SEARCH FOR $2d_{5/2}$ NEUTRON STATES IN ^{69}Ni*

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It has been shown that the neutron $2d_{5/2}$ orbital has to be included in shell-model calculations to explain the large quadrupole collectivity observed in the Fe and Cr of $N = 40$ region, probably a new island of inversion similar to the one known for light nuclei around $N = 20$. Indeed, in these calculations using a large valence neutron space, the position, *i.e.* the single-particle energy, of the $2d_{5/2}$ orbital is a crucial ingredient. The experiment discussed in this paper aims to determine the $\nu 1g_{9/2}$–$\nu 2d_{5/2}$ gap using the neutron stripping reaction $d(^{68}\mathrm{Ni}, p)^{68}\mathrm{Ni}$ which has been performed at GANIL in inverse kinematics. Preliminary results are presented.

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1. Introduction

Due to its many degrees of freedom the atomic nucleus is a system with extremely changeable behaviour. Such a system is difficult to study in a fundamental approach since we do not know yet the full mathematical expression of the interaction between its constituents. To overcome these difficulties nuclear-structure models are devised.

When a large-scale shell-model approach is used, the effective single-particle energies (ESPE) are amongst the cornerstones of the model's interaction. In the $N = 40$ region the neutron $2d_{5/2}$ orbital has to be included in the calculations to explain the large quadrupole collectivity observed in the neutron-rich Fe [1] and Cr [2] isotopes. However, the ESPE of this orbital is not yet known in this region. The Fe and Cr experimental results have been reproduced by adjusting the $2d_{5/2}$ ESPE to data [3].

The present work aims to determine the $1g_{9/2}$–$2d_{5/2}$ gap around $N = 40$. The motivation for the measurement is two-fold. Integrating this information in the interaction used in this region will allow for more reliable calculations on the possible island of inversion around $N = 40$. Secondly, it will give more predictive power to the nuclear shell model. Of particular interest is the evolution of the single-particle structure towards ^{78}Ni, whose magicity (or not) is supposed to play a privileged role in the stellar nucleosynthesis.

^{69}Ni is a suitable candidate for such a study as it has a single valence neutron, which occupies the $1g_{9/2}$ orbital in its groundstate. Excitations of this neutron will scan the single-particle structure above the ground-state and give access to the existing orbitals, in particular the $2d_{5/2}$. Therefore by means of a single-neutron transfer on a ^{68}Ni nucleus, $d(^{68}\mathrm{Ni}, p)$, an excited ^{69}Ni can be created and studied. Angular momenta and spectroscopic factors of the populated states are obtained from the comparison between the experimental differential transfer cross-sections as a function of the proton detection angle and DWBA calculations.

2. The experiment

The stripping reaction $d(^{68}\mathrm{Ni}, p)^{69}\mathrm{Ni}$ was used to populate the ^{69}Ni excited states. The projectile was produced at an energy of 25.14 MeV/u by the fragmentation on a ^{9}Be of a ^{70}Zn primary beam, at an energy of 62.5 MeV/u. Before hitting a 2 mg/cm^2 CD_2 target, the ^{68}Ni was selected, using the LISE3 [4] spectrometer with a remarkable purity of $\approx$ 90%.

The experimental setup consisted of two CATS [6] detectors, used to localise the reaction on the target and of four MUST2 [7] telescopes detecting light reaction products in the backward angles from 100° to 140°. For the greater backward angles (150°–163°) an annular double-sided silicon-strip detector was used. In both types of detector the protons are identified using

E–ToF or ΔE–E techniques and energies and emission angles are measured. γ rays from the reaction are detected using four EXOGAM [5] clovers placed perpendicularly to the beam line. Finally a plastic scintillator coupled to an ionisation chamber were used to identify the ^{69}Ni fragments at forward angles.

A schematic drawing of the full experimental setup is shown in Fig. 1.

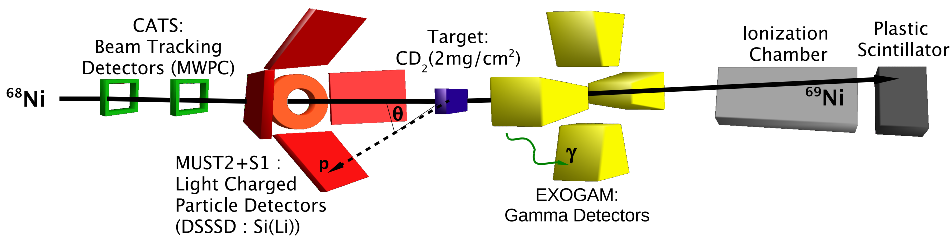
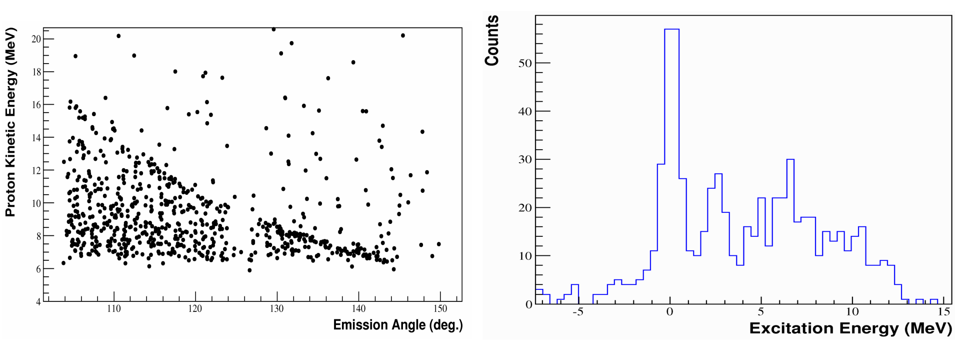


Fig. 1. Schematic drawing of the experimental setup showing respectively from left to right, two beam trackers (CATS), a set of light charged particles detectors (MUST2 and an annular DSSSD), a CD_2 target, four γ rays detectors (EXOGAM clovers), an ionisation chamber and a plastic scintillator. The proton emission angle is calculated event by event, between the ion trajectory and the proton trajectory as shown in the drawing.

3. Preliminary results

Since the energy of the beam-like products is not measured, the populated states in ^{69}Ni are probed with the detected protons in the backward angles based on the reaction's kinematics.



Kinematic lines Excitation energy

Fig. 2. Kinematic-line structure of the protons in the backward angles (left) and the corresponding energy spectrum of the beam-like products (right).

Plotting the energy of the detected proton *versus* its angle of emission reveals a structure of two discrete lines called kinematic lines (see Fig. 3). Each one of them corresponds to a single populated state in the nucleus of interest. These states are best shown in Fig. 3 where the proton energy and its emission angle were both used to calculate the excitation energy of ^{69}Ni. The ground state and an excited state peaked at ≈ 2.6 MeV are clearly visible. Other discrete excited states up to 10 MeV cannot be identified in the preliminary results.

4. Outlook

The preliminary results of the analysis show two kinematic lines corresponding to the ground state and an excited state in the heavy product. The reaction kinematics allows us to see excited states up to 10 MeV. A peak is observed at ≈ 2.6 MeV.

The identification of the $\nu 2d_{5/2}$ orbital entails to, *(i)* subtract the carbon background in the proton spectra, *(ii)* measure the experimental cross section of the stripping reaction and *(iii)* extract orbital angular momenta and associated spectroscopic factors of the populated states.

Once the $\nu 1g_{9/2}$–$\nu 2d_{5/2}$ gap is measured, shell-model predictions for the position of $\nu 2d_{5/2}$ will be verified and calculations around $N = 40$ and Nickel neutron-rich isotopes up to ^{78}Ni can be performed with an improved interaction including this new experimental data.

Finally, the inclusion of three-nucleon forces in shell-model calculations proved to be very promising in understanding the formation mechanism and the evolution of shell structure in neutron-rich light nuclei *i.e.* oxygen [9] and calcium [10]. The $\nu 1g_{9/2}$–$\nu 2d_{5/2}$ gap information is an important ingredient for this type of calculations involving three-nucleon forces, which could be performed to test whether a similar understanding can be achieved in the Nickel region.

REFERENCES

[1] J. Ljungvall *et al.*, *Phys. Rev.* **C81**, 4 (2010).
[2] O. Sorlin *et al.*, *Eur. Phys. J.* **A16**, 55 (2003).
[3] S.M. Lenzi *et al.*, *Phys. Rev.* **C82**, 7 (2010).
[4] R. Anne, A.C. Mueller, *Nucl. Instrum. Methods Phys. Res.* **B70**, 276 (1992).
[5] F. Azaiez, *Nucl. Phys.* **A654**, 1003c (1999).
[6] S. Ottini-Hustache *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A431**, 476 (1999).
[7] E. Pollacco *et al.*, *Eur. Phys. J.* **A25**, 287 (2005).
[8] E. Caurier *et al.*, *Rev. Mod. Phys.* **77**, 61 (2005).
[9] T. Otsuka *et al.*, *Phys. Rev. Lett.* **105**, 4 (2010).
[10] J.D. Holt *et al.*, `arXiv:1009.5984v1 [nucl-th]`.