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2005 J. Phys. G: Nucl. Part. Phys. 31 S1655

(http://iopscience.iop.org/0954-3899/31/10/049)

J. Phys. G: Nucl. Part. Phys. **31** (2005) S1655–S1661 doi:10.1088/0954-3899/31/10/049

Nucleon transfer via (d,p) using TIARA with a ^{24}Ne radioactive beam

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Received 21 March 2005
Published 12 September 2005
Online at stacks.iop.org/JPhysG/31/S1655

Abstract

The first physics results measured using the TIARA array are reported. The reaction ^{24}Ne(d,p)^{25}Ne has been studied in inverse kinematics with a radioactive beam of ^{24}Ne provided by SPIRAL at GANIL. TIARA is very compact with a high geometrical coverage for charged particles, and is designed specifically for the study of transfer reactions in inverse kinematics, with radioactive beams. From the (d,p) differential cross sections, the ground state of ^{25}Ne is assigned to have $J^\pi = 1/2^+$ and the lowest states with $J^\pi = 5/2^+$ and $3/2^+$ are tentatively identified at excitation energies of 1.70 and 2.05 (±0.05) MeV, respectively. Coincident gamma-ray data proved essential to resolve these two excited states. Strongly populated levels observed at 3.30 and 4.05 (±0.05) MeV are candidates for negative parity states. Further analysis of the differential cross sections is in progress, with the aim of improving the identification of the higher lying states and determining absolute spectroscopic factors.

(Some figures in this article are in colour only in the electronic version)

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1. Introduction

Nucleon transfer reactions such as (d,p), (p,d), (d,t), induced by light ions, offer the opportunity to study the occupancies of shell model orbitals and the angular momenta of the states that are populated. The new TIARA array is designed to exploit such transfer reactions with radioactive beams, using inverse kinematics with hydrogen polymer targets. In the present work, we deduce the spins of states in ^{25}Ne from the measured ℓ-transfer in (d,p), studied at 10 MeV/A, and utilize detailed comparisons with shell model calculations. The data show immediately the states that are predominantly of 'core + particle' structure, and this provides complementary information to that on 'core − hole' states obtained by nucleon knockout. This identification of states which have a large component of the pure single-particle structure in their wavefunction is itself a useful result, when studying new or poorly known nuclei. Beyond this, quantitative measures of occupancies—i.e. spectroscopic factor measurements—are an important further aim in transfer work.

The nucleus ^{25}Ne is of interest because it lies in a neutron-rich region where the shell structure is expected to be modified by a 'monopole shift' of the orbitals [1]. In particular, the 'new' magic number $N = 16$ is expected to appear due to the drift upwards in energy of the $0d_{3/2}$ neutron orbital, which moves away from the $1s_{1/2}$ orbital (filled at $N = 16$) for neutron-rich nuclei in which the $0d_{5/2}$ proton orbital is relatively empty [2, 3]. Simultaneously, the neutron $0d_{3/2}$ orbital approaches the $0f_{7/2}$ orbital in the next major shell and this weakens the $N = 20$ magic number [4, 5].

In ^{25}Ne we can measure the excitation energies of the low-lying $J^{\pi} = 3/2^{+}$ and $3/2^{-}/7/2^{-}$ levels relative to the $1/2^{+}$ ground state, which closely relates to the spacing of $0d_{3/2}$ and $0f_{7/2}$ from $1s_{1/2}$. All elements of the $N = 20$ migration to $N = 16$ are thus represented in the ^{25}Ne level scheme.

The experimental challenges for transfer studies using a radioactive beam can be summarized as *efficiency* and *resolution* [6, 7]. The target thickness limits the resolution attainable in excitation energy to about 300 keV in experiments that deduce the excitation from the measured particle energies and angles [8]. For this reason, we adopt an approach in which coincident gamma rays improve the resolution attained.

2. Experimental details

2.1. The TIARA design philosophy

The TIARA array is a highly efficient particle detector, designed to have full ϕ coverage (i.e. annular coverage about the beam axis) for almost all θ. In addition, it has good angular resolution of 1–2° in θ and is compact so that a high efficiency gamma-ray array can be mounted around it. The central target region is surrounded by an octagonal barrel of position-sensitive silicon detectors that span 82% of 4π with active detector. The barrel is less than 75 mm in diameter, so that the segmented Ge gamma-ray detectors can be mounted as close as 50 mm from the beam spot and attain very high efficiency. The ends of the barrel view annular arrays at larger distances from the target. This means that forward-scattered radioactive beam particles are not stopped within view of the gamma-ray detectors, which is vitally important for intense radioactive beams of 10^{8}–10^{9} pps. This first implementation of TIARA deliberately compromises the complexity of the particle detection system, in order to maximize the geometrical coverage by active detector area. The gamma-ray array is mounted as close as is feasible so as to maximize the detection efficiency, using the available detectors which are from the EXOGAM array [9, 10]. This trades increased efficiency against resolution, which is limited by the finite solid angle spanned by the detector. (The gamma-emitting particle has essentially the velocity and direction of the incident beam.) The electrical segmentation of the Ge can assist in reducing this Doppler broadening. Beam particles enter a magnetic spectrometer at zero degrees, after leaving the target. This separates reaction products from unreacted projectiles, and is designed to provide identification in Z and A.

2.2. Details of the TIARA array

The TIARA barrel consists of eight silicon strip detectors, each with four resistive strips mounted along the beam direction. Each detector has a wafer size of 96.8×24.6 mm^2 and an active area of 94.8×22.6 mm^2, with strips 5.65 mm wide. We used the maximum available thickness for 6-inch Si wafers, namely 400 μm. The barrel spans the angular range from 35.6° to 143.4°. The position resolution is better than 0.5 mm (fwhm) for α-particles of 5.5 MeV [11] and somewhat poorer for smaller deposited energies, and the energy resolution is 120 keV. Beyond the barrel, the forward angles are covered by nested annular double-sided strip detectors, one spanning 12.8°–28.1° and the other, more distant annulus covering more forward angles down to 3.8°. At backward angles, an annular array of six wedge-shaped double-sided detectors covers the angles from the end of the barrel to 169.4°, in 2° bins. All detectors in the annular arrays are 500 μm in thickness. Further details of TIARA are given elsewhere [11, 12].

2.3. Deployment of TIARA with the EXOGAM and VAMOS spectrometers

The TIARA array was installed at GANIL and coupled to the VAMOS magnetic spectrometer [13], which was operated in dispersive mode. The direct beam was intercepted using a plastic scintillator finger mounted immediately in front of the first-order focal plane and was counted, whilst protecting the focal plane detectors from the high counting rate. For gamma-ray detection, four of the segmented-clover Ge detectors from EXOGAM [9, 10] were mounted with their front faces forming a cube around the target, 50 mm from the beam spot. The data acquisition systems for TIARA, VAMOS and EXOGAM operated separately, each with access to a common event counter, and the data streams were merged in real time. Commissioning experiments were performed, using stable beams of reduced intensity that could conveniently be scheduled at GANIL. The results in the literature for ^{14}N(d,p)^{15}N measured with normal kinematics were successfully reproduced [14].

2.4. The experiment with the ^{24}Ne beam

An isotopically pure beam of ^{24}Ne with an average intensity of 10^5 pps and an energy of 10 MeV/A was provided by the SPIRAL facility at GANIL. The beam was of high quality, with an emittance limited to 8π mm mrad so that the beam spot on target was estimated to be 2 mm (base width). Thus, the drift chambers installed for beam tracking were not deployed. The target was a self-supporting foil of $(CD_2)_n$ polymer of thickness 1 mg cm^{-2} and diameter 20 mm mounted on a thin frame. For the EXOGAM detectors, in this first experiment, the dedicated electronics were not operating and no segmentation information was available. The segmentation would have improved the gamma-ray energy resolution by a factor 2. Further, the gamma-ray statistics were reduced significantly because of an intermittent discriminator fault. The beam-like products from (d,t) and (d,^{3}He) reactions were well separated from the direct beam at the VAMOS focal plane; the (d,p) products were also clear of the beam stop for proton angles backward of 90–100°. The experiment with TIARA, VAMOS and EXOGAM working together was fully operational for approximately 24 h.

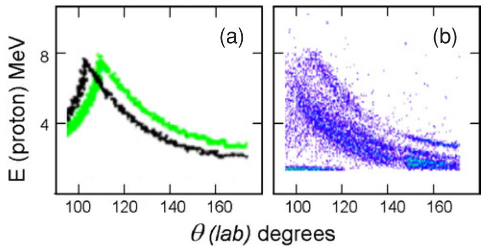

Figure 1. Deposited energy as a function of laboratory angle for d(^{24}Ne,p)^{25}Ne: (a) simulation for ground state (light coloured curve) and a hypothetical 2 MeV state (black curve), (b) data showing the population of states up to an excitation of 4.05 MeV, where a coincidence with a non-beam particle at the focal plane has been demanded.

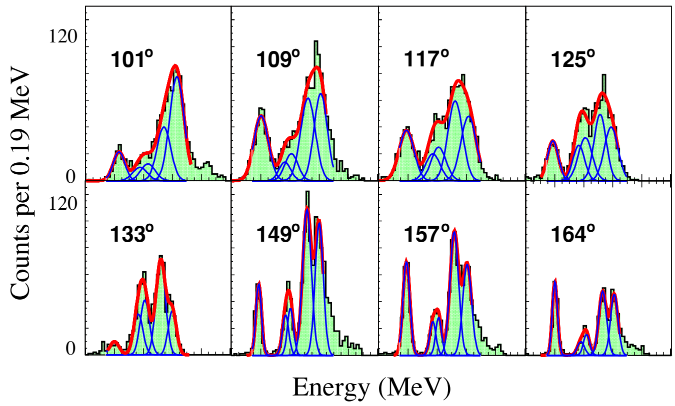

Figure 2. Excitation energy spectra for ^{25}Ne for angle bins centred at the angles indicated, with a bin width of 8° (or 6° for the 164° point).

3. Results

3.1. States in ^{24}Ne(d,p)^{25}Ne deduced from the proton energy spectrum

The measured energies in TIARA as a function of laboratory angle are shown in figure 1, for the backward hemisphere, together with the results of simulations for ^{24}Ne(d,p)^{25}Ne. It is clear that, with the coincidence requirement placed on the particle in VAMOS, the spectrum comprises only protons from the (d,p) reaction.

Using the measured energy and angle, the excitation energy in ^{25}Ne can be deduced. A small angle-dependent correction for energy loss in the target is necessary. The resulting spectra are shown in figure 2 for various bins in angle. It is evident that the resolution is best for the angles backward of the barrel (FWHM $\simeq$ 500 keV for the three highest angle bins). The resolution, dominated by target loss effects [8], is indeed expected to be poorer for less-backward angles. The angular dependence of the resolution is the reason that the relatively coarse angular binning is required. If the fitting of overlapping peaks is not necessary, then bins of 2° according to the angular resolution can be used (compare [15]). The fits are discussed further in section 3.2.

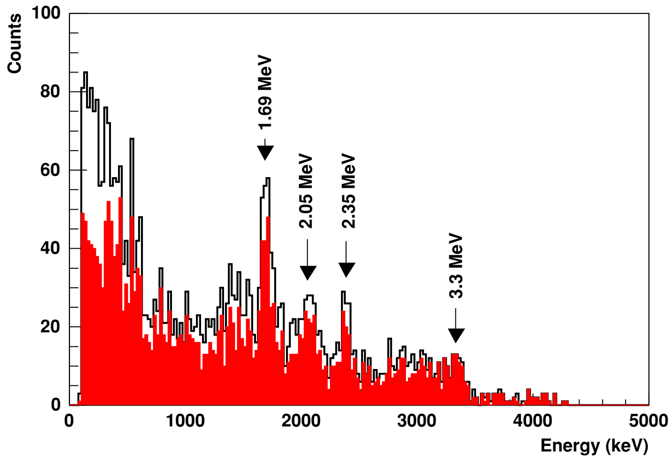

Figure 3. Energy spectrum after Doppler correction for gamma rays in coincidence with protons from ^{24}Ne(d,p)^{25}Ne. The shaded spectrum has the requirement that precisely one clover detector records a signal and shows a suppressed backscatter component.

3.2. Further analysis combining proton and gamma-ray information

The gamma-ray energy spectrum measured in coincidence with the protons from (d,p), shown in figure 3, has limited statistics but shows clear peaks. The data are corrected for Doppler shift and have 'add-back' for scattering within individual clovers. The rise in counts below 400–500 keV is largely due to scattering into the detector from other detectors and adjacent material (see figure caption). In further analysis, the spectra associated with individual proton peaks in figure 2 have been extracted. It was found, for example, that the broad proton peak near 2 MeV gives gamma rays of 1.70 and 2.05 MeV. The energies of the two contributing peaks in figure 2 could then be fixed precisely to these values. In a similar fashion, the energies of the 3.30 and 4.05 MeV peaks could be fixed. The resolution in gamma-ray energy was 50 keV (fwhm) at 1 MeV (note that segmentation information from the EXOGAM detectors [10] was not available). Given the limited statistics, this is also a reasonable estimate of the energy uncertainty both for the observed gamma rays and for the excited state energies. This uncertainty is several times smaller than the errors on the centroid energies when fitting the particle spectra alone, and this together with the factor of 10 better energy resolution provided by the gamma-ray data is key to the present method. Constraining the peak energies using the gamma-ray information gave robust and reliable fits to the proton data.

The differential cross sections for the three lowest energy states in ^{25}Ne are shown in figure 4. The calculated angular distributions, using the adiabatic model [16] for the deuteron channel and with standard correction parameters for finite range and non-locality, are shown. The ℓ-values as shown are the clear best fits to the data. The scaling for the cross sections is arbitrary and is different for the various states. In fact, the cross section to the 2.05 MeV state is larger than that to the 1.70 MeV state by a significant factor. It is clear from shell model considerations that a $3/2^+$ state must be stronger than a $5/2^+$ state in this nucleus, which argues for a $3/2^+$ assignment to the 2.05 MeV state. The USD shell model predictions [17] then suggest $5/2^+$ for the other nearby state at 1.70 MeV. With these assumptions, the spectroscopic factor for the 2.05 MeV state is higher than that for the 1.70 MeV state by a factor of 2.4, which is again consistent with shell model expectations.

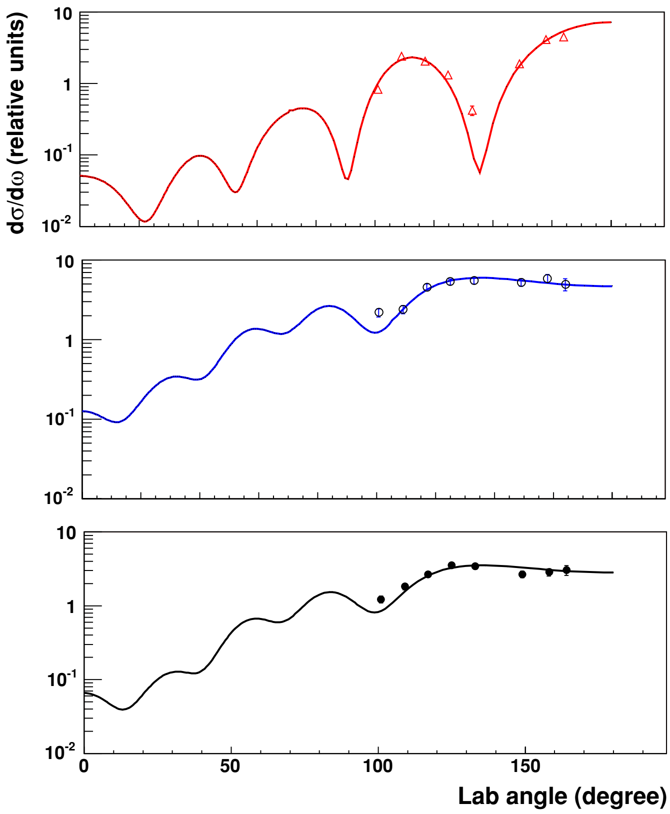

Figure 4. Angular distributions (in arbitrary units) measured in the laboratory frame for states populated in d(^{24}Ne,p) ^{25}Ne: top, ground state with $\ell = 0$ calculation; centre, 1.70 MeV ($\ell = 2$); bottom, 2.05 MeV ($\ell = 2$).

4. Discussion and conclusions

These first results from TIARA have provided interesting new data on a topic of great current interest. The use of a relatively thin target gave sufficient energy resolution in the proton spectrum from (d,p) to measure the yields to individual states in ^{25}Ne, but additional information from coincident gamma rays was critical in specifying the energies in the fitting procedure. The excitation energies in ^{25}Ne are consistent with the results of earlier work [18–20]. The measured $\ell = 0$ for the ground-state transition allows an assignment of $J^{\pi} = 1/2^{+}$. This is in agreement with a recent result measured in neutron knockout from ^{26}Ne [21]. Whereas the knockout work highlighted excited states of hole character in ^{25}Ne, the present work highlights particle states. From a comparison with shell model calculations and the measured $\ell = 2$ for the neutron transfer, we tentatively assign the 2.05 MeV state in ^{25}Ne to be $3/2^{+}$ and the 1.70 MeV state as $5/2^{+}$. This interpretation is consistent with the non-observation [21] of the 2.05 MeV level in knockout. From the considerations given in section 1, and from a comparison with the results of the (d,p) reaction on the isotone ^{26}Mg [22], the peaks at 3.30 and 4.05 MeV are candidates for negative parity levels. Work is in progress to understand the implications of these results more fully, and to extend the full analysis to include the higher lying levels.

Acknowledgments

We acknowledge with thanks the support of the GANIL management and technicians, and also the technicians from LPC Caen, during the installation and commissioning of the TIARA array. Mr Geoffrey Moores (University of Paisley) and the Daresbury design staff are thanked for their vital contributions. This work was supported in the UK by EPSRC grants held at Surrey, Paisley, Daresbury and Birmingham.

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