New investigations on the ^{32}S(^{3}He,d)^{33}Cl reaction at 9.6 MeV bombarding energy

Marco Cinausero[1*], *Daniele* Dell'Aquila[2], *Ivano* Lombardo[2], *Mariano* Vigilante[3;4], *Sandro* Barlini[5,6], *Riccardo* Bolzonella[7;1], *Mauro* Bruno[8;9], *Antonio* Buccola[5;6], *Sara M.* Carturan[7,1], *Giovanni* Casini[6], *Magda* Cicerchia[7;1], *Maurizio* D'Andrea[2], *Meltem* Degerlier[10], *Daniela* Fabris[11], *Leandro* Gasques[12], *Fabiana* Gramegna[1], *Alinka* Lepine-Szily[12], *Giorgia* Mantovani[7;1], *Tommaso* Marchi[1], *Silvia* Piantelli[6], *Valentino* Rigato[1], *Luca* Scomparin[7;1] and *Simone* Valdré[6]

[1] INFN - Laboratori Nazionali di Legnaro, Legnaro, Italy
[2] INFN - Sezione di Catania, Catania, Italy
[3] Università degli Studi di Napoli "Federico II", Napoli, Italy
[4] INFN - Sezione di Napoli, Napoli, Italy
[5] Università degli Studi di Firenze, Firenze, Italy
[6] INFN - Sezione di Firenze, Firenze, Italy
[7] Università degli Studi di Padova, Padova, Italy
[8] Università degli Studi di Bologna, Bologna, Italy
[9] INFN - Sezione di Bologna, Bologna, Italy
[10] Science and Art Faculty, Physics Department, Nevsehir Haci Bektas Veli Univ., Nevsehir, Turkey
[11] INFN - Sezione di Padova, Padova, Italy
[12] Instituto de Fisica da Universidade de São Paulo, 05508-090 São Paulo, Brasil

Abstract. The ^{32}S(^{3}He,d)^{33}Cl one-proton transfer reaction is a powerful tool to investigate the spectroscopy of low-lying states in the proton-rich ^{33}Cl nucleus. However, the extraction of firm differential cross-section data at various angles to benchmark and constrain theoretical models is made challenging by the presence of competitive reactions on target contaminants. In this paper we report on a recent measurement using a new generation hodoscope of silicon detectors, capable to detect and identify emitted deuterons down to energies of the order of 2 MeV. The high angular segmentation of our hodoscope combined with a suitable target to control possible contaminants, allowed to unambiguously disentangle the contribution of various states in ^{33}Cl, in particular the 2.352 MeV state lying just few tens of keV above the proton separation energy.

1 Introduction

The properties of low-lying states in the proton rich ^{33}Cl nucleus can be effectively probed by means of the ^{32}S(^{3}He,d)^{33}Cl one-proton transfer reaction [1,2]. In particular, the spin and parity (J^{π}) and the spectroscopic factors (C^2S_p) can be determined by the measure of the differential cross-section angular distribution of each individual excited state populated in the residual nucleus and comparing the experimental results with the predictions of theoretical models [1,2]. However, while theoretical calculations based on the shell-model approach have reached a very refined level in the description of (s-d)-shell nuclei [3,4], on an experimental point of view the situation is still unclear. For several low-lying states of ^{33}Cl, in fact, contrasting estimates of the C^2S_p factors are reported in the literature [5] and there is no consensus even in the J^{π} assignement. Indeed, the estimate of the C^2S_p is also relevant in nuclear astrophysics, to detemine the (p,γ) reaction rate in the stars [6]. In this context, we have performed a new study of the ^{32}S(^{3}He,d)^{33}Cl reaction at 9.6 MeV incident energy by using a new generation hodoscope of silicon detector, OSCAR [7]. In addition, special care has been taken in the target production to reduce possible contaminants.

2 Experimental details

The experiment has been performed at the CN Van de Graaf accelerator of the Laboratori Nazionali di Legnaro (LNL). A ^{3}He^{++} beam was delivered at an energy of 9.6 MeV on a 53 μg/cm^2 ^{nat}Zn^{32}S target, 99% enriched in ^{32}S, on a thin (15 μg/cm^2) carbon substrate. The target was manufactured and fully characterized (EDS, XRD and RBS analysis) at LNL, and installed in the center of a circular scattering chamber. A rotating plate hosted two silicon telescopes and an OSCAR telescope [7], placed on the opposite side with respect to the beam direction. Both detectors have two detection stages to enable the particle identification via the ΔE-E technique. The OSCAR telescope was composed by a thin (20 μm) 16-strips Single-Sided Silicon Detector (SSSSD) used as the first detection stage, and 16 individual silicon PIN diode pads (300 μm thick) used as the second detection stage. Each vertical strip of the first detection stage is 3.125 mm wide, while the second stage silicon pads have an active area of 1 cm^2. To determine the angular

---

[*] Corresponding author: cinausero@lnl.infn.it

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).

position of each detector with respect to the beam line we performed a dedicated measurement using an optical alignment telescope. Each of the measured positions is determined with an accuracy better than 0.2°. In the OSCAR hodoscope, the correlations between the first and second detection stages can be used to constrain with high precision the impact point on the surface of the detector and therefore the angle of the emitted particles. We define 64 individual pseudo-telescopes, each identified by the correspondence of a particular strip of the SSSSD with a pad in the second detection stage. This method allows to have 64 detection telescopes using only 32 individual electronics channels.

3 Status of the analysis

To reconstruct particles in the OSCAR hodoscope we correlate strips in the first detection stage with pads in the second detection stage. Energy calibration of first and second stages was performed by using the ^{3}He elastic scattering on ^{197}Au at 13 different incident energies. Effects related to electronics were taken into account determining correction factors for each pseudo-telescope and each individual run. This procedure allows to maximize the statistics on the recorded spectra by merging data from different runs without affecting the energy resolution. Average energy resolution of 60 keV [FWHM] is achieved. The particle identification is obtained by means of the ΔE-E technique for each pseudo-telescope. The whole angular range spanned by the detector is divided into 32 different bins by grouping pseudo-telescopes that minimize the θ overlap. This allows to maximize the statistics preserving a good angular resolution. Figure 1 shows the deuteron kinetic energy as a function of the detection angle.

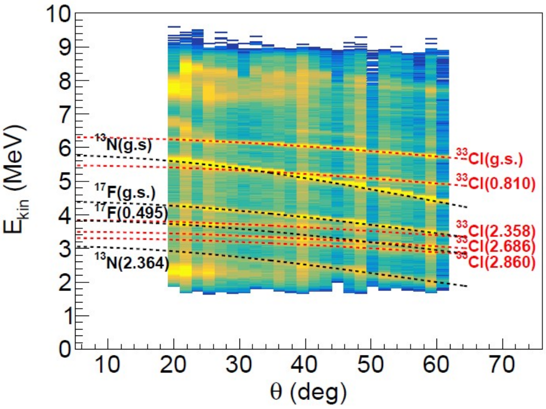

Fig. 1. Experimental deuteron kinetic energy as a function of the detection angle. Red dashed lines show the calculated kinematics lines for the populated ^{33}Cl states. Black lines show the kinematics lines for reactions on target contaminants.

Several lines related to one-proton tranfer in different target nuclei populating different states in the residues are clearly visible in the Figure. Red dashed lines are the result of a kinematical calculation for the ^{32}S(^{3}He,d)^{33}Cl reaction under investigations. Black dashed lines are competing (^{3}He,d) reactions occurring on ^{12}C and ^{16}O contaminants present in the target backing. In this way, the energy peaks related to the states of interest can be clearly identified along the whole spanned angular range. For each angular region, we performed a multi-gaussian fit of the detected peaks in the deuteron E_{kin} spectrum. A typical example of such fits is shown in Figure 2.

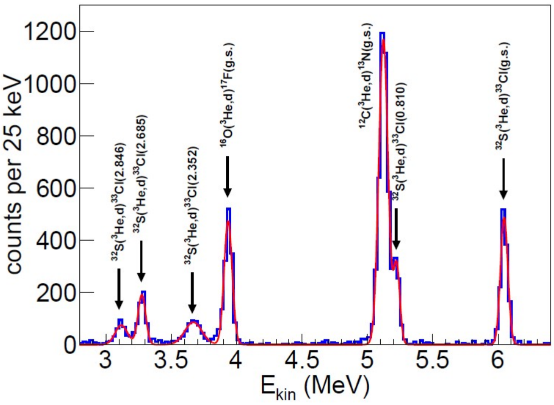

Fig. 2. Experimental deuteron spectrum at θ = 40°. In red is shown the multi-gaussian fit performed. Peaks are identified by labels.

The area under each peak, determined by the fitting procedure, gives the yield of the population of the corresponding state. The absolute cross-section of each ^{33}Cl state can be deduced from these yields by internal normalization to the ^{3}He + ^{nat}Zn Rutherford scattering.

4 Conclusions and perspectives

The ^{32}S(^{3}He,d)^{33}Cl one-proton transfer reaction at 9.6 MeV bombarding energy is investigated by using the new generation hodoscope OSCAR [7]. The good energy and angular resolution achieved by our device allows to disentangle the contribution of reactions of interest from contaminant background. The obtained yields will be used to extract the angular distribution of the differential cross section the identified low-lying states of ^{33}Cl, which will help to solve the experimental ambiguities still present in its spectroscopy.

References

1. G. Inglima *et al.*, Nuovo Cimento A **26**, 211 (1975)
2. R.L. Kozub and D.H. Yongblood, Phys. Rev. C **5**, 413 (1972)
3. B. Wildenthal *et al.*, Phys. Rev. C **4**, 1708 (1971)
4. B. Castel *et al.*, Nucl. Phys. A **162**, 273 (1971)
5. J. Chen and B. Sing, Nucl. Data Sheets **112**, 1393 (2011)
6. C. Iliadis *et al.*, Astr. J. Suppl. Ser. **134,** 151 (2001)
7. D. Dell'Aquila *et al.*, Nucl. Inst. Meth. A **877**, 227 (2018)