First experimental evidence of ^{2}He decay from ^{18}Ne excited states

E. Rapisarda, F. Amorini, G. Cardella, M. De Napoli, G. Raciti, C. Sfienti
Dipartimento di Fisica e Astronomia, Università di Catania, Italy
INFN Sezione di Catania, Italy
INFN Laboratori Nazionali del Sud, Italy

Abstract
Two-proton decay from ^{18}Ne excited states has been studied by complete kinematical detection of the decay products. The ^{18}Ne nucleus has been produced as a radioactive beam by ^{20}Ne projectile fragmentation at 45 AMeV on a ^{9}Be target, using the FRIBs in-flight facility of the LNS. The ^{18}Ne at 33 AMeV incident energy has been excited via Coulomb excitation on a ^{nat}Pb target. The correlated 2p emission has been disentangled from the uncorrelated 2p emission using a high granularity particle detector setup allowing the reconstruction of momentum and angle correlations of the two emitted protons. The obtained results unambiguously show that the 6.15 MeV ^{18}Ne state two-proton decay proceeds through ^{2}He emission (31%) and democratic or virtual sequential decay (69%).

1 Introduction

One of the most exciting new phenomena at the drip-lines of the nuclear chart is the occurrence of new types of radioactivity. In particular for nuclei near or beyond the proton drip-line, where the strong force can no longer bind all protons, one- and two-proton (2p) radioactivity was predicted more than 40 years ago by Goldansky [1]. For odd-Z nuclei, one-proton radioactivity was proposed to occur, whereas for medium-mass and heavy-mass even-Z nuclei the nuclear pairing energy renders one-proton emission impossible. In this case, two protons emission is to be expected. In his first paper, Goldansky proposed many nuclei as possible candidates for 2p emission according to the criterion that two-proton radioactivity candidates should be bound with respect to one-proton emission but unbound with respect to two-proton emission. For ground-state decay this means that the mass of the 1p daughter is higher than the mass of the 2p daughter, whereas for excited levels that no intermediate levels in the 1p daughter nucleus are accessible for 1p emission. Many attempts to find this new nuclear decay mode for the nuclei proposed by Goldansky were unsuccessful. According to recent experimental results ^{45}Fe [2,3], ^{48}Ni [4], and possibly ^{54}Zn [5] were the best cases for ground-state two-proton radioactivity. These nuclei have been already reached and studied both at GSI and GANIL. Simultaneous emission of two protons can also occur from short-lived nuclear resonances (^{6}Be [6], ^{12}O [7], ^{16}Ne [8], ^{19}Mg [9]) and excited states (^{17}Ne [10, 11], ^{18}Ne [12]) where the mechanism of 2p emission may depend on the reaction populating the parent resonance, in contrast to 2p radioactivity.

The recent increasing interest on two protons radioactivity is motivated by the knowledge we could gain in nuclear structure and astrophysics. Indeed, the inverse reaction to 2p decay, namely 2p capture, is expected to play an important role in the synthesis of heavy elements in the Universe, possibly bridging some "waiting points" in the "hot" rp-process, see e.g. Ref. [13].

Besides the observation of simultaneous emission, however, no firm evidence of diproton-type correlation results from the performed experiments. Indeed the true 2p radioactivity implies a correlated emission of the two protons emitted as a ^{2}He cluster. This must be distinguished from the simultaneous but uncorrelated emission of the proton pair, namely the "direct three-body decay" (also called democratic decay). Experimentally one can distinguish these two simultaneous decay modes by measuring the energy and angular correlation of the proton pair.

The present experiment performed at LNS has been dedicated to the study of the decay, via two protons emission, of the 6.15 MeV level of ^{18}Ne produced by the FRIBs facility of the Laboratori Nazionali del Sud (LNS) [14] and populated via Coulomb excitation on a ^{nat}Pb target. This decay is very promising

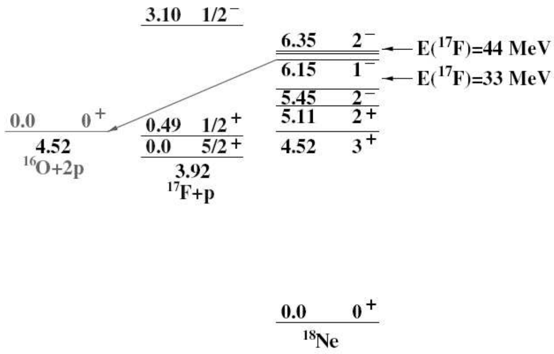

Fig. 1: Energy-loss in the Si-Strip detector versus ToF

since the 6.15 MeV (1^-) level is located in an energy window where sequential decay through ^{17}F is energetically forbidden as shown in Fig. 1. The results of the present experiment [15] reported the first experimental evidence of diproton decay.

2 Experimental setup

The secondary beam has been produced by the fragmentation of a primary stable ^{20}Ne beam at 45 AMeV delivered by the LNS Superconducting Cyclotron (SC) on a ^{9}Be, 500 μm thick, production target. The secondary ions have been separated in-flight by the fragment separator of the LNS operated at a Bρ setting optimized for ^{18}Ne. A primary current of 300 enA produced a total RIBs rate of 10^5 ions/sec

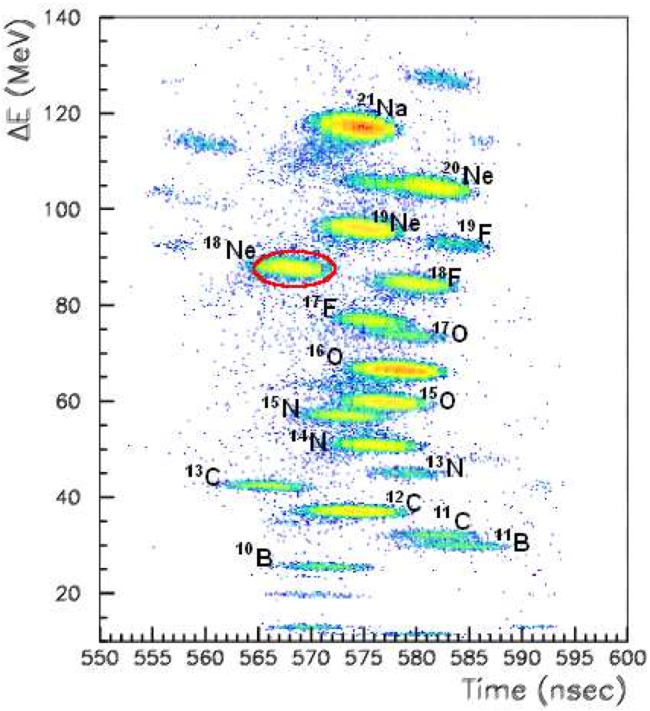

Fig. 2: Energy-loss in the Si-Strip detector versus ToF.

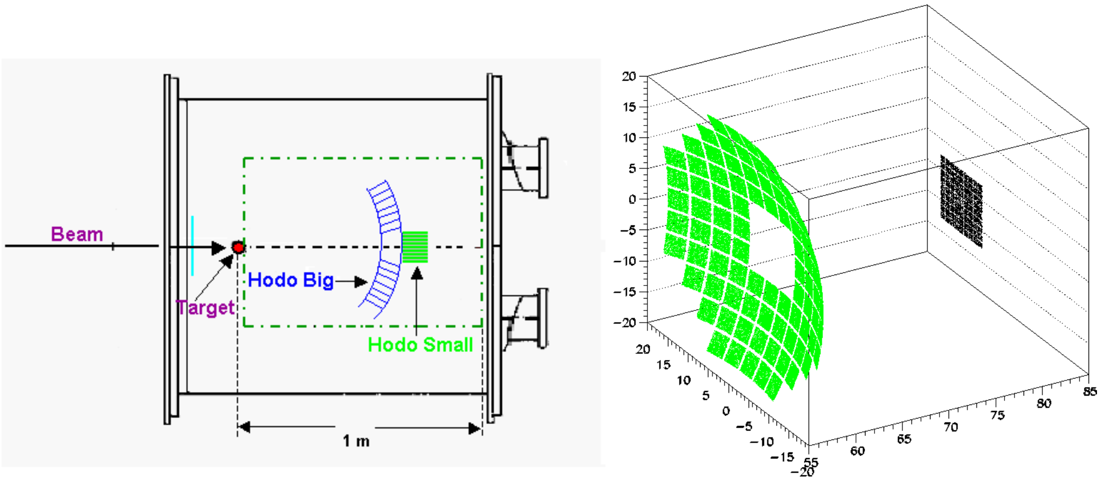

Fig. 3: Left: schematic view of the experimental setup. Right: 3D reconstruction of the hodoscopes geometry.

at the exit of the fragment separator. The secondary beam consists on a mixture of nuclear species (see Fig. 2) all of which fulfill the angle and momentum acceptance of the Fragment Separator. The entire mixture has been transported with 60% of transmission up to the scattering chamber. The ^{18}Ne rate was 9% of the total RIBs mixture rate, i.e. about 5.4×10^3 pps. Reactions induced by the ^{18}Ne radioactive beam have been selected from the ones due to contaminants present in the RIBs mixture by tagging, event by event, each ion of the secondary beam before it impinges on the secondary target. The identification is derived from the energy-loss measured by a double side 16×16 X-Y Si-Strip detector (DSSD) 5×5 cm^2 of active area and 300μm thick and the time-of-flight measured from the same signal of the DSSD with respect to the radiofrequency signal provided by the SC (Fig. 2). The Si-Strip tagging detector is set upstream the target at a distance of about 1 cm.

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

– 81 two-fold 1×1 cm^2 of active area telescopes: 300μm Si detectors followed by a 10 cm long CsI(Tl),
– 89 three-fold 3×3 cm^2 of active area telescopes: 50μm + 300μm Si detectors followed by a 6 cm long CsI(Tl).

The first hodoscope covers, in step of $\pm0.6°$ both in θ and ϕ, the spherical surface around zero degree with an opening angle of $\pm5°$. The second hodoscope covers, in step of $\pm1.5°$ both in θ and ϕ, the spherical surface having an opening angle between $\pm5°$ and $\pm21.5°$. A schematic view of the complete experimental setup is shown in Fig. 3. The whole array covers 0.34 sr of the forward solid angle, including zero degree, with a geometrical efficiency of 72%. Its high granularity is suitable for momentum and angular correlation.

The device allows to simultaneously detect heavy- and light-decay products. In particular the $^{18}\mathrm{Ne}\rightarrow2p+^{16}\mathrm{O}$ diproton decay channel can be detected with an efficiency of 32% as evaluated by Monte Carlo simulation.

3 Kinematics reconstruction procedure

The events triggered by the ^{18}Ne projectile have been discriminated by gating on the ΔE-ToF plot provided by the Si-Strip detector as shown in Fig. 2. The X-Y coordinates of the interaction point on the DSSD were also measured by coupling the signals delivered by the horizontal and vertical strips with a gross resolution of 3 mm. The angles of the decay products were then calculated taking as reference the incident point on the tagging detector. The incident energy on the reaction target was in the range of

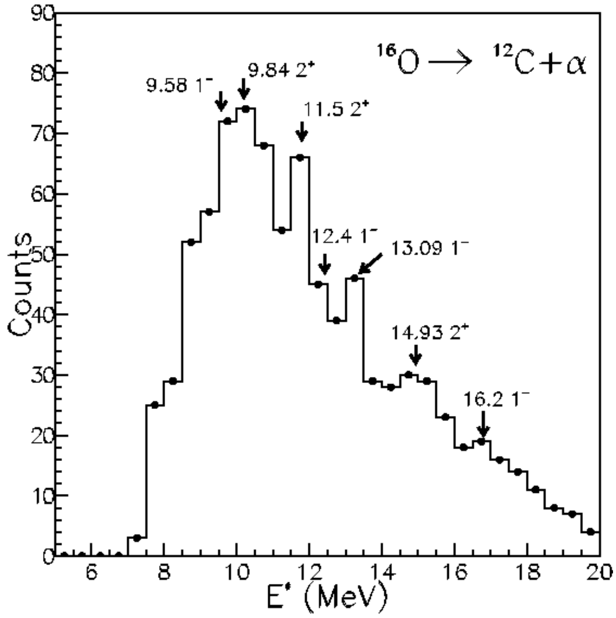

Fig. 4: Excitation energy spectrum of ^{16}O from the $^{12}C + \alpha$ events.

33±1.2 AMeV as evaluated from the energy loss in the Si-Strip. The spread in the projectile energy of ±3.7% was due both to the ΔE/E acceptance of the fragment separator (±2.5%) and to the straggling in the tagging detector (±1.2%).

From the velocities and angles of the decay products measured in the hodoscopes, the center of mass velocity (CM) 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 ΔE 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 with a resolution of ±50μm [16]. The main source of uncertainty in the target slice reconstruction is due to the spread of the incident energy that affects the computation of the minimum difference between the incoming and the outgoing energy. However the procedure allows to distinguish between events coming from the Pb target from events coming from the tagging detector (background).

For checking purpose, the whole procedure has been applied to the well-known ^{16}O nucleus selected on the ΔE-ToF plot provided by the DSSD in the same manner of ^{18}Ne. The excitation energy spectrum of the ^{16}O shown in Fig. 4 was obtained by adding the Q-value for the $^{12}C + \alpha$ decay channel to the reconstructed CM energy. The well-known 1^- and 2^+ excited levels of ^{16}O are recognized despite the poor resolution. The experimental resolution is about 500 keV, mainly dominated by the error in the determination of the interaction point in the thick Pb target. The spectrum presents only 1^- and 2^+ levels as expected since only these levels can be populated via Coulomb excitation.

4 The ^{18}Ne two-proton decay

4.1 Excitation energy spectrum

The same procedure was then applied to the fully measured ^{17}F+p and ^{16}O+2p events produced by the selected ^{18}Ne secondary beam. The excitation energy spectra obtained for the two cases are reported in Fig. 5 where the known 1^- and 2^+ levels of ^{18}Ne are indicated. The spectrum relative to the 1p channel has been scaled by a factor 4 in order to be plotted in same scale. The peaks corresponding to the decay of the 5.09 MeV (2^+), 5.15 MeV (2^+) excited states are recognized only in the ^{17}F+p channel because of the lower mass-excess value (3.92 MeV) with respect to the ^{16}O+2p channel (4.52 MeV). The presence of the 6.15 MeV (1^-) peak both in the ^{17}F+p and ^{16}O+2p channels confirms the observation of one- and

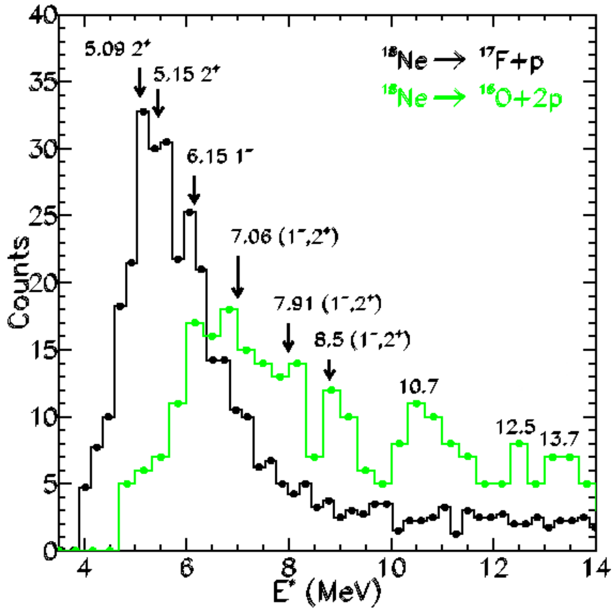

Fig. 5: Excitation energy spectrum of ^{18}Ne extracted from ^{16}O+2p events and from ^{17}F+p events (scaled by a factor 4). The levels values are from Ref. [17].

two-proton decay of this state reported in Ref. [12]. From this level, the sequential 2p decay channel through a ^{17}F level is energetically forbidden. The 2p decay from the known 7.06 MeV (1^-, 2^+), 7.91 MeV (1^-, 2^+) and 8.5 MeV is also observed, but for these levels, the sequential 2p decay is available. The populated known ^{18}Ne levels are essentially 1^- and 2^+ states suggesting again the Coulomb excitation as the main reaction channel. Therefore we propose 1^- or 2^+ spin assignment for the unknown high-lying states at around 8.5 MeV, 10.7 MeV, 12.5 MeV and 13.7 MeV.

4.2 Angle and momentum correlations

In order to understand whether the two-proton decay of the 6.15 MeV level proceeds as diproton or direct three-body decay, the relative angle and momentum spectra of the two emitted protons in the ^{16}O+2p CM system have been studied (Fig. 6). Events where selected in the excitation energy window 5.9<E*<6.5 MeV. The relative momentum and angle spectra for these events clearly show an enhancement at $|q_{rel}|$=*20MeV/c* and θ_{rel}=*50*°, respectively, as expected for the ^{2}He emission.
Data were compared to Monte Carlo simulations, filtered for the geometry and detectors constrains, assuming ^{2}He emission, direct three body decay neglecting final state interaction and virtual sequential decay [15]. As shown by the simulations, the three possible decay mechanisms lead to different momentum and angle correlations between the two protons, provided the correlations are studied over a large enough angular range. Neither the three-body decay nor the virtual sequential decay can reproduce either the asymmetry about 90° in the θ_{rel} or the enhancement observed at 20 MeV/c in the q_{rel} spectrum. In order to break the symmetry in the θ_{rel} we need to include the ^{1}S 2p correlation, that is the ^{2}He emission. In this way, the spectra are best reproduce with a (66±9)% contribution from the direct three-body, (3±2)% from the virtual sequential and (31±7)% contribution from the ^{2}He decay mode.
In order to explore the possibility that other levels of ^{18}Ne could decay by correlated 2p emission, the proton-proton relative momentum spectrum was studied for the ^{16}O+2p events in the excitation energy range E*>6.5MeV. The spectrum, reported in Fig. 7, still shows an enhancement about 20 MeV/c but less evident than the one seen in the decay of the state at 6.15 MeV. The best agreement with the simulation is obtained with (64±7)% contribution from the direct three-body decay, (30±4)% from the true sequential and (6±2)% contribution from the ^{2}He decay modes. This finding suggests the probability,

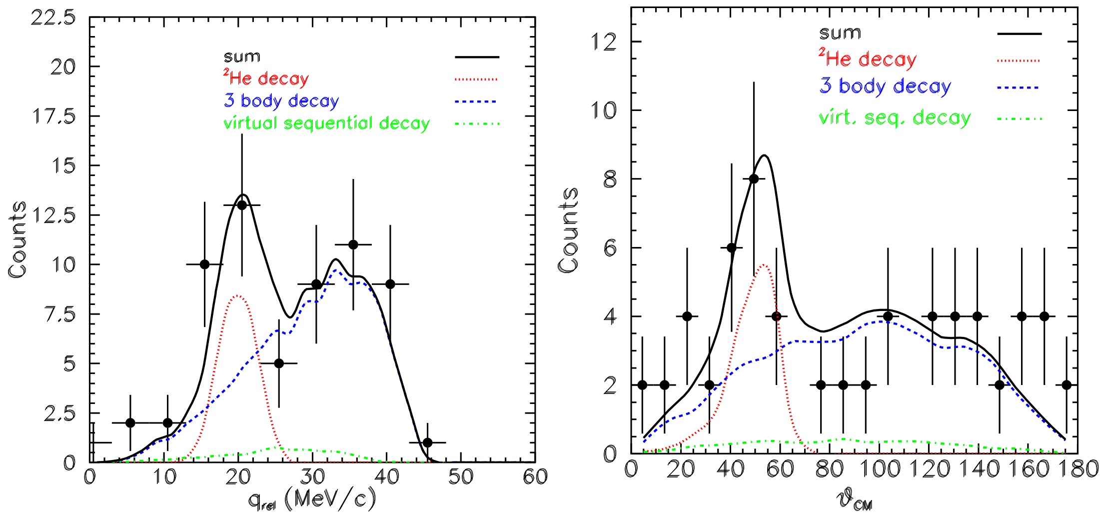

Fig. 6: Relative momentum (left) and relative angle (right) spectra, in the ^{16}O+2p CM system, of the two protons emitted from the 6.15 MeV level, compared to Monte Carlo simulations.

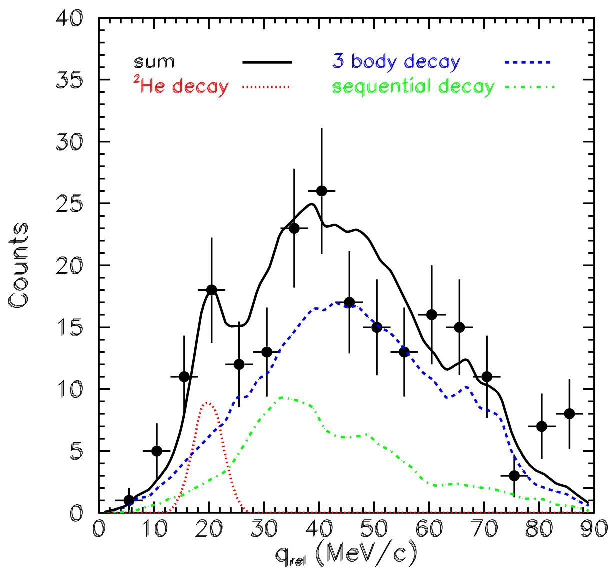

Fig. 7: Two-proton relative-momentum spectrum for the ^{16}O+2p events with E*>6.5 MeV.

although small, that high-lying levels of ^{18}Ne could decay by correlated 2p emission, despite the fact that the sequential branch is widely open. Unfortunately lack of statistics prevents a precise analysis of the 2p decay of each of the high-lying levels.

5 Conclusions

In a recent experiment performed at the Laboratori Nazionali del Sud, the 2p emission from excited states of ^{18}Ne produced by projectile fragmentation with the FRIBs facility, was investigated. Levels of ^{18}Ne were populated by Coulomb excitation reactions on a thick ^{nat}Pb target. The excitation energy spectrum of ^{18}Ne was cinematically reconstructed from the fully measured ^{17}F+p and ^{16}O+2p events. The presence of the 6.15 MeV (1^-) peak in the ^{16}O+2p energy spectrum confirms the already observed two-protons decay of such level. In addition to the known level of ^{18}Ne we report three new excited levels at 10.7 MeV, 12.5 MeV and 13.7 MeV for which we propose 1^- or 2^+ spin assignment. The

analysis of the relative momentum and angle of the two protons in excitation energy window 5.9<E*<6.5 MeV indicates the presence of 31% diproton and 69% democratic or virtual sequential decay mechanism contributions to the 2p emission.
The same analysis applied to the high-lying levels of ^{18}Ne shows that the two-proton decay of such states seems to proceed predominantly via a democratic or true sequential decay mechanism.

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