

Multi-nucleon transfer reactions to explore the boundaries of the Island of Inversion

D. GENNA⁽¹⁾⁽²⁾, S. BOTTONI⁽¹⁾⁽²⁾, G. BENZONI⁽²⁾, K. WIMMER⁽³⁾, P. AGUILERA⁽⁴⁾, F. DRENT⁽³⁾, F. RECCHIA⁽⁴⁾, G. ANDREETTA⁽⁴⁾⁽⁵⁾, F. ANGELINI⁽⁴⁾⁽⁵⁾, M. BALOGH⁽⁶⁾, J. BARDAK⁽³⁾⁽⁷⁾, J. BENITO⁽⁴⁾, B. BLES⁽³⁾⁽⁷⁾, A. BRACCO⁽¹⁾⁽²⁾, D. BRUGNARA⁽⁶⁾, S. CAROLLO⁽⁴⁾⁽⁵⁾, Z. CHEN⁽³⁾, L. CORRADI⁽⁶⁾, G. CORBARI⁽¹⁾⁽²⁾, F. C. L. CRESPI⁽¹⁾⁽²⁾, M. DEL FABBRO⁽⁴⁾, A. ERTOPRAK⁽⁶⁾, E. FIORETTO⁽⁶⁾, F. GALTAROSSA⁽⁵⁾, A. GIAZ⁽²⁾, A. GOASDUFF⁽⁶⁾, B. GONGORA SERVIN⁽⁶⁾, A. GOTTARDO⁽⁶⁾, A. GOZZELINO⁽⁶⁾, A. JUNGCLAUS⁽⁸⁾, T. KRÖLL⁽⁹⁾, G. KOSIR⁽¹⁰⁾, S. LEONI⁽¹⁾⁽²⁾, M. LUCIANI⁽¹⁾⁽²⁾, N. MARCHINI⁽¹¹⁾, R. MENEGAZZO⁽⁵⁾, D. MENGONI⁽⁶⁾, B. MILLION⁽²⁾, G. MONTAGNOLI⁽⁴⁾, R. NICOLÁS DEL ÁLAMO⁽⁴⁾⁽⁵⁾, J. PELLUMAJ⁽⁶⁾, R. PÉREZ-VIDAL⁽¹²⁾, S. PIGLIAPOCO⁽⁴⁾, E. PILOTTO⁽⁴⁾, W. POKLEPA⁽³⁾, M. POLETTINI⁽³⁾⁽¹³⁾, K. REZYNKINA⁽⁴⁾, M. ROCCHINI⁽¹¹⁾, M. SEDLAK⁽⁶⁾, A. STEFANINI⁽⁶⁾, D. STRAMACCIONI⁽⁴⁾⁽⁵⁾, J. J. VALIENTE-DOBÓN⁽⁶⁾, J. VESIC⁽¹⁰⁾, L. ZAGO⁽¹⁾ and I. ZANON⁽¹⁴⁾

⁽¹⁾ *Dipartimento di Fisica, Università degli Studi di Milano - Milano, Italy*

⁽²⁾ *INFN, Sezione di Milano - Milano, Italy*

⁽³⁾ *GSI Helmholtzzentrum für Schwerionenforschung GmbH - Darmstadt, Germany*

⁽⁴⁾ *Dipartimento di Fisica, Università degli Studi di Padova - Padova, Italy*

⁽⁵⁾ *INFN, Sezione di Padova - Padova, Italy*

⁽⁶⁾ *INFN, Laboratori Nazionali di Legnaro - Legnaro, Italy*

⁽⁷⁾ *Faculty of Sciences, University of Novi Sad - Novi Sad, Serbia*

⁽⁸⁾ *Instituto de Estructura de la Materia, CSIC, Madrid - Madrid, Spain*

⁽⁹⁾ *Department of Physics, Technische Universität Darmstadt - Darmstadt, Germany*

⁽¹⁰⁾ *Jožef Stefan Institute - Ljubljana, Slovenia*

⁽¹¹⁾ *INFN, Sezione di Firenze - Firenze, Italy*

⁽¹²⁾ *Instituto de Física Corpuscular, CSIC-Universidad de Valencia - Valencia, Spain*

⁽¹³⁾ *Facility for Antiproton and Ion Research in Europe - Darmstadt, Germany*

⁽¹⁴⁾ *Department of Physics, Stockholm University - Stockholm, Sweden*

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Summary. — Two multi-nucleon transfer reactions, $^{22}\text{Ne} + ^{238}\text{U}$ and $^{26}\text{Mg} + ^{238}\text{U}$, were used to investigate the structure of light nuclei along the Ne and Mg isotopic chains, approaching the Island of Inversion at $N = 20$. The experiments were performed at Legnaro National Laboratories using the AGATA-PRISMA setup. A preliminary comparison of excited-state population patterns in $^{23-25}\text{Ne}$ from the two reactions is discussed.

1. – Introduction

The evolution of nuclear shapes and the related underlying shell structure plays a crucial role in understanding the emergent phenomena at the scale of nuclear energies. In particular, the neutron-rich region towards $N = 20$ has long drawn considerable interest due to the breakdown of traditional shell closures and magic numbers [1], and the emergence of intruder configurations. In these nuclei, due to the increased imbalance between protons and neutrons, residual nucleon-nucleon interactions are enhanced, leading to the stabilization of deformed configurations even at low excitation energy [2-4]. In the most extreme cases, these effects result in the transition towards deformed ground-state configurations, defining the boundaries of the so-called Islands of Inversion (IoI's). The IoI at the closure of the $N = 20$ shell was firmly established by studying the structure of ^{32}Mg ($Z = 12$), populated by a two neutron transfer reaction at REX-ISOLDE, CERN [5]. Among the experimental signatures associated with the onset of the IoI at $N = 20$ are the lowering in energy of negative-parity states belonging to the fp shell in even-odd isotopes, together with the evolution of quadrupole collectivity in even-even systems. Despite these recent advances, the underlying microscopic mechanism responsible for the formation of the IoI, as well as the precise delineation of its boundaries, remains unclear. In particular, the experimental information available [6] on spin-parity assignments, γ -ray decay patterns, and lifetimes of excited states is rather limited both within the IoI and in nuclei approaching it from the $N < 20$ region. This poses a significant challenge for state-of-the-art theoretical models [7-9], including recent *ab initio* calculations [10,11]. Therefore, a more detailed investigation of this preceding region is essential to improve our understanding of nuclei within the IoI and to place stringent constraints on modern nuclear models, which currently struggle to consistently describe the onset of deformation. In this context, the present work focuses on the neutron-rich $^{23-25}\text{Ne}$ isotopes, aiming to track the experimental signatures associated with the IoI as the neutron number increases. Multi-nucleon transfer (MNT) reactions provide an effective tool to populate a wide range of isotopes simultaneously and a selective mechanism to probe nuclear structure effects at the surface. In a direct or quasi-direct regime, the exchange of a few nucleons between reaction partners typically populates final states with relatively low excitation energy, enhancing sensitivity to shell evolution and nucleon-nucleon correlations in the surface region, potentially reflecting the underlying particle-hole configuration. When combined with magnetic spectrometers and high-resolution γ -ray detection, such reactions enable detailed spectroscopy and lifetime studies of the populated nuclei.

2. – Experimental setup

Two experiments were performed at INFN Legnaro National Laboratories (LNL) in April 2023 and June 2024, using the AGATA-PRISMA setup [12,13], with the aim of populating neutron-rich nuclei belonging to the Ne and Mg isotopic chains. Multi-nucleon transfer reactions were induced by accelerated beams of ^{22}Ne and ^{26}Mg impinging on a ^{238}U target with a thickness of a 1 mg/cm^2 . The beam energies were set to 145 MeV and 200 MeV, respectively. The large acceptance magnetic spectrometer PRISMA [14,15] was used to separate and identify reaction products by their atomic number Z , via $E - \Delta E$ method, and mass number A , through time-of-flight measurement combined with event-by-event trajectory reconstruction. The reaction products entered PRISMA with an average velocity $\beta \sim 0.1$. The Advanced GAMMA Tracking Array (AGATA), consisting

of more than 30 electrically segmented HPGe crystals, was employed to measure coincident γ -rays originating from the decay of the populated nuclei. The segmentation of the AGATA crystals enables the use of Pulse Shape Analysis techniques and tracking algorithms to accurately reconstruct the total energy and direction of the incident γ -rays, enhancing detection efficiency and allowing precise event-by-event Doppler correction. In the second experiment, a Nb backing with thickness of 5 mg/cm² was placed downstream of the ²³⁸U target and used as a degrader, enabling lifetime measurements of the excited states of interest in the range of 50 fs to 1 ps using the Doppler Shift Attenuation Method (DSAM).

3. – Data analysis

Data were initially sorted and analysed treating AGATA and PRISMA as stand-alone detection systems. A recently developed approach to PRISMA analysis, specifically optimized for light ions [16], enabled the recovery of the majority of the experimental statistics. After applying a coincidence window of 90 ns between AGATA and PRISMA, event-by-event Doppler shift corrections were performed using the measured recoil velocity and the relative angle between the detected nucleus and the emission direction of the γ -ray. Within this framework, a direct comparison can be made between population patterns of excited states in nuclei produced by both ²²Ne + ²³⁸U and ²⁶Mg + ²³⁸U MNT reactions. The population strength of specific final states is expected to differ between

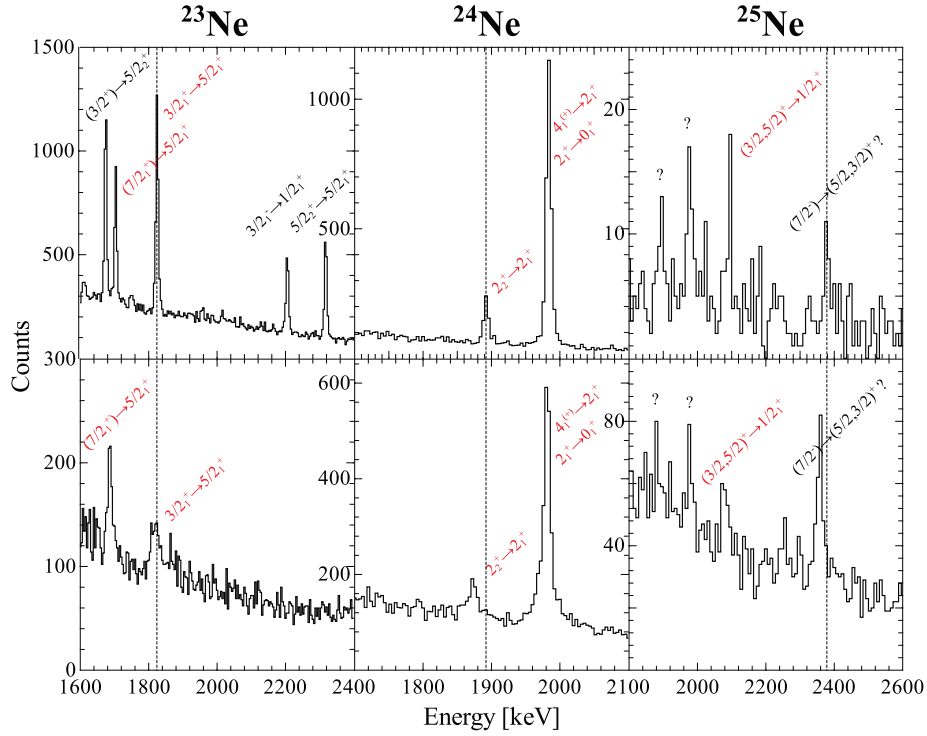


Fig. 1. – Selected portions of the ^{23–25}Ne γ -ray spectra obtained from the ²²Ne + ²³⁸U reaction (upper panels) and from the ²⁶Mg + ²³⁸U reaction (lower panels). See text for details.

the two reactions, reflecting the dependence of the specific transfer process on the overlap between the initial and final state configurations. Figure 1 compares selected portions of the $^{23-25}\text{Ne}$ γ -ray spectra measured in the two experiments. The spectra obtained from $^{22}\text{Ne} + ^{238}\text{U}$ reaction are reported in the upper panels, while those from $^{26}\text{Mg} + ^{238}\text{U}$ reaction in the lower panels. Transitions observed in both datasets are highlighted in red. In the second experiment, owing to the presence of the DSAM degrader, several peaks exhibit characteristic Doppler-broadened lineshapes, associated with the lifetimes of the decaying excited states. For ^{23}Ne , most of the transitions observed in the ^{22}Ne -induced reaction are not populated in the $^{26}\text{Mg} + ^{238}\text{U}$ case. In ^{25}Ne , a transition is observed at 2374 keV in the first experiment, while a sharp peak at 2350 keV appears in the second dataset. At the present stage of the analysis, a firm correspondence between these two transitions is still under investigation.

4. – Conclusions

This paper presents a preliminary comparison of the $^{23-25}\text{Ne}$ γ -ray spectra obtained in two multi-nucleon transfer experiments performed at INFN Legnaro National Laboratories, aimed at studying the structure of neutron-rich Ne and Mg isotopes approaching Island of Inversion at $N = 20$. Distinct population patterns of excited states are observed, reflecting the different proton and neutron transfer channels involved. The analysis of the second experiment is still on-going and further results will be reported in a forthcoming publication.

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