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Shape coexistence in the light francium isotopes: First implementation of alpha-tagged Coulomb Excitation

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Abstract

We propose to carry out Coulomb excitation of post-accelerated beams of ^{203}Fr and ^{204}Fr from the REX-ISOLDE facility. The purpose is to further our understanding of shape evolution in this mass region by identifying excited states in these nuclei for the first time, and extracting transition matrix elements. In particular, we want to explore the effects of unpaired nucleons relative to the ^{202}Rn core, the latter nucleus having been the subject of a recent Coulomb excitation study. We also want to relate the properties of excited states to the ongoing laser spectroscopy measurements of the francium isotopes currently in progress at ISOLDE. These latter measurements on the CRIS beamline can determine not only basic properties like the spin of ground state and isomers but also the quadrupole moment and isotope shift To facilitate Coulomb excitation of the light francium nuclei, we propose to develop a new technique involving alpha tagging.

Introduction

Historically speaking, nuclear physics began with the shell model description of closed shell nuclei which evolved later to include the collective model for deformed nuclei. Heyde and Wood [1] have proposed that a more natural description of nuclei may be to start on the basis that nuclei are in general deformed and that spherical nuclei such as those around closed shells are actually special cases where the spherical states protrude below the deformed configuration. Shape coexistence is therefore a natural state of affairs and a delicate balance exists in nearly all cases between different shape minima. Understanding this delicate balance provides stringent tests of state-of-the-art nuclear models. Another topical and related issue is whether there are genuinely vibrational nuclei, in other words nuclei which follow the prescription for the layout of excited states and transition strengths demanded by the vibrational model. Garrett has shown that even for the classic case of the cadmium nuclei, the vibrational model is rapidly and dramatically violated due to the presence of intruder configurations [2].

An excellent region to address the issues of shape coexistence and the validity of the vibrational model is in the region around the Z=82 shell closure. In this region, extensive work is in progress to obtain matrix elements from Coulomb excitation measurements at REX-ISOLDE from mercury (Z=80) to radon (Z=86). The vibrational model might be expected to provide a good description of excited states in the light Radon nuclei but this has not been borne out in Coulomb excitation studies of ^{202}Rn and ^{204}Rn carried out at REX-ISOLDE over the last couple of years. High statistics have been obtained for excitation of the first 2^+ state in each nucleus, and excitation of the second 2^+ state and 4^+ state is also observed. A puzzle at present is a high X-ray yield which may be associated with excitation of a low-lying 0^+ state in each case. This presently unknown state may be parallel to or even below the first 2^+ state. The Coulomb excitation data is presently under analysis but already from the raw yields, it is clear that the B(E2) (2+ -> 0+) must be reasonably large in each case (~ 10s W.u.) and certainly very dissimilar to what would be expected for a vibrational nucleus which is how these nuclei would be characterized in a naïve examination of the layout of the known excited states e.g. R_{42} ~ 2.0 .

In parallel work, ^{202}Rn and ^{204}Rn have been studied using the SAGE spectrometer – a unique device for coincident gamma ray and conversion electron measurements at the University of Jyvaskyla. This data which is under analysis shows evidence for the population of non-yrast states and we hope to directly measure E0 components in, for example, the 2^+ -> 2^+ transition.

The focus of the present proposal is the light francium isotopes, where there is also evidence for shape coexistence deriving from alpha decay measurements. Decay studies of ^{201}Fr and ^{203}Fr show strong evidence for the presence of a low-lying $\pi s_{1/2}$ intruder state [3]. From the systematics of the region, this state is suggested to become the ground state of ^{199}Fr [4]. In general, the light odd-A francium isotopes should have a simple structure related to coupling an unpaired proton to the underlying radon core. Detailed spectroscopy has been carried out for ^{209}Fr [5], while limited information on excited states exists for ^{205}Fr and ^{207}Fr [6] (see figure 1). The structure of excited states in francium nuclei for A<205 is presently unknown.

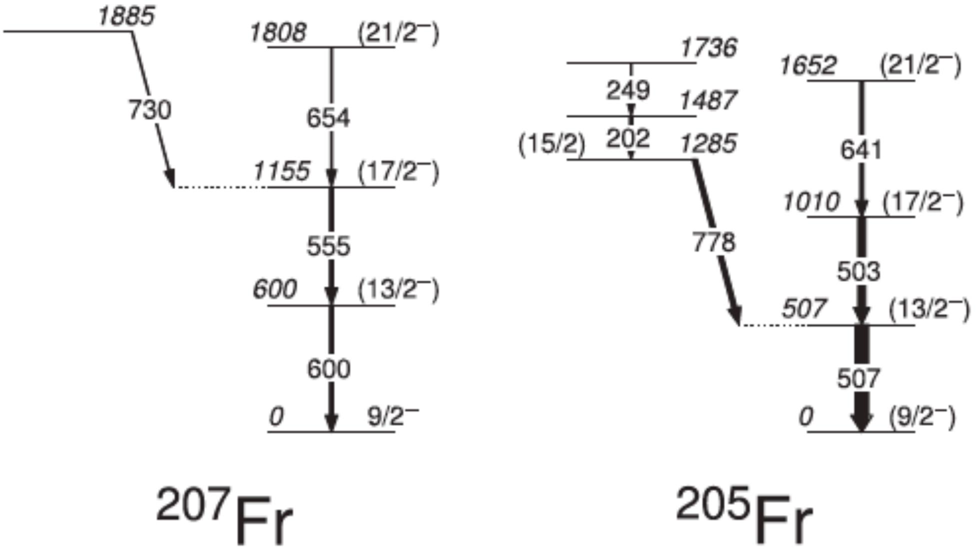

Figure 1: Level schemes for ^{205}Fr and ^{207}Fr [6]

The odd-odd francium isotopes have a somewhat complex structure with a number of different isomeric states. For example, ^{206}Fr (see figure 2) is believed to have a low-spin (2^+ or 3^+) ground state, a (7^+) and (10^-) isomer but all these assignments are tentative. Some information on high spin states feeding the (10^-) isomer is available [6] but nothing regarding excited states built on the lower-spin isomers.

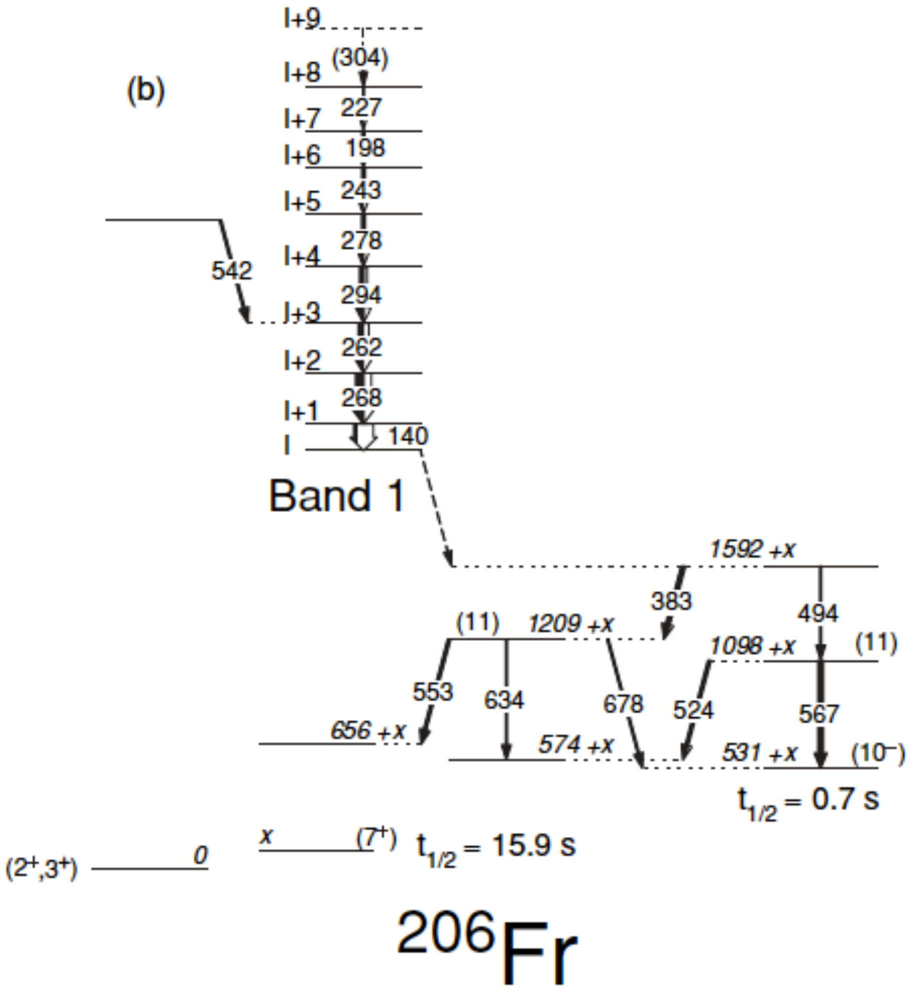

Figure 2: Level scheme for ^{206}Fr [6]

A parallel series of measurements on the light francium isotopes is presently ongoing at ISOLDE using collinear resonant ionization laser spectroscopy (CRIS). This technique suppresses Doppler broadening and affords very high resolution which allows the extraction of not only the spin of ground states and isomers but also their associated *quadrupole moment* and *isotope shifts*. The latter allow the extraction of δr^2 and taken together with the quadrupole moment, permits the static and dynamical aspects of the quadrupole deformation to be disentangled. The CRIS measurement programme is approved (PI: Kieran Flanagan) and will cover the range of francium isotopes from ^{201}Fr to ^{219}Fr. The experimental studies will begin in November 2010 and proceed through 2011.

Proposal

We propose to carry out Coulomb excitation of ^{203}Fr and ^{204}Fr.This will allow us to:

- Identify excited (non-isomeric) states in these nuclei for the first time

- Probe collectivity and shape coexistence in these exotic proton-rich nuclei

- See the effect of the unpaired nucleons relative to the ^{202}Rn core – the latter having been already studied in detail via Coulomb excitation

- Complement laser spectroscopy measurements: The spin of the ^{203}Fr and ^{204}Fr isomers should be determined directly, in a parallel CRIS study, along with the associated quadrupole moments. This will help considerably in the Coulomb excitation analysis. We can therefore probe in detail the evolution of collectivity in these nuclei.

- Develop a novel technique of alpha-tagged Coulomb excitation, which will allow us to separate excitation of the different isomers and suppress isobaric contamination (see detailed description below)

Alpha-tagged Coulomb excitation

Coulomb excitation measurements on the light mercury and radon nuclei have been greatly facilitated by the isobaric purity of the beams obtainable at REX-ISOLDE. This is also largely true of the francium isotopes; francium being a group 1 element with a low ionization potential so contaminants with higher ionization potential like thallium (2 eV higher) can be very largely suppressed. In general in this region, isobaric purity is not guaranteed and this will be the case for many of the heavy nuclei of interest in future studies at REX-ISOLDE. We need to develop a new technique which can sensitively discriminate the excitation of the species of interest in the presence of some isobaric contamination. At the same time, we would like to be able to discriminate isomeric states of the same isotope in the same measurement. We propose to exploit the fact that the light francium isotopes are essentially 100% alpha-decaying by tagging on the characteristic alpha decays. The present CD detector set-up is not able to do this but the necessary modification is straightforward and effective tagging can be achieved given suitable rates in the detector. We propose to replace the present preamplifiers with Mesytec logarithmic preamplifiers which provide a linear response up to 10 MeV, followed by a logarithmic response up to 3 GeV. The alpha particles can therefore be detected in the linear range where it should be possible to achieve an alpha resolution of 25 keV with the current CD detector and associated electronics. The alpha detection efficiency will be around 50%. The scattered heavy ions would be detected within the logarithmic range but this is acceptable as high energy resolution is not needed so long as scattered beam and target particles can be separated by kinematics.

The CD detector has 64 annular rings and 48 sectors (12 per quadrant). The effective number of pixels per quadrant is therefore rather high, although the implantation rate will be higher in the inner rings. In the recent ^{202}Rn Coulomb excitation experiment, where the secondary beam current was very similar to that expected here for ^{203}Fr, the typical rates observed were around 10/s per quadrant, which given that it is spread over several hundred effective pixels, should readily allow implants to be correlated with the characteristic alpha decay over time scales of several seconds. The 25 ns time-stamping of silicon events presently available with the MINIBALL-CD acquisition system will be very suitable for the tagging application and it should be possible to reconstruct correlations between alpha decays and heavy-ion implants in software off-line.

We note that the development of this tagging methodology may also have application to other scenarios such as beta-tagging or conversion-electron tagging e.g. from 8^- isomer in ^{178}Hf. The Physics related to the latter has been presented as a HIE-ISOLDE letter of intent concerning high-K isomers.

Experimental details

The light Francium isotopes can be produced quite strongly using spallation on ThC_x targets. The expected yields from the ISOLDE website are tabulated below along with the alpha-decay properties:

Isotope	Yield (/μC)	Jπ	Half-life (s)	Alpha branch (%)	Alpha energies (keV)
^{203}Fr	2×10^5	(9/2-)	0.55	95	7133
^{204}Fr	2×10^6	(3+)	1.7	80	7031
		(7+)	2.6		7077
		(10-)	1		7013

The yield for ^{203}Fr is around five times less than that for ^{202}Rn which we have recently successfully measured. This does not include losses due to the charge-breeding time. The yield for ^{204}Fr is ten times higher than ^{203}Fr but we expect some distribution over the respective isomers but with the majority in the high-spin (10^-) isomer. Correlations with the respective alpha decays should lift this ambiguity.

We have made an estimate of the Coulomb excitation yields using calculations with the code CLX. The standard MINIBALL-CD detector setup is envisaged: 8 triple-cluster Ge detectors and a CD detector covering the forward angular range of 16 to 53 degrees. The gamma-ray efficiency is expected to be around 7% for 1.3 MeV photons. Following the methodology of the light Radon experiment, we will run for a short period on a Ag target to get good statistics for excitation of the first excited state and then run on a 120Sn target so that the target and projectile excitations do not interfere and we can search for weakly-excited states. In this case, the maximum projectile scattering angle in the lab is around 36.4° (see figure 3). This corresponds to the centre-of-mass angular coverage of 44° to 168°. In addition, as can be seen from figure 3, the target atoms detected in CD covering 32° to 53.3° can be distinguished from the projectile atoms on the basis of kinematics alone, but this can be extended to the smallest lab angles by searching for correlations with alpha particles, further improving the experimental sensitivity.

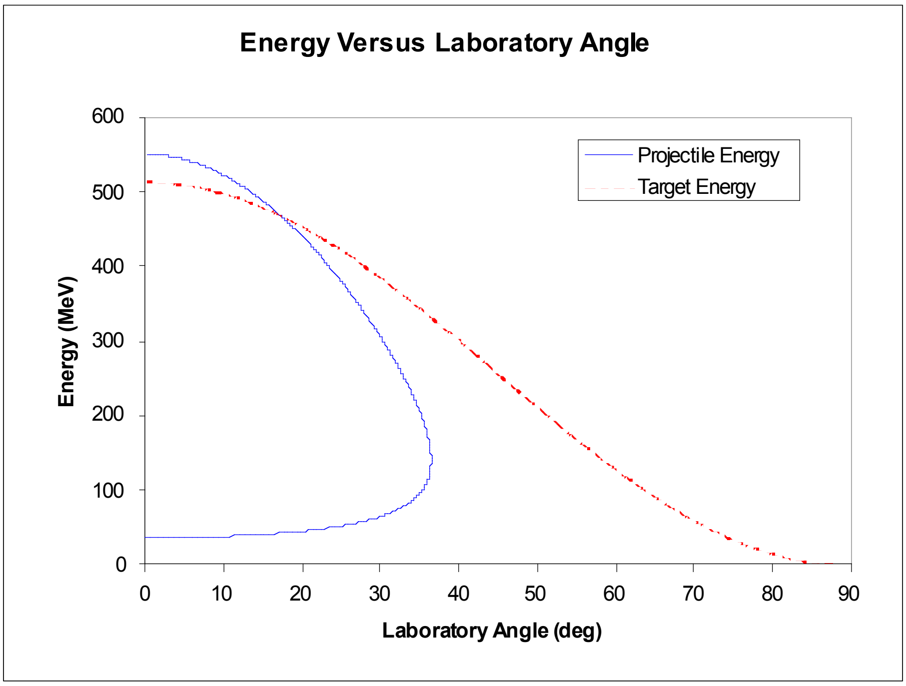

Figure 3: Kinematics for scattering of ^{203}Fr on ^{120}Sn at 550 MeV

We have estimated yields for ^{203}Fr for Coulomb excitation at a centre-of-target energy of 550 MeV, for a 2 mg/cm^2 ^{120}Sn target. We have considered a beam current of 4 X 10^3 /s on target for ^{203}Fr which represents a 2 % efficiency for the transmission through the whole system. We consider only 13/2$^-$ and 17/2$^-$ excited states built on a 9/2$^-$ ground state. The matrix elements along with the location of excited states are presently unknown so we have used the level scheme of ^{205}Fr as a guide, and assumed (very conservatively) B(E2) strengths of 1 W.u. connecting each level. Under these assumptions, the cross-section to the 13/2$^-$ state would be 70 mb, while the two-step excitation to the 17/2$^-$ state is 0.13 mb. The corresponding gamma-ray yield from the 13/2- state would be around 5000 counts per shift, and 10 counts per shift for the 17/2$^-$ state. This will scale proportionately if indeed the transition strengths are considerably larger which appears to be the case in the radon nuclei.

We request 6 shifts for ^{204}Fr and 9 shifts for ^{203}Fr, with the aim of achieving a good precision for the B(E2) for the first excited states and an estimation of the quadrupole moment from the particle angular distribution. Information on higher-lying states will depend on the magnitude of the transition matrix elements. Due to the long-lived ^{195}Au isotope in the ^{203}Fr decay chain, we will be careful only to take ^{203}Fr when accelerated on target and consider carefully possible radiation issues.

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