Eur. Phys. J. Special Topics **150**, 83–86 (2007)
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DOI: 10.1140/epjst/e2007-00272-x

THE EUROPEAN PHYSICAL JOURNAL SPECIAL TOPICS

In-beam γ spectroscopy using DIC with a radioactive Ne beam

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Received: January 31, 2007

Abstract. A study of deep-inelastic and multi-nucleon transfer reactions to populate neutron-rich O, Ne and F nuclei is here presented. The reaction under analysis employed a beam of radioactive ^{24}Ne at 7.9 AMeV, provided by the SPIRAL facility at Ganil, impingin on a ^{208}Pb target. The reaction products have been detected in the VAMOS spectrometer in coincidence with gamma rays measured by the EXOGAM array. Preliminary results here presented show a selectivity in the population of states of different nature.

PACS. 21.10.-k – 25.60.-t – 27.30.+t

1 Introduction

The spectroscopy of nuclei around mass 20 is particularly interesting since these nuclei are located at the boundaries of the so-called "island of inversion". Important experimental information in this region has been gained in recent years using single-or double-step fragmentation [1] and light-particle transfer reactions employing radioactive beams [2,3]. However, both reaction mechanisms are somewhat inefficient in the population of high spin states in such nuclei.

Multi-nucleon transfer (MNT) and deep-inelastic collisions (DIC) can provide complementary reaction mechanisms to study near-yrast states in light neutron-rich nuclei. Studies have been performed in this region employing DIC on a thick target [4], though concentrating on nuclei heavier than Mg. Even though such reactions are not expected to give access to highly-exotic nuclei, they do allow the population of higher spin states [5] than two-step fragmentation and light particle transfer. This concept is the basis for a series of experiments aimed at studying neutron-rich systems in elements from oxygen to neon by comparing MNT reactions induced by stable and neutron-rich radioactive beams. The experiment we report on in this paper is part of a more extended experimental program for which we plan to employ the stable-beam induced reaction ^{22}Ne+^{208}Pb with the PRISMA-CLARA set up, and the radioactive-beam induced reaction ^{24}Ne+^{208}Pb together with the VAMOS-EXOGAM set up.

In this contribution we mainly focus on preliminary results on the reaction mechanism obtained with the experiment performed with the VAMOS-EXOGAM arrays.

2 The experiment

We report on the first of the two experiments, performed at GANIL in June 2005. A ^{24}Ne radioactive beam with a laboratory energy of 7.9 AMeV was delivered by the SPIRAL facility and impinged on a thick (10.9 mg/cm^2) ^{208}Pb target. The ^{24}Ne secondary beam intensity of approximately $1.5 * 10^5$ pps was stable throughout the experiment. The thickness of the target was chosen such as to guarantee a counting rate high enough to enable basic gamma-ray spectroscopic information to be obtained. The selected beam energy was chosen to be well above the

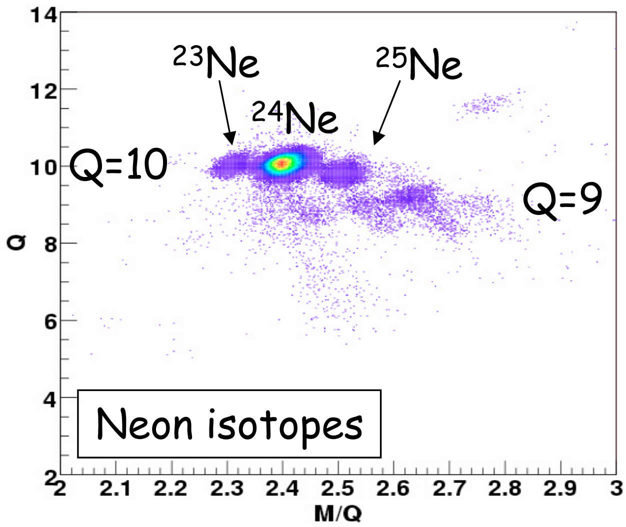

Fig. 1. Q vs. M/Q particle identification plot showing the Ne isotopes populated in the ^{24}Ne+^{208}Pb reaction.

Coulomb barrier (∼95 MeV in the laboratory frame), in order to safely be in the MNT regime. A total of $1.4 * 10^5$ particle-γ coincidences were recorded in 7 days of beam time.

The reaction products were detected in the focal plane of the VAMOS spectrometer [6,7] which was positioned at the calculated grazing angle for this reaction (≈35° to the beam direction). The reaction γ rays were detected by the EXOGAM array [8,9], consisting of 11 segmented germanium Clover detectors, 9 of which had Compton suppression shields.

The focal plane detectors of the VAMOS spectrometer consisted of two position sensitive drift chambers, giving, after software reconstruction, the X_{foc} and Y_{foc} coordinates at the focal plane and the θ and ϕ angles at target position. An ionization chamber divided into 2 sections provided energy loss information (ΔE), and a silicon wall allowed measurements of the residual energy of the transported ions (E). The time of flight (TOF) of the transported ions was measured between the Silicon detectors and the beam radiofrequency, since the secondary electron detector (SED) placed between the two drift chambers was only 20% efficient for such light ions. Combining the information provided by these detectors allowed the identification of the residual nuclei produced in the reaction. For additional details on the individual detectors see [6,7].

The coupling of the VAMOS spectrometer and EXOGAM gamma-ray array allows the study of reaction mechanism dymanics by utilising the structural information provided by the γ rays. In this way, information on both cross sections and angular momentum population can be deduced from such experiments. It is anticipated that the initial results from the radioactive-beam experiment (see below) will be compared with those from the experiment using the stable ^{22}Ne beam which is planned to take place in Autumn 2006.

3 Data analysis

The statistics of the experiment has limited our study mainly to the reaction mechanisms rather than detailed spectroscopy. This is however not a limitation since the understanding of the process leading to nuclei far from stability is important also to plan future measurments. In the following we describe major steps of the data analysis.

The specific nuclei of interest can be identified making use of ΔE-E and Q-M/Q plots. The ΔE-E plot, in fact, selects the different elemental species, while the reconstructed quantities Q (atomic charge state) and M/Q (mass over charge) separate out the different isotopes. The M/Q ratio is calculated combining the TOF and magnetic rigidity (Bρ) measurements, while Q is determined from the ionic energy loss, ΔE. The reaction ^{24}Ne + ^{208}Pb populated mainly neon, fluorine and oxygen isotopes, with the beam-like Ne (Z = 10) isotopes accounting for more than 90% of the statistics. The majority of the remaining cross section produced F (Z = 9) and O (Z = 8) isotopes with small traces of Na (Z = 11) also present.

As expected by calculations performed using the Grazing code [10], the observed Ne isotopes correspond to the transfer of -1n, 0n0p and +1n resulting in ^{23,24,25}Ne respectively (see figure 1). These are assumed to be populated with a cross section of the order of tens of mb, as predicted by the GRAZING code. The fluorine isotopes populated correspond to the -1p, -1p-1n and -1p-2n channels (^{23,22,21}F respectively) while the oxygen isotopes correspond to the -2p-1n, -2p-2n and -2p-3n channels (^{21,20,19}O). These are predicted to be populated with cross sections of less than 1 mb. The γ spectra show specific peaks of the predominant transitions for these nuclei.

By comparing γ multiplicities in coincidence with specific nuclear species a trend was observed of increasing average multiplicity with increasing nucleon transfer (i.e. an enhancement for O and F isotopes compared to Ne). One possible intepretation of this effect is due to the increased 'inelastic' nature of the process which leads to nuclear species different from the beam. This is expected to lead to higher angular momentum transfer to the reaction products and thus the emission of longer γ cascades. This effect will be the object of further investigation using the higher statistics expected from the stable-beam (^{22}Ne) induced experiment.

Figure 1 shows the Q vs. M/Q plot for the neon isotopes identified in the current work. Two distinct locii are observed corresponding to charge states Q = 10 and Q = 9. (The analysis which follows focussed only on the fully stripped, Q = 10 ions). Figure 1 shows the identified nuclei, ^{23,24,25}Ne. Placing software coincidence gates on these nuclei allowed the sorting of isotopically clean γ spectra, examples of which are shown in figure 2 for ^{24,25}Ne.

Table 1 reports the number of ion-γ coincidences registered for each Ne isotope in the current work. The γ coincidence is required in order to discriminate contributions due to elastic scattering of the ^{24}Ne beam. Calculations by Pollarolo [10] predict a similar population of ^{23}Ne and

Table 1. Number of ion-γ coincidences of the Ne isotopes populated in the $^{24}Ne+^{208}Pb$ reaction described in the current work. Only fully stripped ions are considered.

	Ion-γ coinc.	%
^{23}Ne	1037	9.5
^{24}Ne	7323	67.1
^{25}Ne	2553	23.4
Total	10913	

^{25}Ne. The reduced amount of ^{23}Ne observed experimentally can be accounted for by the VAMOS spectrometer not being optimised for the transmission of this particular isotope.

The data analysis is still in progress: in particular the determination of the reaction cross sections is being evaluated. This short note reports on the early results of this work.

4 ^{24}Ne and ^{25}Ne

This analysis concentrates on γ spectra associated with the most intense neon channels (i.e. ^{24}Ne and ^{25}Ne). In order to provide an internal check of the isotopic identification, Doppler corrected γ spectra obtained in coincidence with ions at different positions in the (M/Q,Q) plane were sorted in the offline analysis. Examples of the resulting gamma-ray spectra are shown in figure 2 for the ^{24}Ne and ^{25}Ne nuclei (upper and lower panel respectively). The spectrum associated with ^{24}Ne ions shows a clear contribution from the $2^+ \to 0^+$ transition at 1.9 MeV and a second peak at 500 keV. The analogous spectrum of ^{25}Ne is richer and shows γ peaks up to 3.3 MeV. In particular, the 1.68 MeV $5/2^+ \to 1/2^+$ transition to the ground state is clearly observed, as are the the 2.03 MeV $3/2^+ \to 1/2^+$,

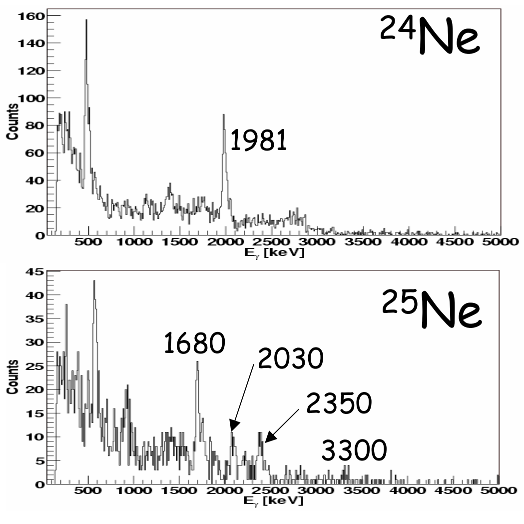

Fig. 2. Doppler corrected γ spectra in coincidence with ^{24}Ne (top panel) and ^{25}Ne (bottom panel) isotopes. γ-ray transitions characteristic of the two nuclei are labeled.

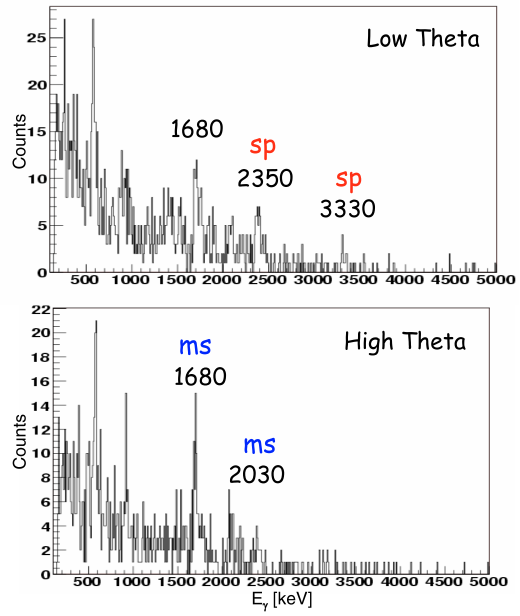

Fig. 3. γ-ray spectra of ^{25}Ne requiring the condition that $\theta < 34°$ (top panel) or $\theta > 34°$ (bottom panel).The labelling *sp* stands for *single particle state* while *ms* for *mixed state.*

2.35 MeV $7/2^+ \to 3/2^+$ and 3.3 MeV transition from the direct decay from the $3/2^-$ level to the ground state. There is also a strong peak at 570 keV and at 890 keV which are recognised to be the decay from the first excited states of the partner nucleus ^{207}Pb left after picking up a neutron from the target.

The transition at 1.68 MeV is a doublet (1.68 and 1.70 MeV), due to the near degeneracy of the $3/2^+$ and $5/2^+$ states. This degeneracy is also predicted by USD calculations and was confirmed by the recent study of ^{25}Ne by nucleon knock-out (see [12] and ref. therein). The energy labelling of the observed transitions in ^{25}Ne is based on the (d,p) experiment by Catford et al., performed with the same array and similar beam intensity [2].

Since the γ spectrum of ^{25}Ne was found to be particularly intense compared to the other reaction channels, the population of the states as function of other available variables such as the X_{FOC} position in the focal plane and the θ angle at target position were also investigated for this nucleus in the current work. The data were resorted such that the gamma spectra were incremented with the requirement that θ was higher or lower than the estimated grazing angle for this reaction (i.e. $\theta <$ (>)34°). The resulting spectra for ^{25}Ne are shown in figure 3. The upper panel of figure 3 shows the spectrum obtained with the condition that $\theta < 34°$ (labelled as *'Low Theta'*) and the lower panel that $\theta > 34°$ (*'High Theta'*). These spectra clearly show different peaks with those present in the *Low Theta* spectrum absent in the *High Theta* cut. The condition of θ being $< 34°$ seems to select mainly transitions from states of single particle character, while the condition $\theta > 34°$ selects states of mixed character. The doublet around 1.7 MeV also seems to be populated in different proportions by these conditions.

A similar dependence of the population of single particle and collective states as a function of the recoil angle and γ multiplicity has been reported by the Surrey group using the CHICO detector coupled to GAMMASPHERE. See [13, 14] and ref. therein.

More quantitative results will be provided after the response function of the VAMOS spectrometer will be unfolded and its combined dependence on angle and momentum examined.

5 Conclusion

In this brief report, preliminary results from the first deep inelastic experiment performed using a radioactive ^{24}Ne beam from SPIRAL have been presented. The presented experiment has been performed with a beam intensity of approximately 1.5*10^5 pps, leading to a total of 10^4 γ-particle coincidences. The data show that, also employing radioactive beams, DIC can selectively populate states of different nature and, therefore, are a good tool to study nuclear structure further away from stability.

The authours would like to acknowledge the help and support from the local VAMOS and EXOGAM technical staff for making it possible to run a very smooth experiment, and the GANIL/SPIRAL accelerator crew for providing a particularly stable radiactive ^{24}Ne beam. This work was partially supported by the EU through the EURONS project under contract No. RII3-CT-2004-506065 and by OTKA (Hungary) contract No. 46901.

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