SPECTROSCOPY OF Ne ISOTOPES TOWARD THE $N = 20$ ISLAND OF INVERSION*

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The structure of light nuclei approaching the $N = 20$ Island of Inversion was investigated in two multi-nucleon transfer experiments performed at Legnaro National Laboratories using the AGATA-PRISMA setup. This paper presents preliminary results on the decay level schemes of ^{23,25}Ne. The analysis presented here focuses on the study of negative-parity states to probe the evolution of shell structure along the $Z = 10$ isotopic chain, and provide stringent constraints for state-of-the-art theoretical models.

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1. Introduction

One of the most striking phenomena in nuclear physics is the evolution of nuclear shapes along with the underlying shell structure. This phenomenon has challenged both experimental and theoretical studies in different mass regions of the nuclide chart, being ultimately rooted in the proton–neutron interaction, governed by the nuclear forces.

As one moves toward the neutron-rich side of the nuclide chart, the pronounced imbalance between protons and neutrons may induce a drastic variation in the standard shell ordering, driven by the increased proton–neutron correlation energy [1]. Higher-lying orbitals may shift downward in energy, narrowing the gap between consecutive shells, and favouring nucleon excitations across them. Macroscopically, this results in the appearance of deformed nuclear shapes, which are found even at low excitation energies.

The so-called Island of Inversion, located at the $N = 20$ shell closure, has drawn particular attention, being accessible by state-of-the-art theoretical calculations based on a variety of approaches, such as modern density functional theories [2], shell model calculations [3], and *ab-initio* methods [4, 5]. Nonetheless, theoretical predictions on level energies and transition probabilities often yield contradictory results, particularly in the Ne and Mg isotopes, showing significant discrepancies compared to the available spectroscopic data [6]. To provide new and stringent tests for these models, the present work focuses on the study of the evolution of negative-parity excited states in the odd–even Ne isotopes, as they may arise by promoting an odd number of neutrons into the lowered negative-parity pf shell. Complementary information on the evolution of the shell gap can be obtained by tracking the development of quadrupole collectivity, especially in the even–even isotopes, intrinsically linked to the shape of the nuclear surface.

For these reasons, we explored the Ne isotopes at the less exotic boundary of the Island of Inversion through two multi-nucleon transfer experiments, as part of an ongoing AGATA campaign at Legnaro National Laboratories (LNL) of INFN [7]. This paper presents preliminary γ-ray spectroscopy results for the even–odd ^{23,25}Ne, populated in the first experiment.

2. Experimental setup

The experiments were performed using the AGATA-PRISMA setup at LNL [8]. The Ne isotopes of interest were produced by means of two multi-nucleon transfer reactions [9] induced by accelerated beams of ^{22}Ne (April 2023) at 145 MeV of total energy, and ^{26}Mg (June 2024) at 200 MeV. In both experiments, a target ^{238}U of 1 mg/cm^2 was used. These beam energies correspond to being approximately 20% and 45% higher than the respective Coulomb barriers. Reaction products were separated using the large acceptance magnetic spectrometer PRISMA [10]. Its dedicated detection system enables a firm identification of the atomic number Z via the E–ΔE method, and of the mass number A, through time-of-flight measurements combined with the event-by-event ion trajectory reconstruction. The mass resolution achieved with the new analysis technique, specifically developed for light ions [11], is $\Delta A/A \sim 1/50$. Figure 1 displays the E–ΔE matrix with the identified elements produced in both reactions.

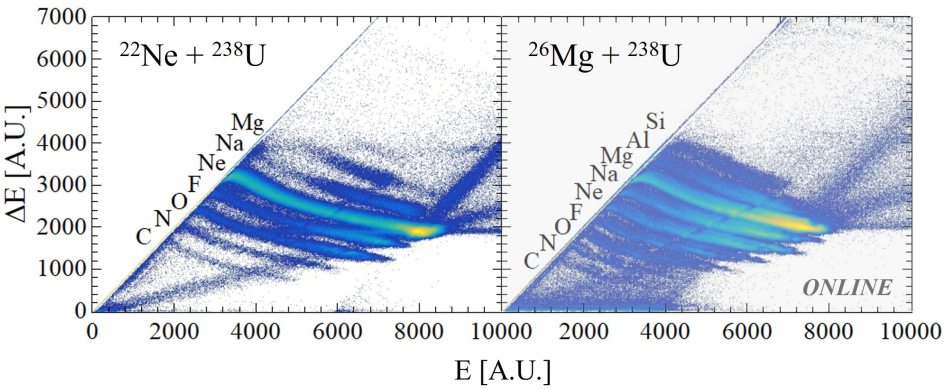

Fig. 1. Reaction products identified from the ^{22}Ne-induced experiment (left) and the ^{26}Mg-induced run (right) using the E–ΔE method with the Ionization Chambers (IC) array [12] of the PRISMA spectrometer. The y-axis corresponds to the deposited energy ΔE in the first of four rows of the IC array, while the x-axis corresponds to the total deposited energy E. The Z identification from the ^{26}Mg-induced run is based on a near-line analysis.

The γ-ray decay of reaction products was measured by the Advanced GAmma Tracking Array (AGATA) [13]. AGATA consisted of 36 electrically segmented HPGe crystals, allowing us to use Pulse Shape Analysis (PSA) and tracking algorithms [14, 15] to extract, on an event-by-event basis, the total energy and the direction of the incident γ-rays. Following the calibration and optimization procedures, the absolute photopeak efficiency was estimated to be $\sim 5.5\%$ at 1 MeV, using a ^{152}Eu source measurement and AGATA tracking mode.

The Ne-induced experiment was dedicated to spectroscopy studies, while the Mg-induced run focused on lifetime measurements. For the latter, a thick Nb backing (5 mg/cm^2) was placed behind the target, allowing lifetime determinations of the excited states of interest using the Doppler Shift Attenuation Method (DSAM).

3. Analysis

To reconstruct the decay level scheme of the Ne isotopes of interest, a 90 ns coincidence window was established between AGATA and PRISMA events, correlating the ions transmitted through the mass spectrometer with their γ-rays emitted in flight. Since the ions were produced with velocities of about 10% of the speed of light, corrections for the Doppler shift were necessary to clearly identify the observed γ-ray transitions. PSA and tracking algorithms allowed us to measure the first interaction point of each incident γ-ray with a precision of approximately 1°. The corresponding ion velocities β were obtained from time-of-flight measurements between the PRISMA entrance Micro-Channel Plate detector [16], acting as the stop signal, and the focal plane Multi-Wire Parallel Plates Avalanche Counter array [12], acting as the start.

The Doppler correction was improved by optimizing the ion time-of-flight measured by the spectrometer, via minimization of the FWHM of a set of reference peaks. At 1 MeV, the energy resolution improved from 0.74% to 0.50%. The resulting optimized recoil velocities were then used in the kinematic reconstruction.

As a final step of this preliminary analysis, decay level schemes were constructed for ^{23,25}Ne, by using energy spectra, γ–γ, and γ–TKEL coincidence matrices, where TKEL denotes the Total Kinetic Energy Loss in the reaction. The γ–γ coincidence matrix was built by requiring that at least two γ-rays, emitted by the same ion, were detected within a 100 ns coincidence window, thereby correlating γ-rays belonging to the same decay cascade. TKEL was obtained as a by-product of the complete event-by-event kinematic reconstruction, enabled by the precise angles and velocity information provided by AGATA and PRISMA. Although the TKEL spectrum had an energy resolution of a few MeV, applying energy conditions can still be effective since the energy difference between higher-lying and lower-lying excited states in the Ne isotopes is well above 1 MeV. Figure 2 reports two examples of TKEL selection (high and low) in ^{23}Ne (left) with the resulting gated γ-ray energy spectra (right). Selecting events with higher TKEL enhances the decay cascade originating from the excited state at 2517 keV — including the $(5/2, 7/2) \to (7/2^+)$ at 815 keV, $(7/2^+) \to 5/2^+$ at 1702 keV, and direct $(5/2, 7/2) \to 5/2^+$ at 2517 keV transitions — while reducing the contribution from $1/2^+ \to 5/2^+$ decay at 1017 keV connecting the first excited state to the ground state.

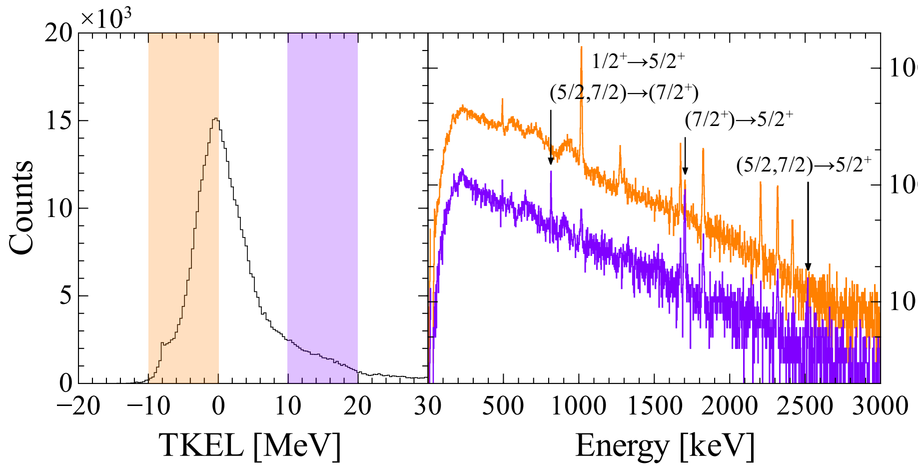

Fig. 2. (Colour on-line) Left: Total Kinetic Energy Loss (TKEL) spectrum obtained in coincidence with the ^{23}Ne identification and (right) corresponding γ-ray energy spectra gated on high (purple/grey) and low (orange/light grey) TKEL.

A portion of the ^{23}Ne and ^{25}Ne level schemes measured in this work are shown in Fig. 3. Transitions and states displayed in black agree with the literature values [6], with spin-parity assignments and lifetimes information adopted from the same source. Newly observed transitions and levels identified in the present work are highlighted in red/grey.

A new level is tentatively proposed in the ^{23}Ne level scheme at 2406 keV of energy, based on the observation of two new γ-ray transitions at energies of 584 keV and 1389 keV, found in coincidence with the known 1822 keV and 1017 keV transitions, respectively. Other possible new excited states at higher energies are currently under analysis.

Due to the lower production cross section for ^{25}Ne, γ-ray coincidences could not be used due to limited statistics. However, a new transition was identified in the energy spectrum at 2374 keV. This transition may correspond to the previously observed $(7/2^-) \to (5/2, 3/2)^+$ decay at 2350 keV, reported with an energy resolution of 40 keV [17].

Further analysis, including the even–even Ne isotopes and other reaction channels, is currently being performed, and will be detailed in a forthcoming publication.

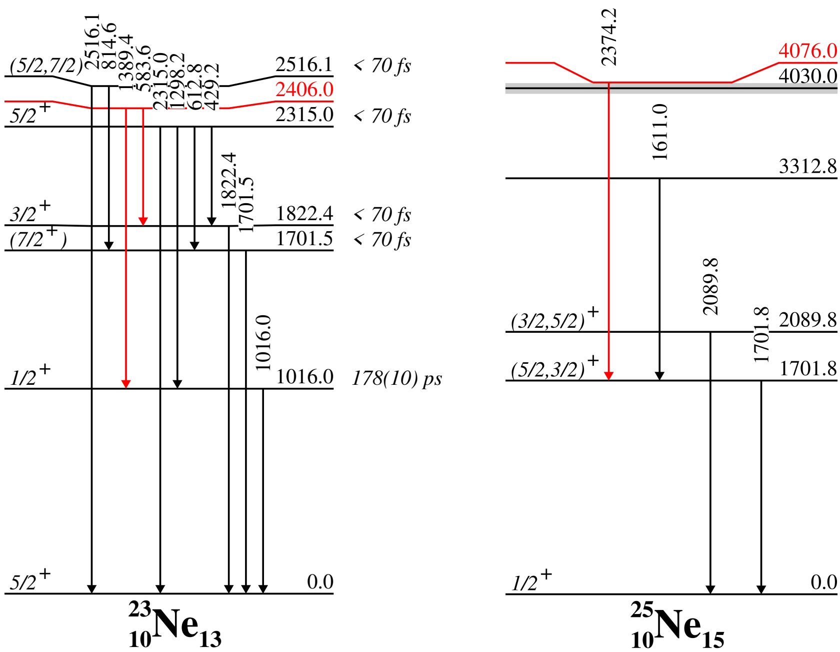

Fig. 3. (Colour on-line) Partial level and decay scheme of ^{23}Ne and ^{25}Ne populated in the ^{22}Ne-induced reaction. Transitions and states previously reported in the literature [6] are shown in black, while those newly identified in this work and tentatively added to the level schemes are highlighted in red/grey (see the text for details). Level and γ-ray transition energies are measured in the present experiment, while spin, parity, and lifetime (reported as $T_{1/2}$) are adopted from NNDC [6]. In ^{25}Ne, the black shaded rectangle represents the uncertainty on the previously reported level at 4030(40) keV [17].

4. Conclusions

This work presented preliminary results on the spectroscopy of ^{23,25}Ne toward the $N = 20$ Island of Inversion, populated in a multi-nucleon transfer experiment at Legnaro National Laboratories of INFN. By using ion–γ and γ–γ coincidence techniques, the level schemes have been reconstructed and extended. In the future, these data will be validated and combined with the lifetimes information from the on-going analysis of the ^{26}Mg-induced experiment. Results will be used to test modern theoretical models, such as [4, 5], based on *ab-initio* methods.

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