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SPECTROSCOPY OF $T = 3/2$ MIRROR NUCLEI VIA TWO-STEP FRAGMENTATION USING RISING*

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Two two-step fragmentation reactions were performed using RISING to populate excited states in $A \approx 50$ mirror nuclei near to the proton-drip line, in order to test isospin symmetry. The experiments were designed to observe gamma decays of excited states in the mirror nuclei ${}^{53}_{28}\mathrm{Ni}_{25}/{}^{53}_{25}\mathrm{Mn}_{28}$, which have a large value of total isospin ($T = 3/2$). In the continuing off-line analysis, gamma transitions have been observed in ^{54}Ni indicating that two-step fragmentation is a successful technique for spectroscopic investigations of proton-rich nuclear systems in this mass region.

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1. Introduction

Investigating fundamental symmetries is a principal aim of nuclear structure physics. Isospin is one of the most basic symmetries, occurring between protons and neutrons in the nucleus due to the charge independent nuclear force. In a pair of mirror nuclei, one can observe the difference in energy between isobaric analogue states, so-called *Coulomb energy differences* (CED), which are typically of the order of tens of keV. Two-body Coulomb matrix elements (CME) can be added to shell model calculations in order to reproduce the experimentally observed CED.

CME can also be extracted from experimental data. This was done by Williams *et al.* who studied the $T = 1/2$ mirror nuclei $^{53}_{27}Co_{26}/^{53}_{26}Fe_{27}$ [1]. Upon exciting a nucleus, pairs of like particles begin to align. The alignment of a pair of protons (proton holes in the case of ^{53}Fe) reduces the Coulomb self-energy of the proton (hole) pair. This, in turn, affects the CED, as the corresponding alignment in ^{53}Co is due to neutrons. Fig. 1 shows the CME extracted from the experimental CED, as a function of spin for a proton pair. One expects to see a decrease in the CME with increasing particle alignment. However, as is evident from Fig. 1, the CME increase at $J = 2$. This anomaly has been observed elsewhere in the $f_{\frac{7}{2}}$ shell but not explained.

Due to the current high level of experimental and theoretical interest in studies of isobaric analogue states, it is essential to push such investigations towards the largest accessible values of isospin. To do this, two two-step fragmentation reactions were performed as a part of the RISING (Rare Isotope Spectroscopic INvestigation at GSI) campaign [2].

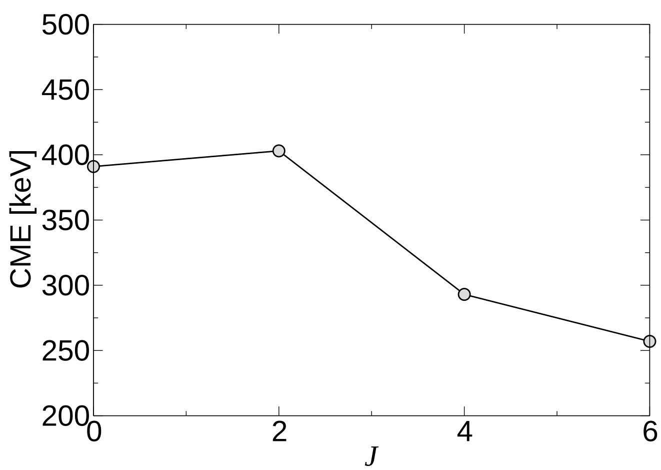

Fig. 1. CME *versus* particle alignment for the $T = 1/2$, $A = 53$ mirror nuclei ^{53}Co/^{53}Fe [1]. There is clearly an anomaly at $J = 2$.

2. Experimental details

A stable beam of ^{58}Ni was incident upon a 4.0 g/cm^2 ^{9}Be target at the entrance to the GSI FRS (FRagment Separator) [3], with an energy of 600A MeV. This primary fragmentation reaction produced a wide range of fully-stripped nuclei, from which one of two radioactive fragments were selected by the FRS: either $^{55}_{28}$Ni$_{27}$, for producing proton-rich mirror pair members, or its mirror, $^{55}_{27}$Co$_{28}$, for producing the corresponding neutron-rich members. The radioactive intermediate beams were only a few nucleons away from the nuclei of interest, since previous fragmentation studies have shown that this provides the highest yield [4, 5].

The time-of-flight through the second stage of the FRS was measured, using two plastic scintillator detectors as start and stop signals. This allowed for the determination of the velocity of the intermediate beam. An ionisation chamber, MUSIC, was used to determine the Z of the intermediate beam particles. The A/Q of the intermediate beam was calculated and a combination of A/Q and Z allowed for perfect beam identification.

The nuclei of interest were produced at a second, 700 mg/cm^2 ^{9}Be fragmentation target, located at the focal plane of the FRS. The emerging recoils had a v/c of approximately 0.45. Fifteen RISING cluster detectors were situated at forward angles to the secondary target, each detector comprising seven independent Ge crystals. The cluster detectors were arranged in two rings at approximately 16° and 34°. The positioning of the detectors provided maximum efficiency for the detection of gamma rays subject to the Lorentz boost, incurred by the high-recoil velocity. Additionally, the HECTOR (High Energy γ deteCTOR) array [6], consisting of eight large volume BaF$_2$ crystals, was arranged at backward angles to the secondary target.

Situated downstream of the secondary target was CATE (the CAlorimter TElescope) [7,8], consisting of nine individual elements arranged in a square, each of which comprised a thin silicon wafer for measuring recoil position and energy loss (ΔE) and a thick CsI wafer for measuring total recoil energy (E). The values of ΔE and E provided information about the Z and A of each recoil, respectively [7, 8].

The condition of beam tracking, provided by two multi-wire proportional chambers along with the position sensitivity of CATE allows for a full tracking Doppler shift correction to be applied.

3. Results

Although the analysis is still at a preliminary stage, some interesting results have already been gleaned from the data. The CATE detector currently gives clear $\Delta E(Z)$ separation for the recoils but so far only limited E (A) separation. Work done to resolve this issue is being carried out by Lozeva *et al.* (see Refs. [7, 8]).

By gating on Z and projecting out the coincident gamma rays, isotopic spectra for all produced masses are obtainable. The observed transitions are from the nuclei with the highest fragmentation cross-section, σ_{frag}. Fig. 2 shows two such spectra: part (a) was made by gating on nickel and is dominated by ^{54}Ni ($\sigma_{\text{frag}} \approx 5$mb); part (b) is dominated by ^{54}Fe ($\sigma_{\text{frag}} \approx 77$mb), the mirror nucleus of ^{54}Ni and was made by gating on all iron isotopes. Cross-sections quoted are predicted by the EPAX parameterization [9, 10].

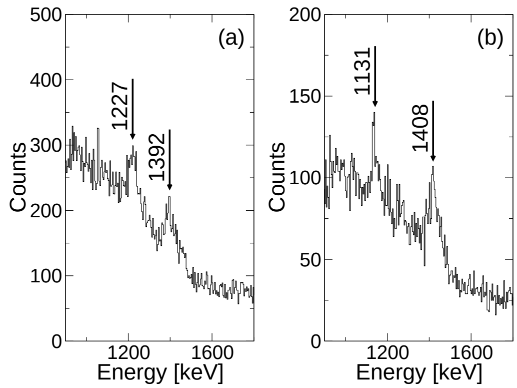

Fig. 2. (a) Nickel gated γ ray spectrum, showing the 1227 keV $4^+ \rightarrow 2^+$ and 1392 keV $2^+ \rightarrow 0^+$ transitions in ^{54}Ni [13, 14]. (b) Iron gated γ ray spectrum, showing the 1131 keV $4^+ \rightarrow 2^+$ and 1408 keV $2^+ \rightarrow 0^+$ transitions in ^{54}Fe, the mirror nucleus of ^{54}Ni [11]. Energies are taken from Gadea *et al.* [13, 14].

The spectra shown in Fig. 2 only have a basic Doppler shift correction algorithm applied; a full event-by-event tracked Doppler shift correction will be implemented to reduce the widths of the peaks. The value of v/c used in the Doppler shift correction was calculated in a simulation using LISE++ [12].

Even at this preliminary stage of the analysis, the $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in ^{54}Ni, which have only recently been identified by Gadea *et al.* [13, 14] using a heavy-ion fusion-evaporation reaction, are clearly visible in Fig. 2 (a). It can be clearly seen from these spectra that the energy shift of the 4^+ state is in the opposite direction to the 2^+ state, providing further evidence of the presence of the "$J = 2$ anomaly".

4. Conclusions

The observation of the mirrored $4^+ \rightarrow 2^+$ and $2^+ \rightarrow 0^+$ transitions in the $A = 54$ mirror nuclei shows that two-step fragmentation can be used successfully for populating excited states in proton-rich nuclear systems in the $A \approx 50$ mass region. Furthermore, the anomalous behavior of the CME at $J = 2$ has now been observed across the entire $f_{\frac{7}{2}}$ shell, with the same effect being seen in the mirror pairs for $A = 42$, 47, 49, 53 (see, for example, Refs. [1, 15, 16]) and $A = 54$ (Refs. [13, 14] and this work). This would seem to indicate that the origin of the anomaly is not based around interactions with the ^{40}Ca core, but originates from elsewhere. Whether or not the anomaly is nuclear or electromagnetic in origin remains to be seen. Observing the anomaly at higher values of isospin will provide more insight into its origin.

The application of a fully tracked Doppler shift correction along with improved A resolution in the CATE spectrometer will allow for improved spectra to be created, in turn allowing for a more accurate determination of γ ray energies and separation of masses to allow discrimination between different isotopes. Judging from the analysis to date, it seems likely that spectroscopy at the level of 1mb or less is feasible within the data. This will allow spectroscopic investigations of unknown proton-rich systems, such as $^{52}_{27}\mathrm{Co}_{25}$ ($N = Z - 2$) and, hopefully, ^{53}Ni.

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REFERENCES

[1] S.J. Williams *et al., Phys. Rev.* **C68**, 011301(R) (2003).
[2] H.-J. Wollersheim, M. Górska *et al., Nucl. Instrum. Methods* **A**, in press (2004).
[3] H. Geissel *et al., Nucl. Instrum. Methods* **B70**, 286 (1992).
[4] K. Yoneda *et al., Phys. Lett.* **B499**, 233 (2001).
[5] J. Enders *et al., Phys. Rev.* **C65**, 034318 (2002).
[6] A. Maj *et al., Nucl. Phys.* **A571**, 185 (1994).
[7] R. Lozeva *et al., Nucl. Instrum. Methods* **B204**, 678 (2003).
[8] R. Lozeva *et al., Acta Phys. Pol. B* **36**, 1245 (2005), these proceedings.
[9] K. Sümmerer, B. Blank, *Phys. Rev.* **C61**, 034607 (2000).
[10] K. Sümmerer, B. Blank, *EPAX version 2.1,* `http://www-w2k.gsi.de/hellstr/asp/gsi/epaxv21m.asp`.
[11] D. Rudolph *et al., Eur. Phys. J.* **A2**, 115 (1999).
[12] D. Bazin, O. Tarasov, M. Lewitowicz, O. Sorlin, *Nucl. Instrum. Methods* **A482**, 307 (2002).
[13] A. Gadea, private communication.
[14] A. Gadea *et al., LNL Annual Report 2003*, INFN (REP) 202/2004, p. 8.
[15] M.A. Bentley *et al., Phys. Lett.* **B437**, 243 (1998).
[16] C.D. O'Leary *et al., Phys. Rev. Lett.* **79**, 4349 (1997).