Two-Proton Decay Experiments at MSU

M. Thoennessen, M. J. Chromik* and P. G. Thirolf*

National Superconducting Cyclotron Laboratory and
Department of Physics & Astronomy, Michigan State University
East Lansing, MI 48824, USA

Abstract. First evidence for direct two-proton radioactivity has been observed in the decay of the first excited state of $^{17}$Ne. The decay is in competition with the $\gamma$-decay back to the ground state of $^{17}$Ne and from the branching ratio the lifetime for the two-proton decay is estimated to be 0.9 ps. The proton-proton angular distribution is statistically not significant to observe any correlations. The first excited state was populated with relativistic Coulomb excitation of the exotic beam of $^{17}$Ne. This method can also be used to study the inverse reaction (2p,$\gamma$). Although the present reaction $^{15}$O(2p,$\gamma$)$^{17}$Ne is not important for astrophysical purposes two-proton capture reactions on heavier proton rich nuclei can have a large impact on the path of the rp-process.

INTRODUCTION

So far all experimental attempts to identify two-proton radioactivity at or near the proton dripline have been unsuccessful (e.g. [1]). Two different experimental approaches have been pursued to search for two-proton decay. In medium mass nuclei where the predicted lifetimes can be on the order of nanoseconds or longer [2,3] the exotic isotopes are produced in fragmentation reactions and then implanted in a detector array where the time correlated decay is observed. The most recent successful observation of $^{48}$Ni offers the opportunity to search for two-proton emission in this doubly magic nucleus [4,5]. In the lighter mass region the Coulomb and centrifugal barriers are much smaller and the lifetimes are significantly shorter. These nuclei can be studied by kinematic reconstruction of the decay products (daughter and two protons) following the decay in flight. Again, the exotic isotopes of interest are produced in high-energy fragmentation reactions [1]. $^{12}$O was the first candidate studied at MSU. An upper limit of 7% for correlated two-proton emission was determined and the dominant decay process was the sequential decay via the broad intermediate ground state of $^{11}$N [1,6-8]. A similar situation is expected for the next heavier candidate $^{16}$Ne, where the decay most likely proceeds via the broad ground state of $^{15}$F. However, another promising candidate is $^{17}$Ne, where the first excited state ($J^+ = 3/2^-$, $E^* = 1.288$ MeV) is bound by 168 keV with respect to one-proton emission but unbound with respect to two-proton emission by 344 keV (for details see [9]). Therefore this state can decay via a simultaneous emission of two protons to $^{15}$O, because the widths of the low-lying states in $^{16}$F are too small ($\sim$ 40 keV) for a sequential decay through their tails. The two-proton decay is in competition with the

*Present address: Luwig Maximilian Universität München , D-85748 Garching, Germany

γ-decay to the ground state of $^{17}\text{Ne}$. In a recent intermediate energy Coulomb excitation experiment the γ-decay from the first excited state to the ground state ($J^\pi = 1/2^-$) has been measured and the experimental yield has been compared to the theoretically expected cross section. The measured γ-ray yield accounts for only 43% of the predicted one, thus encouraging the investigation of a potential two-proton decay branch [9]. Intermediate energy or relativistic Coulomb excitation (as for example $^{17}\text{Ne}(\gamma,2p)^{15}\text{O}$) is not only suitable to study the two-proton decay, it is also useful to measure reaction rates for the inverse process. The inverse reaction $^{15}\text{O}(2p,\gamma)^{17}\text{Ne}$ has been suggested as a possible breakout reaction of the hot CNO cycle [10]. The detailed level structure can have a significant influence on the reaction rates.

In the following we will discuss the latest results of the two-proton decay experiment, followed by reaction rate calculations based on the measured level structure of $^{17}\text{Ne}$ and future possible experiments in heavier nuclei relevant for the astrophysical rp-process.

**THE $^{17}\text{Ne}(\gamma,2p)^{15}\text{O}$ REACTION**

The experiment to search for the two-proton decay of $^{17}\text{Ne}$ was performed at the National Superconducting Cyclotron Laboratory at Michigan State University. A 60 MeV/u radioactive $^{17}\text{Ne}$ beam was produced from a primary $^{20}\text{Ne}$ beam using the A1200 fragment separator. A Wien filter was used to further purify the secondary beam and a 90% pure beam with an intensity of ~5000 $^{17}\text{Ne}$ particles/s was achieved. In order to identify the two-proton decay from the first excited state in $^{17}\text{Ne}$ a complete reconstruction of the decay kinematics in the center-of-mass system (CM) was necessary. Thus the interaction point on the target as well as the energies and directions of all outgoing decay particles were measured. Details of the experimental setup can be found elsewhere [11,12].

The invariant mass and thus the excitation energy spectrum of $^{17}\text{Ne}$ was reconstructed from the energies and angles of the outgoing two protons and $^{15}\text{O}$. The bottom part of Figure 1 shows the data together with fits from simulations that include in addition to the first excited state also high lying states.
which decay sequentially via intermediate states in $^{17}$F. The partial level scheme and possible decay paths are indicated in the upper panel of the figure. Note that the decay energy is measured relative to the $^{15}$O$_p$ separation energy, whereas the indicated peaks correspond to the excitation energy of $^{17}$Ne. The lowest peak at a decay energy of 340±40$^{\text{stat}}$ ±50$^{\text{syst}}$ keV [13] corresponds to an excitation energy of 1284 keV in $^{17}$Ne. This agrees within the uncertainties with the first excited state of $^{17}$Ne at 1288 keV [14,15] and is first evidence for simultaneous two-proton decay of this state in $^{17}$Ne. The peaks at higher decay/excitation energies also correspond to known states in $^{17}$Ne [14,15]. The energy resolution is on the order of 250 keV, mainly dominated by the error in the determination of the interaction point on the target.

Thus it was not possible to resolve the doublets around 1.9 MeV and 2.7 MeV in $^{17}$Ne. Figure 2 shows the angular distributions of the two protons with respect to each other. The simulations include the experimental efficiencies and acceptances. The statistics for the most interesting first excited state is very limited and it is not possible to draw conclusions about any correlations. However, there is no evidence for highly correlated di-proton emission or emission from opposite sides of the fragment. For comparison simulations for simultaneous correlated and simultaneous uncorrelated emissions are also shown. A recent experiment to improve the statistics for the angular distribution was performed and is currently being analyzed [16]. From the calculated excitation cross section and the measured $\gamma$-decay branch it is possible to extract the lifetime for the two-proton decay. In the $\gamma$-ray experiment only 43% of the excitation cross section was detected for the $\gamma$-decay branch [9]. However, attributing all of the missing strength to two-proton decay would result in a lifetime of $\tau_{2p} = 0.08$ ps. This would be substantially faster than estimates of ~360 ps for the barrier penetration of a diproton. From the $\gamma$-ray yield and the number of presently observed two-proton events from the first excited state the branching ratio $\Gamma_\gamma \Gamma_{2p}$ is approximately 7.5. This translates into a 6% decay branch for the two-proton decay. Thus the two-proton yield does not account for all of the missing excitation to the first excited state. Although secondary excitations to higher excited states could account for the remainder of the missing strength, it seems most likely that the B(E2)-value is
overpredicted by the shell model calculations. The branching ratio of $\Gamma_\gamma/\Gamma_{2p} \sim 7.5$ corresponds to a two-proton lifetime of $\tau_{2p} = 0.9$ ps, which is still longer than the barrier penetration calculations. These calculations assumed the emission of a $l = 2$ di-proton. However, it is conceivable that there is a sizable fraction of $d_{5/2} s_{1/2}$ contribution to the $3/2^+$ first excited state of $^{17}$Ne which would reduce the barrier significantly. For example, the barrier for an $l = 0$ transition is reduced by a factor of $\sim 40$ compared to an $l = 2$ transition. However, detailed three-body model calculations are necessary to calculate the lifetime for the two-proton decay from a $d_{5/2} s_{1/2}$ configuration. This reduction, in connection with the possible halo configuration which has been suggested [17], and the uncertainty of 50 keV in the mass of $^{17}$Ne [18] can result in lifetimes on the order of picoseconds which would be consistent with the present experiment.

**THE $^{15}$O($2p,\gamma)^{17}$NE REACTION**

The measurement of the $^{17}$Ne($\gamma,2p)^{15}$O reaction can also be an interesting tool to study the inverse reaction $^{15}$O($2p,\gamma)^{17}$Ne, which could have important implications for astrophysical processes. This reaction in particular has been pointed out to be a possible break-out reaction from the hot CNO cycle [10]. The solid and dot-dashed lines of figure 3 show the calculated reaction rates (left) and the regions where different processes dominate as a function of density and temperature (right). The hot CNO cycle proceeds through $^{15}$O via $\beta$-decay to $^{15}$N. At temperatures and densities above the $\beta = (\alpha,\gamma)$ line the reaction $^{15}$O($\alpha,\gamma)^{19}$Ne begins to dominate and serves as a break-out from the cycle (dot-dashed). Only at very high (unrealistic) densities begins the $^{15}$O($2p,\gamma)^{17}$Ne reaction to dominate. Thus the two-proton capture reaction is not an important reaction for the astrophysical network calculations.

![FIGURE 3](image-url)
These calculations were based on levels in $^{17}\text{Ne}$ deduced from the mirror nucleus $^{17}\text{N}$ [10]. The recent measurement of $^{17}\text{Ne}$ levels found a level inversion of the $5/2^-$ and $1/2^+$ level in $^{17}\text{Ne}$ compared to $^{17}\text{N}$ as shown in Figure 4 [15]. Including this level inversion in the reaction rate calculations result in a large increase of the $2p$ proton capture reaction at low temperatures as shown as the dashed curve in the left part of Figure 3. However, although it also reduced the boundary between the $(\alpha,\gamma)$ and the $(2p,\gamma)$ reactions in these temperature region to lower densities, it is still not sufficient to make a significant contribution to the breakout. The break-out of the hot CNO cycle is still dominated by the $(\alpha,\gamma)$ reaction.

Although in this particular case the detailed structure had no influence on the network calculations this example was meant to demonstrate that even small changes of individual levels can have a large influence on reaction cross sections.

Two-proton capture reactions are predicted to have a significant impact in the medium mass region of the rp-process [19]. For example $^{68}\text{Se}$ is a waiting point of the rp-process which can be bypassed via the reaction $^{68}\text{Se}(2p,\gamma)^{70}\text{Kr}$. Coulomb excitation reaction like $^{17}\text{Ne}(\gamma,2p)^{15}\text{O}$ discussed above can give important information for the inverse reaction. Thus measuring $^{70}\text{Kr}(\gamma,2p)^{68}\text{Se}$ would be an important reaction which should be feasible with the next generation radioactive beam facilities. Of course the mass (and structure of excited levels) of the intermediate (unbound) nucleus $^{69}\text{Br}$ is also important and can be studied with the reaction $^{9}\text{Be}(^{70}\text{Br},^{69}\text{Br})$ similar to the methods used to study $^{12}\text{O}$ and $^{11}\text{N}$ [1,7,8].
CONCLUSIONS

In conclusion, we observed evidence for two-proton radioactivity of the first excited state in $^{17}\text{Ne}$. The preliminary lifetime of 0.9 ps indicates a significant contribution of $d_{5/2}$ $s_{1/2}$ configuration of the $3/2^-$ state. The angular distribution of the two protons in the decay is statistical not significant to make definite conclusions, although it does not seem to be strongly correlated (diproton) nor strongly anti-correlated (two protons on the opposite site of the fragment). Using an improved experimental setup with optimized efficiency and energy resolution will help to clarify the remaining uncertainties in the context of the reported first evidence for two-proton radioactivity. In addition, it has been shown that relativistic (or intermediate) energy Coulomb excitation of exotic nuclei along the proton dripline can be important for astrophysical processes. The ground state contribution to two proton capture reactions can be deduced from the inverse Coulomb excitation reaction.

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