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CERN Doctoral Student Programme

Development of the ISOLDE Decay Station and γ spectroscopic studies of exotic nuclei near the N=20 “Island of Inversion”

Doctoral Thesis Summary

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– 2017 –

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Keywords: radioactive ion-beam facilities, GEANT4 simulation, detection array, nuclear spectroscopy, γ decay, level scheme, intruder configuration, β decay, Shell-Model calculations

Chapter 1

Radioactive ion-beam production techniques. The ISOLDE facility of CERN.

The study of radioactive isotopes is very important for fundamental nuclear physics research and astrophysics and for applications such as energy production, solid state physics and medical treatments. One of the major opportunities in nuclear physics is the possibility to accelerate unstable nuclei, allowing a better insight of the nuclear structure and the improvement of existing nuclear models. The production of exotic nuclei far from stability has many technical obstacles mainly due to the extremely low production cross sections, very short half lives of the nuclei of interest and sometimes overwhelming production of unwanted species in the same nuclear reaction. The progress of nuclear science since 1950 was represented, among others, by major advances of the radioactive ion beam (RIB) production and separation techniques. In the present there are two widely used complementary methods at the large scale facilities: the Isotope On-Line (ISOL) and the In-flight separation techniques. Other newer techniques are applied at smaller scale facilities and involve slightly different production or extraction stages.

The ISOL method uses light ion beams (or neutrons, photons) which induce fragmentation, spallation and/or fission in a thick high-temperature target. Afterwards the resulting nuclei diffuse out of the target, are ionized using various sources and separated using a mass separator. The beams are initially accelerated at a few tens of kV but can be further post-accelerated using special techniques.

The In-Flight method makes use of highly energetic heavy ion beams that produce fragmentation (in the case of high mass projectiles) or fusion-evaporation (for lighter projectiles) reactions in a thin target. The ionized energetic nuclei of various atomic species recoil out of the target and are sent to a fragment separator. Afterwards the separated fragments can be either sent directly to the experiment, to a gas catcher or storage ring.

At the present moment there are three main ISOL-based facilities offering a large choice of beams: ISOLDE, CERN and SPIRAL, GANIL in Europe and TRIUMF in Canada. ISOLDE is the oldest one, pioneering the ISOL technique and is located at CERN, Geneva, Switzerland. The major In-flight high-energy heavy ion facilities in operation since the year 1990, MSU-NSCL, GANIL, RIKEN and GSI, have been operating at an increasing pace being dedicated to RIB production due to the broad scientific opportunities.

ISOLDE uses thick targets, the most used type being the uranium carbide (UCx) which are irradiated with a pulsed beam of protons having an average intensity of 2 μA and being accelerated at 1.4 GeV by the Proton Synchrotron Booster (PSB) of the CERN accelerator complex. In 2016, ISOLDE received 61% of the total number of protons delivered to all CERN experiments, being by far the main user of the proton beam. The protons initiate reactions such as spallation, fragmentation and fission in the heated target and then the exotic isotopes diffuse out of it through a transfer line connected to an ion source. Plasma, hot-cavity or laser ion sources are used to ionize the radioactive ion beams. These beams can be delivered directly to temporary or fixed experimental setups after being accelerated using a 30-60 kV accelerating potential and separated using the General Purpose Separator (GPS) or the High Resolution Separator (HRS). There is also the possibility accelerating the beam with a linear accelerator up to 3.1 MeV/u. This is done by the REX-ISOLDE post-accelerator system. The HIE-ISOLDE upgrade was intended to increase the energy of the radioactive beam to values that reach above 7.5 MeV/u for $A/q = 4.33$ in 2017 and the intensity of the primary proton beam to 6 μA, although this is still to be achieved, probably after the second long shutdown (LS2) of CERN between 2018 - 2020.

Chapter 2

The ISOLDE Decay Station setup

The ISOLDE Decay Station (IDS) is a fixed experimental setup at ISOLDE, CERN, being operational since 2014. It is used for β-decay spectroscopic studies of the low-energy radioactive beams delivered by ISOLDE and it is composed of a flexible and versatile array of γ, neutron and charged particles detectors and a moving-tape station. In the three years spent at ISOLDE as a PhD student, I have been contributing to the development of IDS and I have participated to all the experiments that have taken place.

The Data Acquisition System (DAQ) used for IDS is similar to the Total Data Readout system developed by STFC, Daresbury, UK, and widely used at JYFL. It consists of 3 NUTAQ VHS-ADC modules of 105 MSPS, 14-bit ADC and Virtex4 FPGA, each having 16 channels. The channels are read out asynchronously in singles mode and each data item is time-stamped using an external clock . The system is capable to handle rates of $\approx$30 kHz/ch and the data recording framework is based on the MIDAS system.

The HPGe Clover detectors (CANBERRA EUROBALL) represent the core part of IDS. They are composed of 4 HPGe crystals of 50 mm diameter and 70 mm length encapsulated in the same cryostat and offer very good efficiency and energy resolution for γ detection. Because they are used in every experiment, it was of high interest to characterize them and perform GEANT4 simulations in order to better describe their efficiency.

With a core of four germanium clusters (HPGe) used for gamma detection, four different setups can be assembled depending on the case under study and physics aim.

- high efficiency $\beta - \gamma$ spectroscopy
- β-decay fast-timing studies using $LaBr_3(Ce)$ detectors
- β-delayed charged particles spectroscopy using Si detectors
- β-delayed neutron time-of-flight spectroscopy

Chapter 3

Monte Carlo simulations of the ISOLDE Decay Station setup

Because of the high demand of trustworthy simulations from the particle physics, nuclear physics, medical and applied sciences communities, a joint effort was made to build a more comprehensive package. As a result, the GEANT4 (GEometry ANd Tracking) "toolkit for the simulation of the passage of particles through matter" was created. It is widely used, freely available, continuously updated and provides extensive physics libraries and geometry design classes. It provides simulations based on theory, data or parametrisation. The physics available through GEANT4 has a wide range - hadronic interactions from thermal energies up to 1 PeV, electromagnetic interactions as well as the production and propagation of optical photons. GEANT4, first developed in 1994-1998 by the RD44 collaboration, was completely rewritten in C++ with a modern object-oriented design compared to its predecessor, GEANT3, dating back to 1982 and written in FORTRAN.

A dedicated code, G4IDS (Geant4 IDS), was created for the IDS detection system as part of this work, based on the GEANT4 framework. It represents a joint effort together with Christophe Sotty (KU Leuven, IFIN-HH) and having as a starting point a previous code developed by Florin Rotaru (IFIN-HH). The geometries of the supporting frame and detectors were carefully defined, using AutoCAD models. The main purpose of the code was to evaluate the detection efficiency of the IDS detectors, starting with the HPGe detectors. As the IDS system became more versatile, other detectors and implantation chambers were included in the simulations, such that the latest iteration of the code contains the following geometries:

- HPGe Clovers
- $LaBr_3$(Ce) detectors
- Plastic scintillators
- The T-shaped implantation chamber for fast-timing studies
- The IS530 implantation chamber for beta-gamma spectroscopy
- The IDS polyhedron frame

Thanks to the more simplistic implementation of the detector geometry and being able to run the G4IDS code with the latest version of GEANT4 (*geant4.10.01.p02*), the agreement was dramatically improved, as shown in Fig. ??, the relative error being around the limit of 5%. The absolute efficiency was extracted by integrating the number of events in the photopeak and dividing by the total number of γ rays generated. It must be noted that the simulations are not renormalised to fit the data, they represent exactly the result of placing one detector at the specified distance from the source.

Another application for the G4IDS code was to find a solution for the large background present in the high energy region ($> 2\,\mathrm{MeV}$) of the HPGe spectra during spectroscopy experiments at ISOLDE.

CHAPTER 4

Theoretical interpretation of the $N = 20$ "Island of Inversion"

The disappearance of the $N = 20$ magic number produced one of the oldest known "Islands of Inversion" centred on ^{32}Mg, but its boundaries are still an open question to both experiment and theory. The interest for neutron-rich N∼20 nuclei dates back to the mass measurement of C. Thibault published in 1975 when a region of strong deformation, unpredicted by the *sd*-shell model at that time, was discovered around ^{31}Na. Explained qualitatively by the fact that the ground states are dominated by neutron excitation across the $N = 20$ shell gap, this region was therefore labelled “Island of Inversion” by Warburton et. al in 1990.

In the shell-model framework, the shell structure of an atomic nucleus is governed by the *monopole* hamiltonian ($\hat{H}_{mon}$) responsible for the spherical mean field in which the nucleons are confined. This term is also responsible for the shell structure evolution both with the number of protons and neutrons and, for a given nucleus. The monopole term can in turn be decomposed into *central*, *spin-orbit* and *tensor* components, each of them being able to modify the amplitude of spherical shell gaps.

The rest of the nucleon-nucleon interaction is gathered in the *multipole* hamiltonian ($\hat{H}_M$) that is dominated by the pairing and the quadrupole-quadrupole interactions. The multipole term has a very important role in the disappearance of magicity far from stability and the onset of deformation, in particular when the spherical shell gap is reduced by monopole-driven effects. In this context, the spherical (closed shell) configuration, has a zero particle-hole character ($0p - 0h$), while the deformed configuration has multi-particle multi-hole ($np-nh$) excitations, from the normally occupied orbits into the valence orbits.

The recent experimental results on the $0^+_{1,2}$ states in ^{34}Si, and ^{32}Mg has brought further credit to the description in which a crossing between normal and intruder regime occurs between these two nuclei. However, having the same spin values, these two 0^+ states likely mix in each nucleus, blurring the determination of the crossing point between normal and intruder configurations. The ground state of ^{33}Al ($N = 20$) is outside the $N = 20$ "Island of Inversion", although it should be noted that a significant mixture ($\sim$50%) of intruder configuration was determined for the case of the ^{33}Al ground state. Therefore, ^{34}Al ($N = 21$) offers a lot of potential to explore this crossing for two reasons. First, two β-decaying states with spin values 4^- and 1^+ were discovered there, likely corresponding to normal and intruder configurations, respectively. Second, an abnormal cross-over on the S_{2n} surface, has been found between the Al and Mg chains at $N = 21$, suggesting a structural change there.

Chapter 5

Experimental β decay study of ^{34}Mg at ISOLDE-CERN

The presently reported results were extracted from the IS530 experiment which took place in September 2015 at ISOLDE and represented the continuation of the ^{34}Mg beta decay measurement performed in 2012. One of the goals of the present study was to find which of two long-lived β-decaying states in ^{34}Al is the ground state, and what is the energy difference between these two configurations. The results were reported in Ref. R. Lica et al., Phys. Rev. C95, 021301 (2017). In the case of ^{34}Si, there is high interest in determining the $B(E2;2_1^+ \rightarrow 0_2^+)$ value with increased precision, indicating how normal and intruder configurations are interleaved, in comparison with the state-of-the-art shell model calculations that treat the nuclei using the full $sd-pf$ valence space. Information of astrophysical interest will be extracted, such as β-decay half-lives, neutron emission probabilities and absolute intensities in the decay chain of ^{34}Mg.

The present detection system consisted of five HPGe Clover detectors in close geometry (four at 75 mm and one at 60 mm from the implantation point) and a 3 cm thick rectangular NE102 plastic scintillator as β trigger covering a $\sim$ 95% solid angle around the implantation point. The plastic was read simultaneously by 2 photomultiplier tubes (PMTs) which increased the beta efficiency close to the geometrical limit by lowering the energy threshold below the PMTs noise level when only coincident signals in both PMTs were considered as real β events. All the signals were recorded in a triggerless mode using Nutaq VHS-V4, the 100 MHz dedicated data acquisition (DAQ) of IDS. In parallel, signal traces from the PMTs were recorded using a fast 1 GHz CAEN digitizer in order to identify double hit events in the plastic scintillator originating from the E0 decay in ^{34}Si.

The beam of ^{34}Mg ions was produced at the ISOLDE-CERN facility by the PS-Booster 1.4 GeV pulsed proton beam directly impinging on a standard uranium carbide (UC_x) target. The Mg atoms thermally diffused out of the target matrix and were laser ionized selectively using RILIS. After being accelerated at 40 kV, mass $A = 34$ was selected with the ISOLDE General Purpose Separator (GPS) and finally implanted on the movable tape at the center of the ISOLDE Decay Station (IDS) experimental setup.

Chapter 6

Interpretation of experimental results and comparison with shell-model calculations

The calculations validate very well experimental data for the even-even isotopes where the configurations involved have mostly fixed $np - nh$ structures. It must be noted that when configurations with different particle-hole structures mix, as it is usually the case of some $N = 19$ and $N = 21$ isotopes, different amounts of energy gains due to correlations start to compete. The balance between correlation gains and monopole energy losses is very delicate, therefore there is an increased difficulty in predicting energy splittings between normal and intruder bands especially if they are smaller than 100 keV.

The interplay between the two factors, correlation energy and energy gap, places the two β-decaying states in ^{34}Al at a somehow similar energy, within 500 keV. It is seen that the final (small) splitting results from two large numbers which cancel out each other. Therefore, a prediction power of the order of 50 keV, as would be needed to account for the observed 46-keV energy difference between the 4^- and 1^+ states, is out of reach of the present SM calculations capabilities.

Similar to the case of ^{34}Al, shell model calculations were performed in order to describe the decay of the 4^- and 1^+ β-decaying states of ^{34}Al towards excited states in ^{34}Si using the SDPF-U-MIX effective interaction.

The calculated negative parity states are shifted up in energy compared to the experimental counterparts as it was already the case for ^{30,32}Mg. This probably comes from an overestimated $N = 20$ gap or by too large correlations in the ^{34}Si ground state that shifts the negative parity states downwards. This trend is confirmed by the fact that the first 3^- and 4^- states are also overestimated by calculations.

The present experiment provides a more precise determination of the reduced transition probability of the $0_2^+ \rightarrow 2_1^+$ transition compared to the previously reported one and agrees with the state-of-the-art shell model calculations which predict a 19% mixing of deformed $2p - 2h$ configuration in the ground state of ^{34}Si.