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Search for $2p$ decay of the first excited state of ^{17}Ne

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Abstract

Structure of nuclei located near and beyond the drip-lines plays important role in the explosive astrophysical processes. The problem of two-proton decay of the ^{17}Ne first excited state is a good example of such situation. The two-proton radiative capture is a possible bypass of the ^{15}O waiting point in the rp-process. The rate of this process drastically depends on the value of the weak $2p$-decay branch which is anticipated for the first excited state of ^{17}Ne. The first excited state of ^{17}Ne ($J^{\pi} = 3/2^{-}$), located only 344 keV above the $2p$ decay threshold, has extremely small $\Gamma_{2p}/\Gamma_{\gamma}$ branching ratio for which only upper limit was obtained experimentally. In the recent experiment at the ACCULINNA fragment-separator at the $2p$ decay of the low-lying states of ^{17}Ne was studied. The use of the $p(^{18}Ne, d)^{17}Ne$ transfer reaction in combination with a novel combined-mass method allow us to set a new limit for the decay ratio of the ^{17}Ne $3/2^{-}$ state, $\Gamma_{2p}/\Gamma_{\gamma} \leq 0.016(3)\%$, that is about fifty times lesser than the existing value. The proposed method is promising tool to search for $2p$-decay partial width at a level of $\Gamma_{2p}/\Gamma_{\gamma} \approx 10^{-6}$.

1. Introduction

The ^{17}Ne nucleus is located on the proton dripline, and it is relatively loosely bound with respect to the $2p$ breakup ($E_b = 944$ keV, see Fig. 1). There are several physical problems

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connected with this nucleus which are actually tightly interwoven. However, multiple efforts to investigate it, both theoretically and experimentally, still have not provided convincing clarity about this point. The $2p$ halo predicted for the ground state of ^{17}Ne and the true $2p$-decay branch assumed for its first excited state rise interest to different aspects of its nuclear structure. We don't touch upon here the issue of the ^{17}Ne $2p$ halo structure which was discussed in the theory [1–3] and the experimental [4, 5] works. The $2p$-decay energy of the first excited state in ^{17}Ne is small: $E_T = -S_{2p}(^{17}Ne) = 344$ keV. This state belongs to the class of the so-called true $2p$-emitters [6]. The true $2p$ decay from the ground state was observed for many nuclei lying close to the proton drip line, while the ^{17}Ne is only known nuclide where this decay can take place from the excited state. This point explains the considerable interest appearing for nuclear theory to the study of the $2p$-decay branch which is assumed for this excited state of ^{17}Ne.

Experimental observation of $2p$-emission from the first excited state of ^{17}Ne is complicated by concurrent channel of γ-decay which partial width is drastically greater one for $2p$-decay. That make branching ratio of $\Gamma_{2p}/\Gamma_\gamma$ extremely small. Up to now only an upper limit of $\Gamma_{2p}/\Gamma_\gamma \leq 7.7 \times 10^{-3}$ is experimentally achieved [7]. In the Same time theoretical estimates of $2p$-decay partial width provide the value for $\Gamma_{2p}/\Gamma_\gamma$ about $(0.9 - 2.5) \times 10^{-6}$ [8].

Problem of the observation of $2p$-emission from the $3/2^-$ state of ^{17}Ne has important astrophysical application. The ^{15}O nucleus is a "waiting point" in the astrophysical rp-process as its half-life $T_{1/2} = 122.24$ s is comparable to the timescale of the typical rp-process scenarios. The radiative $2p$-capture is known to be a possible bypath for this waiting point [9]. *Resonant* particle radiative capture reaction rate of the selected resonant state at temperature T is proportional to

$$\langle\sigma_{\mathrm{part},\gamma}\rangle(T) \sim \frac{1}{T^{3n/2}} \exp\left(-\frac{E_r}{kT}\right) \frac{\Gamma_\gamma \Gamma_{\mathrm{part}}}{\Gamma_{\mathrm{tot}}}, \tag{1}$$

where E_r is the resonance position, Γ_γ and Γ_{part} are partial widths of the resonance E_r into gamma and particle channels [10]. So far unknown $2p$-decay width of the first excited state of ^{17}Ne ($E^* = 1288$ keV, $J^\pi = 3/2^-$) makes a key point for solving the bypass problem of the ^{15}O waiting point. Taking into account this (previously omitted) state in the calculation of the *resonant* radiative capture rate strongly modified the corresponding rate in a broad temperature range around 0.15 GK [11]. This modification is as large as $3 - 8$ orders of magnitude, where the variation corresponds to the uncertainty in $2p$ width of the 1.288 MeV $3/2^-$ state predicted in theory works [8, 11].

We can formulate following complex the ^{17}Ne problem of first excited state: the covering of the gap between experimental limit and theoretical predictions for the

$\Gamma_{2p}/\Gamma_{\gamma}$ branching ratio as an "intermediate stage", and experimental observation of the first excited state $2p$-decay as a "final goal".

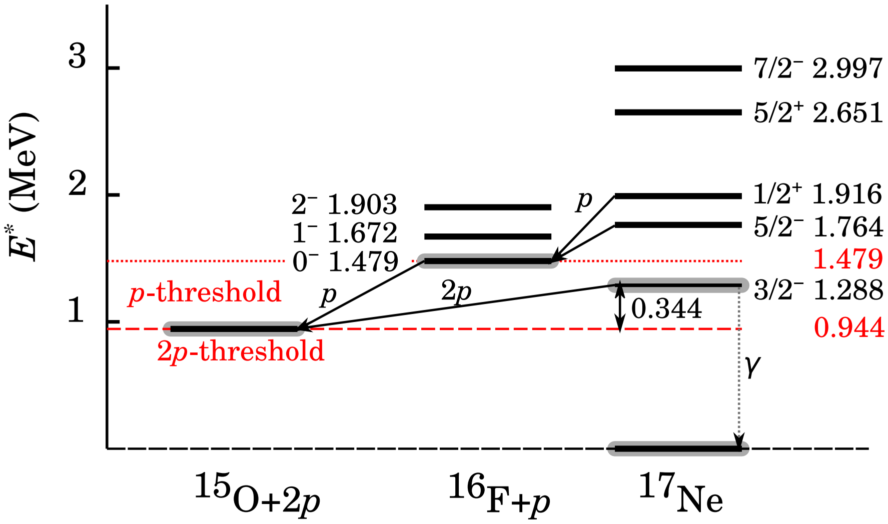

Figure 1: The level schemes for ^{17}Ne, its one-proton subsystem ^{16}F, and decay scheme for ^{17}Ne states.

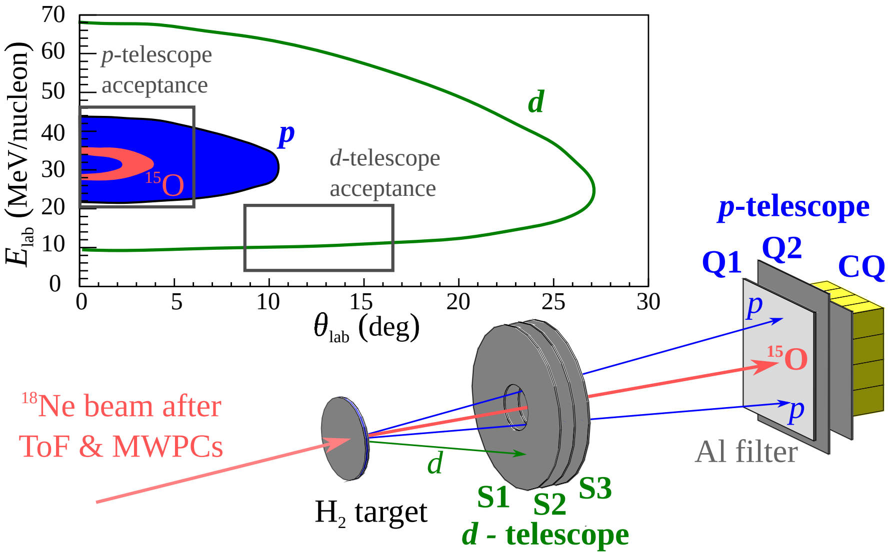

Figure 2: The experimental setup and kinematic plot for the reaction products.

2. Experiment

For experimental search of such rare events as the ^{17}Ne first excited state $2p$-decay one should solve two general problems. The first one is the accumulation of enough statistics for the event of interest observation. The second problem is the separation of the $2p$-decay events of the interested $3/2^-$ state from other excited states located above which are also decaying by $2p$-emission. One can see on Figure 1 that above first excited state with $J^\pi = 3/2^-$ there are other excited states decaying by $2p$-emission.

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Having only few events from state of interest we can separate them only in *inclusive* spectrum. There are two ways to reduce background in the inclusive spectrum: (a) reduce the population of states located above and (b) improve energy resolution.

We performed a dedicated search for the $2p$-decay branch of the first excited $3/2^-$ state of ^{17}Ne [12]. In comparison with work [7] two methodological improvement were applied. The neutron transfer reaction ^{1}H(^{18}Ne,d)^{17}Ne which was used to populate $3/2^-$ state which provides significant background suppression from highly excited states and using of original experimental approach of "combined mass" method. The "combined mass" method is based on *combination* of the missing mass method and invariant mass method. In this approach recoil particle (the deuteron in our case) and the light fragment of the decay (protons) are detected. Obtaining center of mass momentum of the decaying nucleus from the recoil particle and momenta of light decay products allow one to reconstruct decay energy with relative good precision. This pick of detected particles provides several advantages: (a) one obtains full kinematic of the reaction, (b) the detection of deuteron provides information about population of the excited states of 17Ne (including bound states) in the reaction, (c) the detected particles can be easily separated from the beam that significantly reduce the detectors counting rate, and (d) in some kinematics condition (see [12] for details) the "combined mass" method provides relative good energy resolution even for setup with thick targets.

Above explained approach allowed us to maximize luminosity and to keep the resolution at appropriate level (~ 500 keV) in the presented experiment. Figure 2 shows a schematic drawing of the detector setup. The annular telescope (d-telescope on Figure 2) detected the recoil deuterons from the $^1H(^{18}Ne,d)$ reaction. The telescope consisted of three position sensitive Si detectors with an inner (outer) radius of the sensitive area of 16 (41) mm and a thickness of 1 mm each. Particle identification was performed by standard $\Delta E - E$ analysis. Signals from any sector of the S1 detector triggered the data acquisition system. Another telescope located on the beam axis (p-telescope) was intended for the detection of protons from the $^{17}Ne^* \rightarrow {}^{15}O + 2p$ decay. The telescope consisted of two square 6×6 cm^2, 1 mm thick silicon detectors (Q1 and Q2). Following the pair of Si detectors installed was a wall of 16 CsI(Tl) crystals with PMT readout (CQ). To ensure the normal working conditions for the detectors a 1.4 mm thick aluminum filter was installed directly in front of the telescope. This was enough to stop all the nuclei making the beam cocktail while the protons from the decay of $^{17}Ne^*$ lost only a small part of their energy in the aluminum filter. Data presented in the experiment were collected in experiments carried out with Experimental data were collected using a secondary beam of total intensity of 2×10^5 pps at the target plane. The ^{18}Ne ions comprised about 18% of beam cocktail.

3. Width ratio evaluation

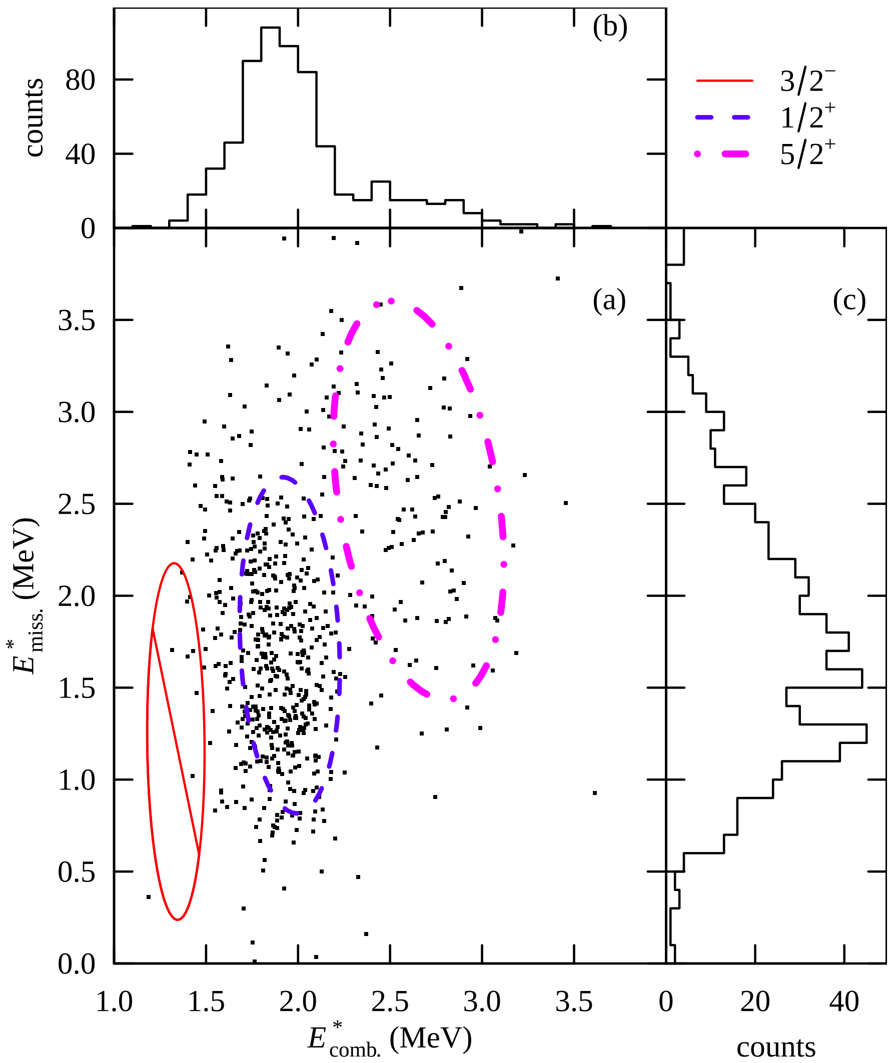

Figure 3: (color online) Excitation energy spectrum of ^{17}Ne: (a) Scatter plot showing the excitation energy of ^{17}Ne measured by the missing mass method ($E^*_{\text{miss.}}$) versus the energy obtained by the combined mass method ($E^*_{\text{comb.}}$). The ellipses shown by solid red, dashed blue, and dash-dotted magenta curves correspond to the loci where the observation of 68% of events for the $3/2^-$, $1/2^+$, and $5/2^+$ states, respectively, is expected, (b) combined mass spectrum, (c) missing mass spectrum.

Figures 3b and 3c show excitation energy spectra from the triple $d-p-p$ coincidences associated with decay of ^{17}Ne excited states obtained by the “combined mass” method and the missing mass method, respectively. One can see a peak of $1/2^+$ state which dominates in both spectra. In the missing mass spectrum the location of $3/2^-$ state is fully overlapped by $1/2^+$ peak tails. In the “combined mass” spectra due to better resolution only several events fall into location of $3/2^-$ state. To clarify the source of

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this event (decay of the $3/2^-$ state or $1/2^+-$ state) the correlation plot in Figure 3a was derived from the data. The solid red ellipse corresponds to locus where 68% of events from $3/2^-$ decay are concentrated. One can see eight events in this locus, however, all of these events are located in the top-right part of the ellipse and no one in the bottom-left. Note that the events from the $3/2^-$ state should come upon both parts of the locus with approximately equal probabilities. Therefore most feasible source of this events is decay of $1/2^+-$ state and no events which could be associated with $2p$-decay from $3/2^-$ state were observed. Thus, we can only claim new limit for $\Gamma_{2p}/\Gamma_\gamma$ ratio.

The $\Gamma_{2p}/\Gamma_\gamma$ value can be evaluated by the following equation

$$\frac{\Gamma_{2p}}{\Gamma_\gamma} = \frac{N_{2p}}{\varepsilon_{2p} N}. \tag{2}$$

Having number of $2p$-coincidences $N_{2p} < 1$, number of events with population of $3/2^-$ $N = 38(6) \times 10^3$, and probability that $2p$-decay event is observed at bottom-left part of the locus $\varepsilon_{2p} = 0.16$ one get limit for the ratio of $\Gamma_{2p}/\Gamma_\gamma < 1.6(3) \times 10^{-4}$.

4. Summary

A dedicated search for the $2p$ decay branch of the first excited $3/2^-$ state of ^{17}Ne populated in the $^1H(^{18}Ne, d)^{17}Ne$ was performed. Based on the experimental data the new upper limit $\Gamma_{2p}/\Gamma_\gamma \leq 1.6(3) \times 10^{-4}$ is established. This significantly (about a factor of 50) reduces the value of the limit defined in the previous work [7]. The strong improvement of the $\Gamma_{2p}/\Gamma_\gamma$ limit was achieved due to the choice of the transfer reaction used as a tool to populate excited states of $^{17}Ne^*$ and application of the novel "combined mass" method for the reconstruction of the ^{17}Ne excitation spectrum. The latter allowed us to improve significantly the instrumental resolution in the measurements made with the thick target. The measured limit for the rate value rules out the predictions made for the $2p$ decay width of the ^{17}Ne first excited state by the simplified di-proton decay model [13], but it is still insufficient to be restrictive for the realistic theoretical predictions [8].

We see prospects for a considerable (by 1-2 orders of magnitude) reduction of the $\Gamma_{2p}/\Gamma_\gamma$ upper limit in the proposed experimental method without revolutionary modification of the setup. Such improvements open a way to the direct experimental observation of the true, radioactive $2p$-decay of the ^{17}Ne $3/2^-$ state taking the theoretically predicted ratio of $\Gamma_{2p}/\Gamma_\gamma \sim (0.9 - 2.5) \times 10^{-6}$ as a trusted aim.

There is a general issue of the development of methods applicable to the studies of weak particle (alpha, proton, or two-proton) decay branches of excited states which reside well below the Coulomb barrier and thus have extremely small $\Gamma_{\text{part}}/\Gamma_\gamma$ ratios.

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The possibility to derive directly such weak decay branches in one experiment makes promising the application of the proposed approach to the problems of nuclear astrophysics, in particular to problem of the explosive hydrogen burning.

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