Excitation and decay of the first excited state of ^{17}Ne

M. J. Chromik, B. A. Brown, M. Fauerbach, T. Glasmacher, R. Ibbotson, H. Scheit, and M. Thoennessen

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

P. G. Thirolf

Ludwig-Maximilian Universität München, D-85748 Garching, Germany

The first excited state of ^{17}Ne has been populated via relativistic Coulomb excitation with a radioactive beam of ^{17}Ne on a ^{197}Au target and the subsequent γ-ray decay has been observed. This $\frac{3}{2}^-$ state is bound with respect to proton emission but unbound to two-proton decay. The measured γ-ray yield accounts for $43^{+19}_{-14}\%$ of the predicted yield from an excitation cross section of 28 mb. It is unlikely that the missing cross section can be attributed to two-proton emission because the lifetime of this branch would have to be a factor 1700 smaller than predicted by standard barrier penetration calculations. [S0556-2813(97)00904-7]

I. INTRODUCTION

The search for diproton (^{2}He) radioactivity has still not been successful [1,2] although it has been predicted over 30 years ago [3]. In nuclei along the proton dripline ($Z > 20$) where large Coulomb and angular momentum barriers are present, relatively long lifetimes ($\sim$ milliseconds) can be expected [4,5] which can be measured with standard techniques [1]. In lighter nuclei, where the lifetimes can be extremely short, the observation of two-proton emission has to be determined from complete kinematical reconstruction of the decay products [2]. Neither method has yielded any evidence for the existence of correlated diproton emission.

So far all measured two-proton decays, for example β-delayed two-proton emission [1,6] or the breakup of ^{6}Be [7] and ^{12}O [2] were sequential. In these cases an intermediate state exists through which the decay could proceed. Thus it seems essential for the observation of diproton emission that no intermediate states are energetically open for the sequential decay.

It was recently noticed [8] that the first excited state of ^{17}Ne is bound with respect to one-proton emission to ^{16}F but unbound with respect to two-proton emission to ^{15}O. Thus this state is a potential candidate for diproton emission. However, this decay mode has to compete with γ-ray decay back to the ground state of ^{17}Ne. Figure 1 shows the decay scheme including the low lying states of ^{17}Ne and ^{16}F [9–11]. The energies of the excited states of ^{17}Ne were recently measured by Guimarães *et al.* [11] using the ^{20}Ne(^{3}He, ^{6}He)^{17}Ne transfer reaction. The spins and parity assignments were derived from the mirror nucleus ^{17}N and the isobaric mass multiplet equation [11]. The first excited state was assumed to be $\frac{3}{2}^-$. The ground state of ^{16}F is about 200 keV above ($\Gamma \sim 40$ keV) the $\frac{3}{2}^-$ state in ^{17}Ne [10]. Therefore the uncorrelated sequential emission of protons through the tail of the wave function of this state is strongly suppressed. The low lying excited states in ^{16}F are also rather narrow ($\Gamma \approx 40$ keV) and should not allow the sequential decay.

A comparison of standard shell model and barrier penetration calculations shows, however, that the γ-decay width is predicted to be substantially larger than the diproton width. The shell-model calculation using the WBP interaction led to an estimated partial decay width of the γ decay of 5.5×10^{-9} MeV corresponding to a lifetime of 1.2×10^{-13} s, which is comparable to the measured lifetime of the mirror state in ^{17}N (0.9×10^{-13} s) [10].

The diproton decay from the $\frac{3}{2}^-$ state in ^{17}Ne to the $\frac{1}{2}^-$ ground state in ^{15}O can proceed only via a pair of sd-shell protons. Assuming a barrier penetration factor starting at $R = 4$ fm, an angular momentum of $2\hbar$ and a Q value of 0.344 MeV leads to a single-particle width of 4.4×10^{-12} MeV. The estimated decay width with a cluster spectroscopic factor [4] of 0.40 is then 1.8×10^{-12} MeV corresponding to a lifetime of 3.7×10^{-10} s.

These estimates could be influenced by the recent predictions that ^{17}Ne is a proton halo nucleus candidate [12] which potentially would increase the diproton decay width. So far, neither the γ ray nor the $2p$ branch from the first excited state have been observed. Thus, in a first experiment we measured the γ decay of the first excited state in ^{17}Ne in order to extract the decay width of this branch.
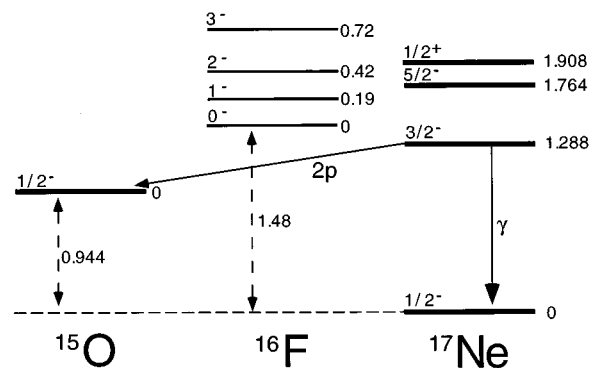

FIG. 1. Level scheme of the low lying states of ^{15}O, ^{16}F, and ^{17}Ne. The energies are given in MeV.
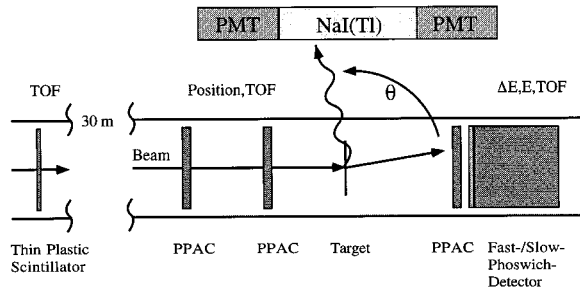
FIG. 2. Schematic diagram of the experimental setup.

II. EXPERIMENTAL PROCEDURE

The present experiment was performed at the National Superconducting Cyclotron Laboratory at Michigan State University using an exotic ^{17}Ne beam and the method of intermediate energy Coulomb excitation to populate the first excited state of ^{17}Ne. The radioactive ^{17}Ne beam was produced in the fragmentation reaction of 100 MeV/nucleon ^{20}Ne on a 790 mg/cm^2 ^{9}Be target. The secondary beam (60 MeV/nucleon) was separated using the A1200 fragment separator [13]. In the second dispersive intermediate focus, an achromatic plastic wedge equivalent to 233 mg/cm^2 Al was used to purify the beam further.

The purity of the ^{17}Ne beam before the secondary target was only 7.5%, with ^{15}O as the dominant contamination (85%). The position of each fragment incident on the secondary target (532.7 mg/cm^2 Au) was measured with two parallel plate avalanche counters (PPAC's). Together with a thin plastic scintillator behind the A1200 focal plane the PPAC's measured also the time of flight (TOF) of secondary beam particles. Fragments scattered into a laboratory angle of 4.05° were detected in a cylindrical fast-plastic–slow-plastic phoswich detector after passing through a third PPAC located in front of the phoswich detector. The energy loss and total energy in the phoswich detector together with the time of flight measurements yielded excellent isotopic resolution and allowed the rejection of events from beam impurities and the breakup reactions of the projectiles in the secondary target. Photons were measured in coincidence with the scattered fragments in an array of 38 position sensitive NaI(Tl) detectors [14]. Figure 2 shows a schematic diagram of the setup. The NaI(Tl) crystals were of cylindrical shape, with a length 18 cm and a diameter of 5.75 cm, enclosed in a 0.45 mm thick aluminum capsule. The detectors were oriented in three concentric rings parallel to the beam direction with a radius of the innermost ring of ≈11 cm. The target was located in the center of the NaI array [15]. Thus the setup covered an angular range in the laboratory frame from 55° to 125°. Since the largest part of the photopeak efficiency of the NaI array was provided by the innermost ring of 11 detectors, the present analysis was restricted to the γ-ray spectra accumulated in these counters.

The energies and positions of the incident photons were reconstructed from the photomultiplier tube signals at each end of the NaI(Tl) crystal. To shield the NaI(Tl) array from photons originating at the fragment detector and from room background, the entire array was surrounded by a 16.6 cm thick layer of low background lead bricks. Time measurements between the detection of the photons in the NaI(Tl)
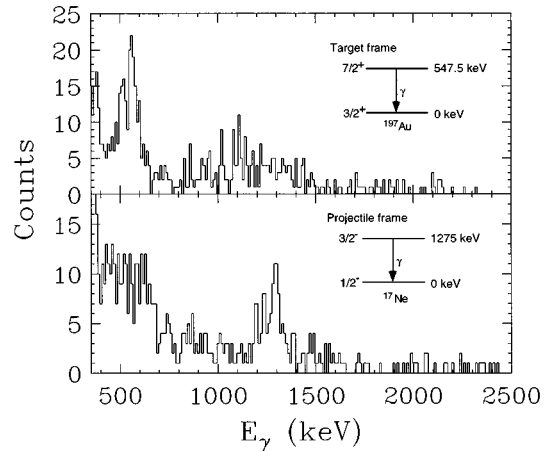

FIG. 3. γ-ray spectra following the reaction ^{17}Ne + ^{197}Au in the target rest frame (top) and the projectile rest frame (bottom).

and the detection of the scattered fragments in the 0° detector were recorded for each event and used to veto in the off-line analysis back-scattered photons from the 0° detector as well as accidental coincidences. A position dependent energy calibration was performed with photon sources of ^{88}Y, ^{152}Eu, and ^{208}Th. The energy resolution was typically 9% at 898 keV. The position resolution was approximately 2 cm, resulting in an angular resolution better than 10° for the emitted photon. This position resolution was essential for the Doppler shift correction. The ^{88}Y and ^{152}Eu sources were also used to measure the energy and position dependent absolute photopeak efficiency $\epsilon_{\rm ph}$. Corrected for isotropic emission, a value of $\epsilon_{\rm ph} = 8.5\%\,(4.6\%)$ could be extracted for 898 keV and 1836 keV, respectively.

III. DATA ANALYSIS AND RESULTS

Figure 3(top) shows the measured γ-ray spectrum in the target rest frame. The 547 keV transition from the $\frac{7}{2}^+$ to the $\frac{3}{2}^+$ ground state in ^{197}Au is present in the spectrum. In the region of 1.3 MeV, where the decay of the first excited state of the ^{17}Ne projectile is expected only a broad enhancement is visible. The same spectrum is shown in Fig. 3(bottom) after the Doppler shift correction into the projectile rest frame ($\beta = 0.317$) was applied. While the transition from the ^{197}Au target broadens, a peak at 1275 ± 22 keV appears. This energy is consistent with the $\frac{3}{2}^-$ state recently observed by Guimarães et al. [11] at 1288 keV. The number of observed decays $N_{\rm obs} = 86 \pm 22$ was determined from a Gaussian fit of the peak where the background was subtracted.

In order to determine the branching ratio for this state, the number of observed γ decays has to be compared with the calculated number of expected γ decays $N_{\rm calc}$ given by

$$N_{\rm calc} = \sigma_{\rm ex} \cdot \epsilon_\gamma \cdot N_T \cdot N_{^{17}{\rm Ne}}. \qquad (1)$$

$\sigma_{\rm ex}$ is the excitation cross section, ϵ_γ the detection efficiency of the array for the specific decay, N_T the number of particles in the target per unit area, and $N_{^{17}{\rm Ne}}$ the number of incident ^{17}Ne detected by the fragment detector.

The calculation of the population only included a Coulomb interaction because the opening angle of the fragment detector ($\theta \leqslant 4.05°$) restricted the distance of closest approach between the target nucleus and the projectile to ~ 20 fm. This distance is ~ 10 fm larger than the nuclear interaction radius [16] so that nuclear excitation was negligible.

The Coulomb excitation cross section was calculated using the method of virtual photons as described by Baur and Bertulani [17]. We used the intermediate energy approximation which takes Rutherford bending into account. The number of virtual $E2$ and $M1$ photons were $n_{E2} = 34\,881$ and $n_{M1} = 20$, respectively. The relativistic description assuming straight line trajectories yields $\sim 5\%$ higher values. The total cross section for the excitation of the $\frac{3}{2}^-$ state is then given by

$$\sigma_{ex} = n_{E2} \cdot \sigma_\gamma^{E2} + n_{M1} \cdot \sigma_\gamma^{M1}, \qquad (2)$$

where $\sigma_\gamma^{\pi\lambda}$ is the photon absorption cross section given by

$$\sigma_\gamma^{\pi\lambda} = \frac{(2\pi)^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2} \sum_f \rho_f(\epsilon) k^{2\lambda-1} B(\pi\lambda). \qquad (3)$$

$\rho_f(\epsilon)$ is the density of states which in the present case is taken to be a δ function at the excitation energy of the $\frac{3}{2}^-$ state.

The $B(E2)$ and $B(M1)$ were calculated using the WBP interaction by Warburton and Brown [18]. The wave functions and harmonic-oscillator $B(E2)$ values are very close to that expected in the weak coupling of the $p_{1/2}$ neutron hole to the ^{18}Ne 0^+ state to form the $\frac{1}{2}^-$ ground state of ^{17}Ne and to the ^{18}Ne 2^+ state to form the excited $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states. The weak-coupling relationship for the $B(E2)$ values is:

$$B(E2,\ ^{18}\text{Ne}, 0^+ \rightarrow 2^+) = B(E2,\ ^{17}\text{Ne}, \tfrac{1}{2}^- \rightarrow \tfrac{3}{2}^-)$$
$$+ B(E2,\ ^{17}\text{Ne}, \tfrac{1}{2}^- \rightarrow \tfrac{5}{2}^-), \quad (4)$$

where the $B(E2)$ to the $\frac{3}{2}^-$ and the $\frac{5}{2}^-$ states are in the ratio 2 to 3. The $\frac{5}{2}^-$ state in ^{17}Ne was measured to be at 1.764 MeV [11] compared to 1.907 MeV in the mirror nucleus ^{17}N [10]. The full shell-model calculations with harmonic-oscillator radial wave functions ($\hbar\omega = 13.35$ MeV) require a proton effective charge of $e_p = 1.67e$ in order to reproduce the experimental $B(E2)$ value for the $0^+ \rightarrow 2^+$ transition in ^{18}Ne, which is $266 \pm 25 e^2$ fm^4 [19]. This model yields a $B(E2)$ of $102\ e^2$ fm^4 and a $B(M1)$ of $0.44\mu^2$ for the transition from the $\frac{1}{2}^-$ ground state to the $\frac{3}{2}^-$ state. The $B(E2)$ for the transition to the $\frac{5}{2}^-$ state is $156\ e^2$ fm^4. Although this $\frac{5}{2}^-$ state is also populated strongly, the γ-decay branch is small and was not observed because the energy of this state is above the one proton binding energy and it will most likely decay by sequential emission of two protons through intermediate states of ^{16}F. For the mirror nucleus ^{17}N we calculate $B(M1) = 0.61\mu^2$ for the $\frac{1}{2}^-$ to $\frac{3}{2}^-$ transition, in reasonable agreement with the experimental value of $0.46 \pm 0.18\mu^2$ [10].

In order to take into account the relatively loose binding of the protons in ^{17}Ne and ^{18}Ne we have repeated the $B(E2)$ calculations with Woods-Saxon radial wave functions [20] with the separation energy of the sd shell protons fixed at their experimental values. For ^{18}Ne we used 3.0 MeV which is the average of the separation energies from the 0^+ and 2^+ states to the ^{17}F ground state, and for ^{17}Ne we used 0.8 MeV which is the average of the separation energies of the $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states in ^{17}Ne to the ground state of ^{16}F. For ^{18}Ne the $B(E2)$ increased from 264 e^2 fm^4 to 317 e^2 fm^4 and for ^{17}Ne the $B(E2)$ increased from 102 e^2 fm^4 to 183 e^2 fm^4. Thus the loose binding gives a $B(E2)$ for ^{17}Ne relative to ^{18}Ne which is 50% larger than that predicted by the weak-coupling and harmonic-oscillator shell-model results, with a final value of $B(E2, {}^{17}\text{Ne}, \frac{1}{2}^- \rightarrow \frac{3}{2}^-) = 153\ e^2$ fm^4. The uncertainty in this value is at least 10% due the uncertainty in the experimental ^{18}Ne $B(E2)$ value. The uncertainty due to the model dependence in the calculation is difficult to estimate but is $\sim 20\%$.

The resulting photoabsorption cross sections are $\sigma_\gamma^{E2} = 7.9 \pm 1.6 \times 10^{-5}$ fm^2 and $\sigma_\gamma^{M1} = 1.95 \times 10^{-3}$ fm^2. Although the $M1$ absorption cross section is larger than the $E2$ absorption cross section, the total excitation cross section of $\sigma_{ex} = 28 \pm 6$ mb is dominated by $E2$ excitation due to the substantially larger number of $E2$ virtual photons. The uncertainty of the number of virtual photons due to the uncertainty of the minimum impact parameter determination from the opening angle of the fragment detector is small (~ 1 mb) compared to the uncertainty of the $B(E2)$.

In order to determine ϵ_γ for the decay of the $\frac{3}{2}^-$ state one has to fold the angular distribution of the transition transformed into the target rest frame with the measured detector photopeak efficiency ϵ_{ph}. The angular distribution of the photons was calculated by including the relative population of the magnetic substates during the excitation extracted from Winther and Alder [21,22]. The corrected photopeak efficiency was $5.4 \pm 0.5\%$ compared to 6.2% for the isotropic radiation. The uncertainty of the influence of the angular distribution can be estimated by calculating the extremes of $\Delta M = 0$ and $\Delta M = 1$, yielding 7.8% and 5.0%, respectively. The decay is dominated by $M1$ rather than $E2$ transitions because of the smaller lifetime for the $M1$ decay. Including these uncertainties the efficiency is $\epsilon_\gamma = 5.4^{+1.5}_{-0.6}\%$.

The total number of detected ^{17}Ne was $N_{^{17}\text{Ne}} = 8.214 \times 10^7$ and the number of target nuclei per unit area was $N_T = 1.63 \times 10^{-5}$ fm^{-2}. The expected number of decays out of the first excited state in ^{17}Ne is then $N_{calc} = 200^{+70}_{-50}$. Thus the number of observed γ transitions $N_{obs} = 86 \pm 22$ accounts for only $43^{+19}_{-14}\%$ of the calculated yield N_{calc}. The uncertainty of N_{obs} is purely statistical, while the uncertainty for the calculated yield includes the uncertainties for the calculated $B(E2)$, the efficiency and the impact parameter cutoff.

IV. DISCUSSION AND CONCLUSION

Before attributing the missing strength to the diproton decay branch, alternative explanations have to be considered and cannot be excluded. Potential contributions from nuclear excitations would only increase the discrepancy. Second-order excitations to higher excited states of ^{17}Ne would reduce the γ-decay probability from the first excited state and subsequently higher excited states would then decay by se-

quential two proton emission through intermediate states of ^{16}F and thus would not decay back to the ground state of ^{17}Ne.

However, if the missing strength decays via diproton emission one can estimate the decay width from the above yields via

$$\Gamma_{2p} = \Gamma_{\text{tot}} - (\Gamma_{M1} + \Gamma_{E2})$$

and assuming that N_{obs} corresponds to the sum of the $M1$ and $E2$ γ-decay branch and N_{calc} to the total width. $\Gamma_{M1} = 5.5 \times 10^{-9}$ MeV and $\Gamma_{E2} = 2.2 \times 10^{-10}$ MeV were derived from the shell-model calculation. The decay width for the diproton decay would then have to be $\Gamma_{2p} = 7.6^{+4.9}_{-3.7} \times 10^{-9}$ MeV, which is substantially larger than the prediction from the barrier penetration calculation of 1.8×10^{-12} MeV. With the indication that ^{17}Ne is a potential proton halo candidate, it is conceivable that the assumptions for the penetration calculation are not valid and could be modified. For example, a cluster spectroscopic factor of 1, would increase the decay width. In addition, the uncertainty of the mass of ^{17}Ne is 50 keV [23], so that the decay energy

could be as large as 394 keV. Even with these modifications the predicted diproton decay width is only 4.7×10^{-11} MeV which is still at least a factor of 80 smaller than the value extracted from the present experiment. Thus it is unlikely that the diproton branch can account for all of the missing strength. However, the possibility that a small diproton branch is present cannot be excluded.

In conclusion, the γ-ray decay of the first excited state of ^{17}Ne ($\frac{3}{2}^-$) was measured by relativistic Coulomb excitation. The γ-ray energy was 1275 ± 22 keV. The number of observed γ decays was only $\sim 43\%$ of the predicted value based on the virtual photon absorption cross section and shell-model calculations. Attributing this strength to the diproton branch is certainly too speculative and a direct search for this decay mode is necessary in order to verify this hypothesis.

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