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^{2}He Decay from ^{18}Ne Excited States: Status and Perspectives

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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 MeV/u 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%).

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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. 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. 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]).
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 experiment performed at LNS was 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) [13] and populated via Coulomb excitation on a ^{nat}Pb target. This decay is very promising 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-left. The results of the present experiment [14] 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 at the exit of the fragment separator. The secondary beam consists on a mixture of nuclear species (see Fig. 1) 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. 1). The Si-Strip tagging detector is set upstream the target at a distance of about 1 cm.

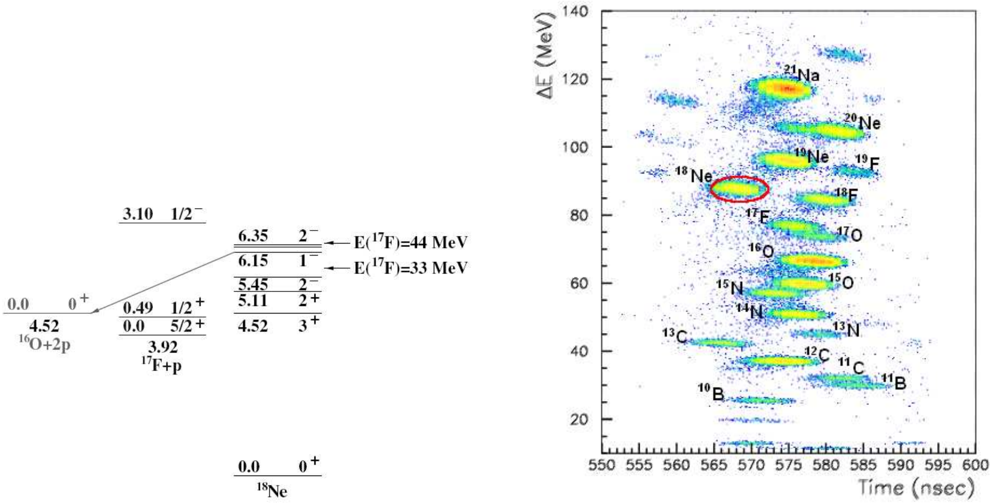

Figure 1: Left: ^{18}Ne decay scheme. Right: Energy-loss in the Si-Strip detector versus ToF.

The detection system consisted on two Si-CsI hodoscopes with different granularity:

- 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 whole array covers 0.34 sr of the forward solid angle, including zero degree, with a geometrical efficiency of 72%. The device allows to simultaneously detect heavy- and light-decay products and its high granularity is suitable for momentum and angular correlation.

3. The ^{18}Ne two-proton decay

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. 1. The incident energy on the reaction target was in the range of 33±1.2 AMeV as evaluated from the energy loss in the Si-Strip.
The excitation energy spectrum of the ^{18}Ne was obtained from a kinematics reconstruction procedure. 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 total kinetics energy was then calculated in the center of mass system and by adding the Q-value of the decay the excitation energy was obtained. In Fig. 2 the excitation energy spectrum of the ^{18}Ne is shown from both the ^{17}F+p and ^{16}O+2p fully measured events produced by the selected ^{18}Ne secondary beam.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 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 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

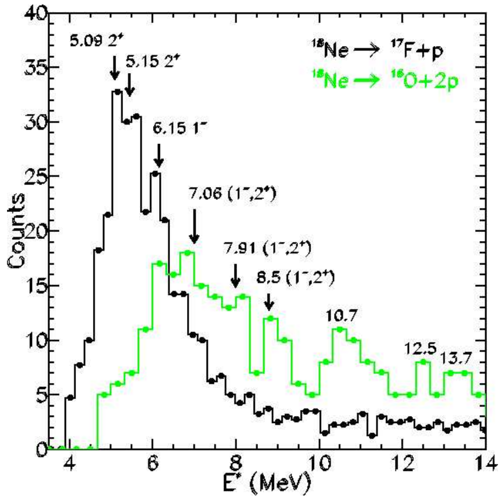

Figure 2: Excitation energy spectrum of ^{18}Ne extracted from ^{16}O+2p events and from ^{17}F+p events (scaled by a factor 4). The levels values are from Ref. [15].

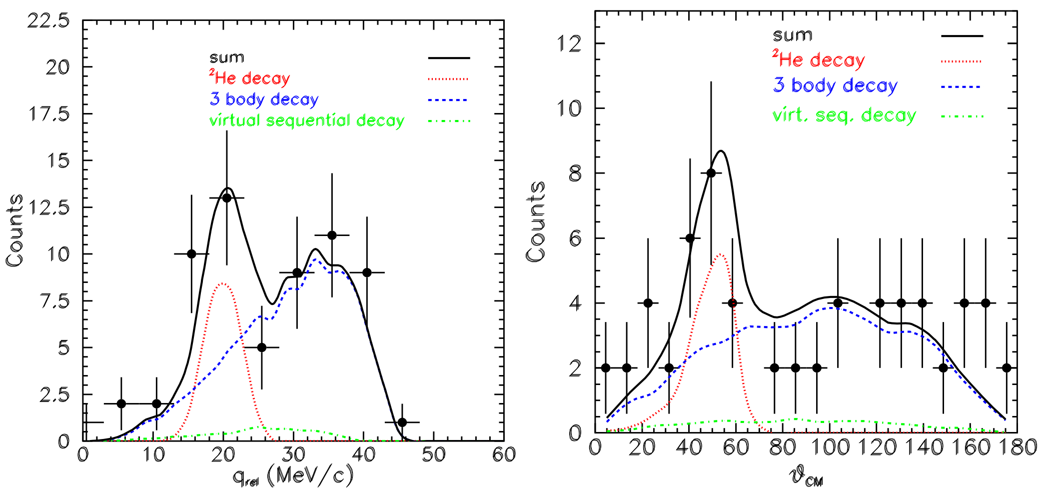

Figure 3: Relative momentum (left) and relative angle (right) spectra, in the ^{16}O+2p CM system, of the two protons emitted from the 6.15 MeV level, compared to Monte Carlo simulations.

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.

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. 3). 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 [14]. 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. 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.
The possibility that other high-lying levels of ^{18}Ne could decay by correlated 2p emission was also explored but lack of statistics prevents a final conclusion.

4. 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.

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