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Spectroscopy of nuclei approaching the proton drip-line using a secondary-fragmentation technique with the RISING detector array

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Abstract

An experiment utilizing a double fragmentation reaction was performed to study isobaric analogue states in $A \sim 50$ nuclei approaching the proton drip-line. γ-ray spectroscopy will be used to identify excited states in the neutron-deficient nuclei produced in the second fragmentation reaction. Excited state level schemes will be obtained, through comparison with states in their well-known mirror partners, along with information on Coulomb effects through measurements of the Coulomb energy differences between isobaric analogue excited states. The validity of isospin symmetry for nuclei approaching the proton drip-line can also be investigated and the information gained will aid in testing and improving fp shell model calculations. The analysis of the collected data is at a preliminary stage and current status of this work is reported.

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1. Introduction

The study of exotic nuclei near to the proton drip-line has had renewed interest as more and more nuclei have become experimentally accessible, due to technological and accelerator improvements. Fragmentation reactions have proven their ability of producing $N \sim Z$, $A \approx 50$ nuclei with large cross-sections compared with fusion–evaporation reactions. The production of these neutron-deficient nuclei, along with their mirror partners, is of great interest as they provide ideal laboratories for investigating isospin symmetry and Coulomb effects for large proton excess and also probe the extent of nuclei bound to ground or excited state proton emission. Full fp shell model calculations have been shown to be successful when explaining the properties of nuclei in the upper half of the $f_{7/2}$ shell but fall short for nuclei in the lower half where excitations from the closed ^{40}Ca core contribute to the excited state wavefunctions. Spectroscopic information gained from this work on the produced neutron-deficient fp-shell nuclei can be used to test and improve shell model calculations in this region. Nuclei such as ^{45}Cr and ^{44}V for which no γ-ray transitions have yet been observed and ^{43}V which is the lightest bound V isotope with the last proton being bound by ∼200 keV are of particular interest. It is expected for ^{43}V that a combination of the centrifugal and Coulomb barriers will strongly inhibit proton emission from the yrast excited states and that γ decays will be observed. In fact, γ decays have recently been observed from yrast states between $J^{\pi} = 3/2^-$ and $13/2^-$ in ^{61}Ga [1] where the proton binding energy is very similar.

2. Experimental details

The experiment was performed at the GSI laboratory in Darmstadt, Germany and utilized a two-step fragmentation reaction. A beam of ^{58}Ni (5×10^8 pps) was accelerated to 600 MeV A^{-1} and impinged on a ^{9}Be target (4 g cm^{-2}) located at the entrance of the FRagment separator (FRS) [2]. The FRS separated the fragments of interest which were then identified using a combination of inline detectors, multi-wire and scintillation detectors and an ionization chamber. The separated fragments ($\sim 4 \times 10^5$ pps), with energies ∼170 MeV A^{-1}, then impinged on a second ^{9}Be target (700 mg cm^{-2}) where a second fragmentation reaction occurred. De-excitation γ rays emitted from these high velocity fragments ($v/c \approx 50\%$) were detected by the rising Ge detector array. References [3, 4] give a detailed description of the experimental setup. The fragments from the second reaction were detected downstream in a CAlorimeter TElescope (CATE) [5] which consisted of nine individual position sensitive Si detectors arranged in a square geometry behind which were nine CsI detectors arranged in the same geometrical configuration. The Si detectors provide an energy loss signal for the fragments passing through which can be used to provide Z identification and the residual energy deposited in the CsI detectors combined with the energy loss in the Si detectors can provide fragment mass identification. By correlating implanted and identified fragments with detected prompt γ rays, spectroscopy of exotic neutron-deficient nuclei can be performed.

3. Data analysis

The selection of primary fragments of ^{55}Ni (or ^{55}Co) and secondary fragments of Ni (or Fe) in CATE (without any isotopic selection), allows prompt γ-ray spectra to be produced. Figure 1(a) shows such a Doppler corrected γ-ray spectrum for all the Ni isotopes produced. Transitions at 1227 and 1392 keV can clearly be seen which correspond to the $4^+_1 \rightarrow 2^+_1$ and $2^+_1 \rightarrow 0^+_1$ transitions respectively, in ^{54}Ni [6], which has the largest production cross-section.

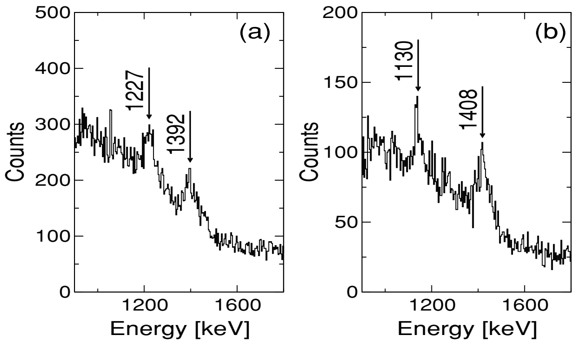

Figure 1. (a) Ni gated γ-ray spectrum showing clearly the 1227 keV $4_1^+ \rightarrow 2_1^+$ and 1392 keV $2_1^+ \rightarrow 0_1^+$ transitions in ^{54}Ni [6], the Ni isotope with the largest production cross-section. (b) Fe gated γ-ray spectrum showing the 1130 keV $4_1^+ \rightarrow 2_1^+$ and 1408 keV $2_1^+ \rightarrow 0_1^+$ transitions in ^{54}Fe [7], the mirror nucleus of ^{54}Ni.

Figure 1(b) shows the resulting spectrum for the mirror partner of ^{54}Ni, ^{54}Fe, with transitions $4_1^+ \rightarrow 2_1^+$ at 1130 keV and $2_1^+ \rightarrow 0_1^+$ at 1408 keV [7].

In order to produce similar spectra for fragments with smaller production cross-sections than that of ^{54}Ni such as ^{53}Ni, ^{45}Cr and ^{44,43}V, mass separation for the secondary fragments is required. Several signal corrections need to be applied to the CATE CsI detectors to achieve definitive fragment mass resolution, these are due to:

- the variation of energy signal with fragment implantation position,
- the energy resolution dependence on the velocity spread of the primary and secondary fragments,
- the energy resolution dependence on fragment implantation rate.

A correction for the variation in the detected energy signal with implantation position can be performed by determining the implantation position from the position sensitivity of the Si detectors. The (x, y) position of the interaction in a particular Si detector segment is calculated from the charge collected at the four corners of the front face of the Si wafer in a similar way to a two-dimensional potential divider. The charge collection points are attached to different amplifiers with different gains which need to be matched before a correction for the well-known 'pin cushion' effect can be applied. The 'pin cushion' effect, which arises from the $1/r$ dependence of the charge collection, is discussed in [8, 9] and a software method of correcting this effect has been developed by Lozeva *et al* [10].

The corrections performed in this work use a new and different approach that involves using the correlation between the charge collected at diagonally opposite collection points for each implantation signal. This new approach is required as the average charge collected at each corner is not the same due to the distribution of fragments being non-uniform across each segment. The correlation method is used to gain match the individual signals in a self-consistent way after which the resulting (x, y) position is mapped onto the results from a Monte Carlo simulation to recover the true geometrical implantation position. Although the fragment energy resolution in the CsI detector is dependent on implantation position, the main limiting factor to the achievable mass resolution is the spread in the velocity of the primary fragments. This contribution to the resolution can be improved somewhat by using time-of-flight and Bρ information from the FRS and the beam tracking detectors. An energy resolution of ~1% FWHM is sought for this data set to have adequate mass separation and a resolution of 2–3% [11] has already been achieved by Lozeva *et al* from a preliminary analysis of these data. The resolution dependence on the implantation rate into the CsI detectors is yet to be investigated as these complex detector correction procedures are still ongoing.

4. Summary

In summary, the analysis of the collected data is still at a preliminary stage. The spectra shown in figure 1 are a testament to the technique used and show that spectroscopy using this method to populate excited states in neutron-deficient nuclei in the $A \approx 50$ region is possible. The complexity of the experimental setup and the multi-array detection systems means that novel analysis techniques are being employed in order to obtain γ-ray spectra of exotic nuclei approaching the proton drip-line.

References

[1] Anderson L L *et al* 2005 *Phys. Rev.* C **71** 011303
[2] Geissel H *et al* 1992 *Nucl. Instrum. Methods* B **70** 286
[3] Wollersheim H J *et al* 2005 *Nucl. Instrum. Methods* A **537** 637
[4] Hammond G *et al* 2005 *Acta. Phys. Pol.* B **36** 1253
[5] Lozeva R *et al* 2003 *Nucl. Instrum. Methods* B **204** 678
[6] Gadea A *et al* 2003 *LNL Annual Report* p 8
[7] Rudolph D *et al* 1999 *Eur. Phys. J.* A **4** 115
[8] Doke T *et al* 1987 *Nucl. Instrum. Methods* A **261** 605
[9] Yanagimachi T *et al* 1989 *Nucl. Instrum. Methods* A **275** 307
[10] Lozeva R *et al* 2005 *Balkan Phys. Lett.* at press
[11] Lozeva R *et al* 2005 *Acta. Phys. Pol.* B **36** 1245