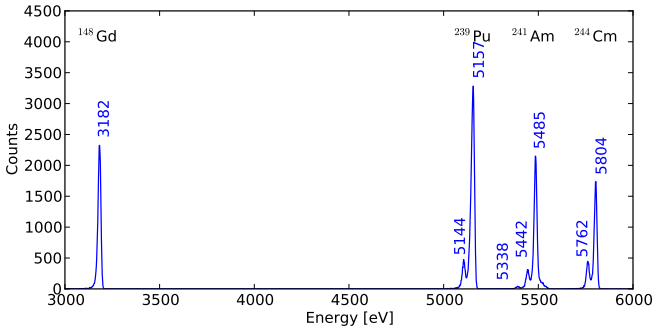


Figure 6. Alpha spectrum of a quadruple-alpha source for the solid silicon detector.

5. Outlook

The current set-up uses analogue electronics and an ADC for data acquisition. A digital data acquisition system is due to be implemented, using DGF modules and a dedicated acquisition programme. The first experiment will study neutron-deficient francium isotopes, and future campaigns will involve isotopes previously hidden because of large isobaric contaminations.

Acknowledgments

Measurements were performed on the decay spectroscopy station by two students from KU Leuven, S De Schepper and K Dewolf, as part of their Bachelor's Project. We thank the ISOLDE technical group and the KU Leuven technical staff for their support and assistance during this work.

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