Half-life Limit of $^{19}$Mg

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A search for $^{19}$Mg was performed using projectile fragmentation of a 150 MeV/nucleon $^{36}$Ar beam. No events of $^{19}$Mg were observed. From the time-of-flight through the fragment separator an upper limit of 22 ns for the half-life of $^{19}$Mg was established.

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I. INTRODUCTION

The search for the di-proton decay predicted over 40 years ago has recently intensified with the observation of two-proton decay from $^{45}$Fe. These experiments extracted the total energy of the decay, but they did not measure the individual proton energies and angles. This information is necessary in order to determine the nature of this decay, whether it is a di-proton ($^2$He) or a three-body decay.

Another promising candidate for di-proton decay is $^{19}$Mg. $^{19}$Mg is predicted to be unbound by 0.9 ± 0.3 MeV with respect to two-proton emission and bound by 0.66 ± 0.5 MeV with respect to one-proton emission, which is the ideal situation for the possibility of di-proton decay. The predictions of the two-proton decay energy are based on extrapolations of the mass tables. Microscopic calculations have predicted that $^{19}$Mg might even be bound depending on the choice of the force used in the calculation. However, recent theoretical work by Grigorenko et al. suggests a half-life that is significantly smaller than the previously mentioned calculation. Although a potentially very interesting nucleus, no dedicated searches for the existence of $^{19}$Mg have been performed so far.

A search for the $T_z = -1$ nuclei $^{23}$Si, $^{27}$S, $^{31}$Ar, and $^{35}$Ca, discussed in Ref., should have observed $^{19}$Mg if it was indeed bound, however, it was not observed and the implications of this are not mentioned. If $^{19}$Mg is unbound, the experimental requirements to study its decay mode depend critically on the expected lifetime. The lifetime is a strong function of the decay energy and the predicted range covers many orders of magnitude.

We started a dedicated search for $^{19}$Mg using projectile fragmentation and extracted a first limit on its lifetime from the time-of-flight through the fragment separator.

II. EXPERIMENTAL PROCEDURE

The experiment was performed at the Coupled Cyclotron Facility (CCF) at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. $^{36}$Ar nuclei were accelerated by the K500×K1200 combination to 150 MeV/nucleon with a charge state of 18$^+$ and bombarded a 689 mg/cm$^2$ thick beryllium production target. The average beam intensity was 4.3 pnA. The fragments of interest were selected with the A1900 fragment separator, shown in Figure 1. A 300-mg/cm$^2$-thick aluminum wedge was placed at the intermediate image and the momentum acceptance was limited to 0.5%. The detectors at the focal plane of the separator consisted of a 470-μm-thick $\Delta E$ silicon detector and a 10 cm thick plastic scintillator. The horizontal position acceptance at the focal plane was limited to 15 mm in order to reduce the background from lighter ions. The fragments were identified by their energy loss in the silicon detector and the time-of-flight measured between the plastic scintillator and a thin scintillator located at the intermediate image. The total length of the A1900 from the production target to the focal plane is 35.5 m.

III. DATA ANALYSIS AND RESULTS

Figure 2 shows the energy loss versus time-of-flight as measured at the focal plane. The $N = 7$ isotones $^{13}$C, $^{14}$N, $^{15}$O, and $^{17}$Ne were clearly identified while no events for $^{19}$Mg were detected. Although contributions from pile-up, incomplete charge collection, and other processes produced counts in the spectrum, the region where $^{19}$Mg is expected is background free. This non-observation confirms that $^{19}$Mg is indeed unbound with respect to proton emission. It could be unbound with respect to one- or two-proton emission, or both.

An upper limit of the half-life can be extracted from
the predicted number of produced $^{19}$Mg and the transmission efficiency, and the time of flight through the A1900 separator.

The fragment production of nuclei along the proton dripline has to be extrapolated from the production of nuclei closer to the line of stability and depends strongly on the reaction model. The most commonly used approaches are the EPAX parameterizations \([11, 12]\) and calculations based on the abrasion-ablation model \([13]\). In order to select the best reaction model for the production of $^{19}$Mg, we tuned the A1900 to maximize the production of $^{20}$Mg, which is particle stable. With the 689-mg/cm$^2$-thick Be target, we measured a rate of 4 pps/pnA of $^{20}$Mg. The simulation program LISE++ \([14, 15]\) predicted rates of 5 pps/pnA, 10 pps/pnA, and 25 pps/pnA employing the EPAX1 \([11]\), EPAX2 \([12]\), and the abrasion-ablation model, respectively. The fragment velocities and momentum distributions were calculated following the parameterization of Morrissey \([16]\). The EPAX1 calculation is within 20% of the measured $^{20}$Mg rates and is the smallest prediction for the production of very proton rich nuclei in this mass region for the given projectile and target combination. Since the prediction by EPAX1 is the smallest of the three approaches, they represent the most conservative approach for extracting the upper limit of the half-life of $^{19}$Mg.

It should be mentioned that $^{36}$Ar is not the optimum choice as a primary beam. A more intense and pure beam of secondary beam of $^{20}$Mg can be produced from a primary beam of $^{24}$Mg \([17]\). However, this beam was not available for the present experiment.

EPAX1 yields a rate of 0.018 pps/pnA of $^{19}$Mg to be transmitted to the focal plane. We collected a total of 15.5 hours of beam on target with an average beam intensity of 4.3 pnA. This would result in 4320 $^{19}$Mg transmitted to the focal plane detectors if it was particle stable.

The total flight path through the separator consists of two parts. In the first half after the production target the average velocity of $^{19}$Mg is calculated to be $v = 0.46 \ c$. The velocity in the second half is reduced to $v = 0.44 \ c$ following the 300 mg/cm$^2$ aluminum wedge. The resulting time of flight is $T_{A1900} = 263$ ns.

The upper limit of the half-life assuming that one $^{19}$Mg has not decayed before reaching the focal plane was calculated using the number of transmitted $^{19}$Mg ($N$) and the total time-of-flight ($T_{A1900}$):$
T_{1/2} < T_{A1900} \frac{\ln 2}{\ln N}.
$

This results in an upper limit of 22 ns for the half-life of $^{19}$Mg. The number of $^{19}$Mg produced as predicted by LISE++ is the largest uncertainty in the preceding equation. However, Figure 3 shows the relationship between the extracted limit on the half-life and the predicted production. The half-life is not strongly influenced by over- or under-predicting the rate of $^{19}$Mg. For instance, an over-prediction of the rate by a factor of 2 results in an upper half-life limit of 20 ns which is a difference of 10%.

The upper half-life limit can be compared to recent three-body calculations \([18, 19]\). In contrast to single proton emitters, where the half-life can be directly related to the decay energy through barrier penetration calculations \([18]\), the situation for two proton emitters is more complicated.

Grigorenko et al. derived the half-life of $^{19}$Mg as a function of decay energy for three-body, di-proton and uncorrelated two-proton decay \([8]\). Figure 4 shows the extracted half-life for the possible decay energies of Descouvemant (<0.5 MeV) \([7]\), Brown (1.1±0.3 MeV) \([10]\), and Audi-Wapstra (0.9±0.3 MeV) \([8]\). The light shaded areas correspond to the limits based on the decay energy uncertainties and the three-body model of Ref. \([8]\), while the dark shaded areas include the limits for the di-proton and uncorrelated two proton decay. The fourth column of Figure 4 shows the half-life predictions from a refined three-body calculation by Grigorenko et al. \([8]\) and the last column is the experimental limit extracted from the present work. The experimental limit is consistent with
the predictions. It rules out that $^{19}$Mg is particle-stable but does not put constraints on the calculations.

A different experimental approach is necessary to search for the di-proton emission of $^{19}$Mg. Simply increasing the production of $^{19}$Mg nuclei by extending the beam time or increasing the beam intensity will not lead to a significant improvement as can be seen in Figure 3. Fragment separators are particularly useful in this type of experiment because the fragmentation products are cleanly separated and identified. In case no events are observed, it is essential that the region where $^{19}$Mg is expected to occur is background free. However, the limit on the half-life is directly proportional to the flight time. Therefore if one assumes that $^{19}$Mg exists before decay on the order of a few ns, an experiment apparatus with a smaller flight time is necessary.

One possibility to reduce the time-of-flight that is currently pursued is the use of single-neutron stripping reactions from a secondary beam of $^{20}$Mg to directly observe the decay [20, 21].

IV. SUMMARY AND CONCLUSIONS

The non-observation of $^{19}$Mg from the fragmentation of $^{36}$Ar confirms the expected particle instability of this potential di-proton emitter. An upper limit of the lifetime of 22 ns was established for the first time. However, this limit is not yet sufficient to constrain the experimental search for the di-proton decay of $^{19}$Mg.

Acknowledgements

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