$^2$He decay from the $^{18}$Ne 6.15 MeV (1$^-$) excited state.

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Abstract. The decay of $^{18}$Ne excited states into 2p+$^{16}$O channel has been studied. The $^{18}$Ne secondary beam, at 33 AMeV incident energy, was produced by fragmentation of a primary $^{20}$Ne beam at the LNS-FRIBs facility. Coulomb excitation on a $^{nat}$Pb secondary target was found to be the main interaction process leading to the population of $^{18}$Ne excited levels. The two-proton decay of the 6.15 MeV (1$^-$) level has been confirmed, but in addition other high-lying states decaying via 2p emission were observed. A significant branching ratio of $^2$He decay has been deduced from the analysis of the relative angle and energy correlation spectra of the two protons emitted from the 6.15 MeV (1$^-$) state.

1. Introduction

The possibility of two-proton emission from the ground-state of neutron-deficient Z-even nuclei was first suggested by Goldanskii in 1960 [1]. Indeed, it was evidenced that even when a single proton is bound, it is energetically possible for two protons to be emitted simultaneously either as an $^2$He cluster (diproton) or as the result of two separate barrier penetration (democratic emission of the two protons). In the latter case, the two protons do not have any correlation beyond the phase-space constrains and, therefore, only energy- and momentum-conservation laws apply. Such a decay pattern yields an isotropic angular distribution of protons which share the total decay energy, with individual proton energies ranging from zero to the total decay energy. This picture is changed when a more realistic description of the tunnelling process is taken into account, because the barrier penetration strongly favors the emission of two protons with similar energies [2]. In the case of diproton emission, protons are emitted as a $^2$He cluster which, due to final state interaction, breaks apart outside of the Z-2 daughter nucleus. The simultaneous emission of two protons is, in general, in competition with the sequential 2p decay, where the two protons are emitted sequentially via an intermediate state. Generally, the decay is sequential when levels in the Z-1 daughter nucleus are accessible for 1p emission. This situation is easily encountered when the emission takes place from highly-excited states of the 2p emitter. Therefore, in searching for the two-proton radioactivity, one has to avoid the possibility of sequential emission. Indeed, many experiments performed so far, such as the breakup of $^8$Be [3] and $^{12}$O [4, 5] or the $\beta$-delayed 2p emissions from light- and intermediate-masses nuclei [6, 7, 8], seem to indicate that the sequential decay dominates, as long as intermediate states for 1p
emission are energetically accessible. The first observation of simultaneous emission of two protons came from the $^{45}$Fe [9, 10] at ground state. Clear evidence for 2p decay was reported also for the $^{48}$Ni [11] and $^{54}$Zn [12] ground states and for the 6.15 MeV excited state of $^{18}$Ne [13]. Despite significant efforts, complete characterization of the two-proton radioactivity has yet to be reached, and $^2$He emission has not been unambiguously observed. Progress in this field is of the utmost importance, since it may offer insights into pairing and three-body effects inside nuclei.

Recently, in order to improve the quality of data on the 2p decay of $^{18}$Ne previously reported [14], a new experiment was performed by using the $^{18}$Ne beam at 33 AMeV, produced by the FRIBs facility [15, 16] at the Laboratori Nazionali del Sud (LNS-Catania).

2. The experimental set-up

The $^{18}$Ne secondary beam was produced by fragmentation of a primary stable $^{20}$Ne beam accelerated to 45 AMeV by the LNS Superconductive Cyclotron (SC) on a $^9$Be production target, 500 $\mu$m thick. The secondary ions have been separated in-flight in the fragment separator of the LNS with a $B_\rho$ setting optimized for the $^{18}$Ne transmission. A primary current of 300 enA produced a total RIBs rate of $10^5$ ions/sec at the exit of the fragment separator. The secondary beam has been transported with a 60% efficiency up to the TRASMA scattering chamber. The $^{18}$Ne rate, 9% of the total transmitted RIBs mixture, was $5.5 \times 10^3$ pps.

In order to disentangle the contributions coming from the different projectiles of the RIBs cocktail, the tagging method was applied [15, 16]. It consists on the measurements event-by-event of energy, charge, mass, via $\Delta E$-ToF technique, and position of each ion of the transported RIBs, before the interaction with the secondary $^{nat}$Pb target. The time-of-flight was measured with respect to the radio frequency (RF) signal provided by the SC and the energy loss was measured by a 16×16 X-Y Si-Strip detector (tagging detector) $5 \times 5$ cm$^2$ of area and 300$\mu$m thick (Fig. 1). The $^{18}$Ne incident energy on the $^{nat}$Pb target was 33±2AMeV (FWHM) as evaluated from the measured energy loss in the Si-Strip (Fig. 2).

The detection system consisted on two Si-CsI hodoscopes with different granularity (Fig. 3):

- 81 two-fold telescopes: 300 $\mu$m Silicon detectors $1 \times 1$ cm$^2$ of active area followed by a $1 \times 1$ cm$^2$ and 10 cm long CsI(Tl);
89 three-fold telescopes 50 µm + 300 µm Silicon detectors both having 3×3 cm² surface followed by a 6 cm long CsI(Tl) of the same surface. Due to its granularity and low threshold, the array is a suitable detector for momentum and angular correlation measurements. The two-folds telescopes cover the forward hemisphere with an opening angle of $\theta_{\text{lab}} = \pm 5^\circ$ and in step of $\pm 0.6^\circ$, while the three-folds telescopes cover the solid angle between $\pm 5^\circ$ and $\pm 21.5^\circ$ in step of $\pm 1.5^\circ$, with a total geometrical efficiency of 72%.

The device allows to simultaneously detect heavy- and light-decay products. In particular the $^{18}\text{Ne} \rightarrow 2p + ^{16}\text{O}$ diproton decay channel has been detected with an efficiency of 32% as evaluated by Monte Carlo simulations.

3. Kinematic reconstruction procedure
The projectiles have been selected by gating on the $\Delta E$-ToF plot provided by the tagging detector (Fig. 1-right panel) and then a complete reconstruction of the decay kinematics in the center-of-mass system (CM) was performed. The X-Y coordinates of the interaction point on the target as well as the energies and angles of all outgoing decay particles were measured on an

Figure 2. Energy spectra before and after the 300µm Si-Strip tagging detector. Spectra are indirectly reconstructed from the energy-loss measured by the Si-Strip.

Figure 3. Left: schematic view of the experimental setup. Right: 3D reconstruction of the hodoscopes geometry: the covered solid angle is 0.34 sr and the geometrical efficiency is 72%.
event-by-event basis. From the velocities and angles of the decay products measured in the hodoscopes, the CM velocity, i.e. the velocity of the decaying nucleus, was determined. The CM kinetic energy, including Q-value and energy loss in the target, must be almost equal to the projectile energy, reconstructed from the $\Delta E$ measured in the Si-Strip. With an iterative procedure it was possible to identify the target slice where the energy conservation is satisfied, i.e. where the reaction takes place [17]. Therefore it was possible to reconstruct, event-by-event, the invariant mass in the CM system and thus the excitation energy spectrum. Background produced by reactions on the Si-Strip tagging detector has been measured with empty frame runs and subtracted from the data.

The whole procedure was first checked for the well-known $^{16}\text{O} \rightarrow ^{12}\text{C} + \alpha$ decay. Figure 4 (left panel) shows the excitation energy spectrum as determined from the fully measured $^{12}\text{C} + \alpha$ events produced by the $^{16}\text{O}$ break-up. The well-known $1^-, 2^+$ excited levels of $^{16}\text{O}$ [18, 19] are recognized despite the poor energy resolution. Indeed, the experimental energy resolution was about 500 KeV, mainly dominated by the error in the determination of the depth of the interaction point in the thick $^{nat}\text{Pb}$ target [17]. The spectrum presents only $1^-$ and $2^+$ levels as expected for Coulomb excitation process.

In Ref. [20] the Coulomb excitation cross section of the 13.09 MeV ($1^-$) state in $^{16}\text{O}$ projectiles incident on $^{nat}\text{Pb}$ target was calculated as a function of the incident energy. For an incident energy of 30 AMeV the calculated Coulomb excitation cross section is 0.9 mbarn. In order to further validate the assumption of Coulomb excitation as the main process, we measured the absolute cross section for the $^{12}\text{C} + \alpha$ decay from this $^{16}\text{O}$ level. The peak corresponding to the 13.09 MeV ($1^-$) level in the spectrum of Fig. 4 (left panel) was integrated by correcting for the contribution of the other neighboring levels and for the hodoscopes efficiency. Having measured the number of incoming $^{16}\text{O}$ projectiles by the Si-Strip and considering the branching ratio of about 20% [19] for the decay of this level in the $^{12}\text{C} + \alpha$ channel an experimental cross section of 0.87±0.22 mbarn has been estimated, which is quite near to the calculated one [20].

The excitation energy spectrum of the $^{17}\text{F} + p$ events produced by selecting the $^{18}\text{Ne}$ projectile is shown also in Fig 4 (right panel). The peaks corresponding to the decay of the 5.09 MeV ($2^+$), 5.15 MeV ($2^+$) and 6.15 MeV ($1^-$) $^{18}\text{Ne}$ excited states [19] are recognized although partially

**Figure 4.** Left: Experimental excitation energy spectrum of $^{16}\text{O}$ from the $^{12}\text{C} + \alpha$ events (left) and of $^{18}\text{Ne}$ from the $^{17}\text{F} + p$ events (scaled by a factor of four) and from the $^{16}\text{O} + 2p$ events (right). The indicated levels are listed in Ref [19].
Figure 5. Relative angle (left) and relative energy (right) in the CM reference system of the two protons emitted from the 6.15 MeV level. Solid and dashed lines show the Monte Carlo simulations of the $^4$He and democratic decay modes, respectively.

superimposed, indicating again the Coulomb excitation as the main population process.

4. 2p decay of $^{18}$Ne

The same procedure was then applied to the fully measured $^{16}$O+2p events produced by the selected $^{18}$Ne secondary beam. The excitation energy spectrum for this class of events is shown in Fig. 4 (right panel). The presence of the 6.15 MeV (1$^-$) peak confirms the evidence for simultaneous two-proton decay of this $^{18}$Ne state already reported in Ref. [13]. Indeed, for this level, the sequential 2p decay is energetically forbidden. Whether the presence of two protons in the decay of known 7.06 MeV (1$^-$, 2$^+$), 7.91 MeV (1$^-$, 2$^+$) and 8.5 MeV (1$^-$, 2$^+$) levels indicates a simultaneous two-proton decay mechanism, deserves further investigations since, for these levels, the sequential 2p decay channel is available. Moreover, Coulomb excitation allowed to populate unknown high-lying states around 10.7 MeV, 12.5 MeV and 13.7 MeV, possible future candidates for two-proton radioactivity. Indeed, recently, in the study of the decay of excited states of $^{17}$Ne, performed at GANIL[21], the observed data seem to indicate that one or several high-lying states could decay by a correlated 2p emission, despite the fact that the sequential branch is widely open.

In order to disentangle the diproton and democratic, two-proton decay-modes of the 6.15 MeV level, the relative energy and angle correlation of the two emitted protons have been measured. Figure 5 shows the relative energy and the relative angle of the two protons in the CM reference frame for events selected inside the excitation energy window $5.9 \leq E^* \leq 6.5$ MeV. Data are compared to Monte Carlo simulations assuming $^4$He emission (solid line) and three-body decay, neglecting final state interaction (dashed line). The Monte Carlo code simulates the 2p-decay mechanism (sequential or simultaneous) taking into account the excitation energy width taken from [19], the measured beam properties, the detector responses and the geometrical efficiency of the setup. As shown by the simulations, the two decay mechanisms for simultaneous two-proton emission lead to different energy and angular correlation between the two protons, provided the correlations are studied over an angular range large enough [13].

Despite the poor statistic, the relative energy and angle indicate the presence of events where the two protons are emitted both uncorrelated and in the form of a $^4$He. In order to extract
the branching ratios corresponding to the diproton and the direct 3-body decay, the simulation curves, normalized to the data, have been integrated: the $^2$He emission is about 35% of the total two-proton decay whereas the three-body emission is about 65%.

5. Summary
In a recent experiment performed at the Laboratori Nazionali del Sud (LNS-Catania) the 2p emission from excited states of $^{18}$Ne was studied. The $^{18}$Ne was produced as secondary beam by $^{20}$Ne fragmentation at 45AMeV and excited states were populated by Coulomb excitation on a natPb target. The excitation energy spectrum was kinematically reconstructed from the fully measured $^{17}$F+p and $^{16}$O+2p events. The presence of the peak at 6.15 MeV (1$^-$) in the $^{16}$O+2p spectrum confirms the observed 2p decay of this level. The relative energy and angle correlation spectra between the two protons, for events belonging to the excitation energy range $5.9 \leq E^* \leq 6.5$ MeV, indicate the presence of both diproton (35%) and democratic (65%) decay mechanism. However, for a more precise measurement of the branching ratio more statistics is needed. Moreover the Coulomb excitation process allowed to populate high-lying known and unknown states in $^{18}$Ne which also decay by two protons emission. Whether in these latter cases the presence of two protons is the results of a simultaneous emission is still under investigation.

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