Reaction dynamics and gamma spectroscopy of Ne isotopes by the heavy ion reaction ^{22}Ne+^{208}Pb

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Abstract
The heavy-ion reaction ^{22}Ne+^{208}Pb at 128 MeV beam energy has been studied using the PRISMA-CLARA experimental setup at Legnaro National Laboratories. Elastic, inelastic and one nucleon transfer differential cross sections have been measured and a comparison with semiclassical and distorted wave Born approximation (DWBA) calculations is presented. Similar results are discussed for the unstable ^{24}Ne nucleus, using existing data from the reaction ^{24}Ne+^{208}Pb at 182 MeV (measured at SPIRAL with the VAMOS-EXOGAM setup). In both cases the DWBA model gives a good reproduction of the experiment, pointing to a strong reduction of the β_2^C charge deformation parameter in ^{24}Ne.

1 Introduction

Low-energy transfer reactions with heavy ions have recently become a powerful tool for the production and investigation of exotic neutron-rich systems, making use of the combination of a large acceptance magnetic spectrometer with a high efficiency and high resolution multi-detector array for γ spectroscopy (based on Ge detectors) [1–3]. Recent works have clearly demonstrated the possibility to employ heavy-ion transfer reactions both for detailed particle-spectroscopy (with enhanced sensitivity to specific excited states by γ-gating techniques), and to perform full in-beam γ-spectroscopy [4–6].

In this work [7] we discuss the results of the analysis on light neutron-rich nuclei around ^{22}Ne populated by the reaction ^{22}Ne+^{208}Pb (at 128 MeV), performed at Legnaro National Laboratories with the PRISMA-CLARA setup. The analysis focuses on the measurement of differential cross sections for the elastic, inelastic and one particle transfer channels. The experimental data are interpreted by the semiclassical model GRAZING [8] and by the distorted wave Born approximation approach (DWBA), implemented in the code PTOLEMY [9]. In the case of the inelastic scattering to the 2^+ state of ^{22}Ne, the present results are also compared with existing data from the reaction ^{24}Ne+^{208}Pb (at 182 MeV), obtained in a similar experiment at GANIL using the VAMOS-EXOGAM setup and employing the radioactive ^{24}Ne beam from SPIRAL [10]. In both cases, a DWBA analysis is performed and β_2^C deformation parameters for the nuclear charge distributions are extracted.

2 The experiment

The experiment has been performed at Legnaro National Laboratories of INFN, using the PRISMA-CLARA experimental setup [11]. The ^{22}Ne beam, provided by the PIAVE-ALPI accelerator complex at 128 MeV of bombarding energy, impinged on a ^{208}Pb target 300 μg/cm^2 thick, sandwiched between two layers of ^{12}C (10 and 15 μg/cm^2 thick respectively) [7]. The magnetic spectrometer PRISMA, described in Refs. [12–15], was placed around the grazing angle for this reaction, which has been estimated to be $\theta_{lab} = 70°$. As described in detail in Ref. [4], the identification of the reaction products is achieved by the reconstruction of ion trajectories inside the spectrometer. The coupling of the PRISMA spectrometer with the γ-array CLARA, placed opposite to PRISMA, made possible particle-γ coincidence measurements for each ion detected.

3 The Analysis

The aim of the present work is the evaluation of absolute differential cross sections for elastic, inelastic and one-particle transfer channels, starting from the elastic case. Following the method described in Ref. [16] and successfully applied in previous works [4,10,16], total kinetic energy loss spectra (TKEL), defined as TKEL=-Q_{value}, have been constructed, as a function of the scattering angle, for ^{22}Ne ions. The elastic cross section has been determined by subtracting TKEL spectra of ^{22}Ne measured in PRISMA and the one measured in coincidence with γ transitions detected in the CLARA array (inelastic contribution), as shown in Fig.1. The angular distribution of the ratio of the elastic cross section with respect to the Rutherford cross section is presented in the inset of Fig.1. The data have been normalized to the theoretical ratio $\sigma_{el}/\sigma_{ruth}$ calculated by the semiclassical code GRAZING [8] and compared with the DWBA model implemented in the PTOLEMY code [9]. The first allows to extract a conversion factor between counts and mb/sr which has been used to study cross section on absolute scale, while the second provides the optical parameters of the potential of the colliding system.

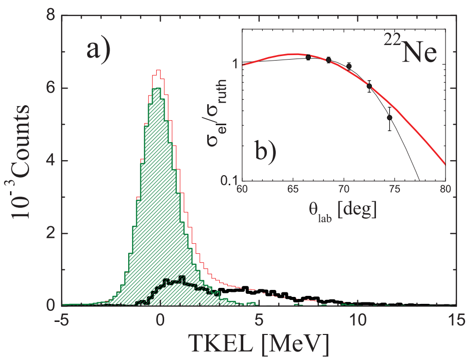

Fig. 1: (Color online) TKEL spectra for ^{22}Ne ions detected by PRISMA (thin red line) and in coincidence with γ transitions detected in CLARA (thick blue line). The shaded green area is the difference spectrum corresponding to elastic events. Inset: Elastic cross section over Rutherford cross section as a function of the scattering angle normalized in the Rutherford region to the theoretical calculation performed by the code GRAZING (thin black line). The calculation performed by the PTOLEMY code is shown by the thick red line.

Fig.2 (top) shows the inclusive (energy integrated) angular distribution for the elastic channel (^{22}Ne in panel a)), the one neutron pick-up channel (^{23}Ne in panel b)) and the one proton stripping channel (^{21}F in panel c)), which are the most intense reaction products. The experimental data are compared with theoretical calculation performed by the semiclassical GRAZING model. We see that the experimental angular distributions are rather well reproduced by the calculations, with a global agreement between data and theory. Similar quality of agreement was also obtained for the one-nucleon transfer channels in the work of Ref. [10], where the more exotic ^{25}Ne and ^{23}F channels were studied, following the heavy ion reaction ^{24}Ne+^{208}Pb. This indicates that the basic ingredients entering the prescription of the reaction dynamics by the GRAZING model are still valid in the case of heavy-ion reactions induced by rather light systems such as Ne isotopes, and moving away from the stability valley. In Fig. 2 (bottom) the γ spectra measured by the CLARA array in coincidence with ^{22}Ne, ^{23}Ne, ^{21}F are also presented.

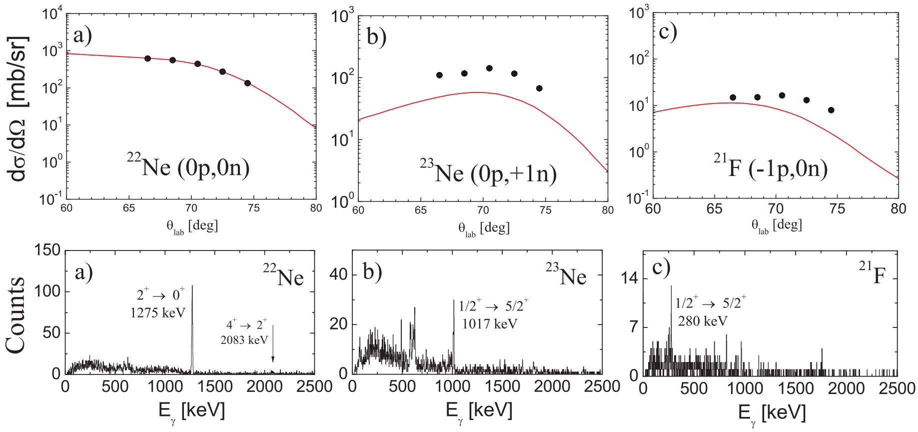

Fig. 2: (Color online) Top: inclusive angular distributions for the most intense reaction channels ^{22}Ne, ^{23}Ne and ^{21}F (panels a), b) and c)). Symbols correspond to experimental data, solid red lines to theoretical calculations by the semi-classical model GRAZING [8]. Bottom: gamma spectra of ^{22}Ne, ^{23}Ne and ^{21}F (panel a), b) and c), respectively). In each spectrum the γ transition from the first excited state to the ground state is clearly visible. In the case of ^{22}Ne, the arrow indicate the position of the $4^+ \rightarrow 2^+$ decay, at 2083 keV, not observed in this experiment.

In the case of ^{22}Ne, the $2^+ \rightarrow 0^+$ transition at 1275 keV has enough statistics to determine the differential cross section for the inelastic scattering to the 2^+ state. This has been done by integrating the area of the 1275 keV peak, for each θ_{lab} angle covered by the acceptance of PRISMA. As reported in Ref. [4], this procedure provides the direct population of the first excited state, after subtracting the feeding contribution from higher lying levels and taking into account the γ efficiency of the CLARA array. In this case, the feeding from the $4^+ \rightarrow 2^+$ decay is negligible, as indicated by the absence of the corresponding γ peak in Fig.2 a), while at most a 25% feeding contribution can be expected from higher-lying states around 5 MeV. This is suggested by the presence of a high-energy tail in the TKEL spectrum gated by the $2^+ \rightarrow 0^+$ γ-transition, as shown in the inset of Fig.3 a). In the same panel, the results (open symbols) are presented together with the data corrected for this feeding contribution (filled circles). In panel b) we present inelastic scattering data taken from Ref. [10], relative to the 2^+ state of the unstable ^{24}Ne, populated by the ^{24}Ne+^{208}Pb reaction at 182 MeV.

Calculations of the inelastic scattering to the 2^+ state have been performed for both experiments, using the Distorted Wave Born Approximation model, implemented in the code PTOLEMY [9]. For the Wood-Saxon optical model potentials we used the parameters obtained by the fit of the elastic distribution. Furthermore, we have put $\beta_2^C = \beta_2^N$, because the fit to the inelastic cross sections favored very similar values for the nuclear and Coulomb deformation parameters. We note that the fit of the inelastic distribution is not very sensitive to the value of β_2^N, while the variation of β_2^C influences the strength of the inelastic cross sections in a similar way for both nuclei. As a consequence, in the following we discuss our results in terms of charge deformation parameters β_2^C only. The results are shown in Fig.4 as filled diamonds. It is found that ^{22}Ne has a rather large quadrupole deformation ($\beta_2^C \approx 0.4$), with a value consistent with the one obtained by an earlier analysis of ^{22}Ne+^{208}Pb inelastic-scattering data, performed with a rotational coupled-channel model [17]. In that work the reaction ^{22}Ne+^{208}Pb was also studied, and a very similar value was obtained for ^{20}Ne (following the ^{20}Ne+^{208}Pb reaction), as shown by open diamonds in Fig.4 a). On the contrary, in the present analysis small values for the deformation parameters of ^{24}Ne are found ($\beta_2^C \approx 0.1$).

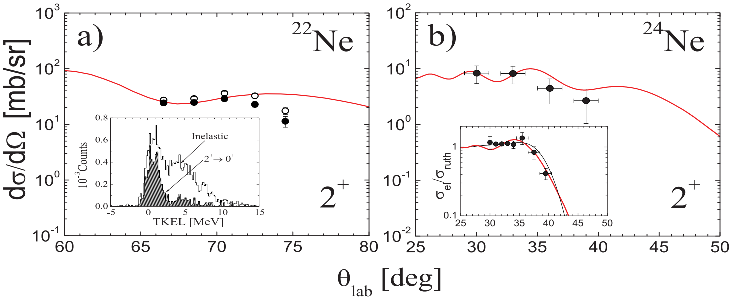

Fig. 3: (Color online) Panel a): Angular distribution of ^{22}Ne ions measured in coincidence with the $2^+ \rightarrow 0^+$ γ transition of 1275 keV. Filled (open) symbols refer to the analysis performed on the γ spectrum of ^{22}Ne taking (not taking) into account the feeding from high-lying states around 5 MeV. Inset of Panel a): inelastic TKEL spectrum of ^{22}Ne and the contribution coming from the $2^+ \rightarrow 0^+$ γ-decay (shaded blue area). Panel b): Angular distribution of ^{24}Ne, measured in coincidence with the $2^+ \rightarrow 0^+$ γ transition of 1982 keV. The inset of panel b) shows the elastic over the Rutherford cross section of ^{24}Ne, as a function of the scattering angle. Experimental data are indicated by symbols, while theoretical calculations performed by the code PTOLEMY (GRAZING) are given by thick (thin) red (black) lines. Data for ^{24}Ne are taken from Ref. [10].

It is interesting to compare our β_2^C values with the charge deformation parameters derived from experimental B(E2;$0^+ \rightarrow 2^+$) measurements (Coulomb excitation or lifetime analysis techniques). In Fig.4 a) we show by open circles the "adopted" β_2^C values [18], while filled circles refer to the most recent measurements, derived from intermediate energy Coulomb excitation experiments (at MSU and RIKEN) and from low-energy Coulomb excitation measurements (at ISOLDE) [19–22]. These recent values are systematically lower than the adopted ones, clearly indicating the difficulty in determining experimentally a firm value for the β_2^C parameter. Our results are also significantly smaller than the adopted value. They correspond to a 30% reduction in the case of ^{22}Ne (which could be accounted for by the uncertainty of the different experimental techniques), and to a much larger suppression (of the order of a factor of 5) for ^{24}Ne. In this case, the adopted value corresponds to the only existing $B(E2)$ measurement via lifetime technique, reported in Ref. [23]. Such a large discrepancy is rather puzzling and definitely calls for additional experimental investigation on the collectivity in ^{24}Ne, a nucleus of key importance for understanding the evolution of shell gaps in light systems, moving towards the neutron drip line.

In Fig.4 b) we show the deformation parameters of the ground state, β_2^{gs}, obtained in three recent theoretical calculations of the ground state of even Ne isotopes, such as the deformed Hartree-Fock plus BCS calculations with Skyrme interaction [24], the deformed mean-field approach including pair correlations treated by the BCS model [25] and the very recent relativistic Hartee-Fock-Bogoliubov model [26]. We note that these studies are found to reproduce quite accurately the experimental charge radii of Ne isotopes (determined by optical isotope shifts measurements [27]), across the sd neutron shell. As shown in the figure, the models predict that the deformation decreases close to the middle of the sd shell, as a consequence of the closure of the $d_{5/2}$ subshell [27,28]. Our data may suggest a similar trend, but a direct comparison is not possible, because the transition strengths are not calculated in these studies.

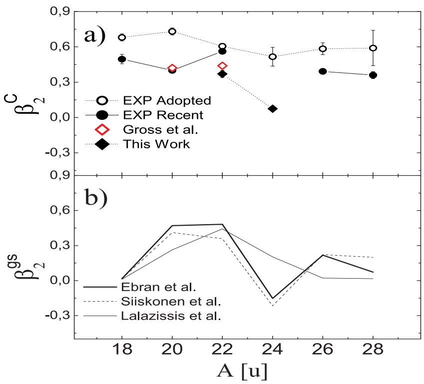

Fig. 4: (Color online) Panel a): Quadrupole deformation parameter β_2^C of the nuclear charge distribution, along the isotopic Ne chain, as derived from experiments. Filled diamonds refer to this work, open diamonds to a similar analysis performed by Gross et al. [17], open circles to the experimental adopted values [18], filled circles to the most recent results from Coulomb excitation experiments [19–22]. Panel b): Theoretical predictions for the ground state deformation parameter β_2^{gs}, as indicated by the legend [24–26]. (See text for details).

4 Conclusion

In this paper we have studied the dynamics of the heavy ion reaction ^{22}Ne+^{208}Pb at 128 MeV beam energy [7]. Elastic, inelastic and one nucleon transfer differential cross sections have been measured and compared with semiclassical and distorted wave Born approximation (DWBA) calculations, resulting in a global agreement between data and theory. A key point of the analysis was the study of the angular distribution of the 2^+ state of ^{22}Ne by the DWBA model, together with similar calculations performed for the 2^+ state of the unstable ^{24}Ne nucleus, based on existing data from the ^{24}Ne+^{208}Pb reaction at 182 MeV beam energy [10]. The analysis provides a very small β_2^C value for ^{24}Ne. This is consistent with the trend predicted for the evolution of ground state quadrupole deformation β_2^{gs} along the Ne isotopic chain, which suggests a subshell closure at N=14. Such a result calls, indeed, for additional experimental investigation on this nucleus, which is of key importance for the understanding of the shell structure along the Ne isotopic chain.

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