FRIB PAC1 PROPOSAL
Study of the β-decays of ^{22}Al and ^{26}P

I. Physics Justification

The decay of the nuclei along the proton dripline between Mg and Cl are poorly known. For these exotic nuclei the beta-decay Q-values are typically 15-20 MeV while the 1p, 2p, 3p, and α-separation energies in the daughters are 1-10 MeV. Thus, to fully disentangle these complex decays, low energy beams are needed, which can be gently stopped by thin foils surrounded by large area, segmented Si detectors. Then the final states of 1, 2, or 3 protons in coincidence with gamma-rays and/or beta-particles can be measured and resolved. But the neutron deficient elements between Mg and Cl are difficult, or impossible, to produce at ISOL facilities due to the chemical properties of these elements. Therefore, up to now it has only been possible to produce these isotopes as fast beams. However, by stopping the fast beams in a gas cell it is now possible to make low energy beams of most of these isotopes with unprecedented yields.

Here we propose as a first step to exploit this new opportunity by initiating a study of the β-decays of the two dripline isotopes ^{22}Al and ^{26}P. A proposal was accepted for NSCL, but due to the Covid19 pandemic, this experiment could not be completed before the transition to FRIB was started. At a later stage we are also interested in pursuing measurements of other isotopes along the proton dripline such as ^{22,23}Si, ^{27}S, ^{31}Ar and ^{35}Ca. The physics justification for these cases combines three main themes; one primary and two secondary. **The primary theme** is the exploration of the mechanism by which the nucleus ejects two or three protons in the exotic decay channels open to them due to the high Q-values in the β-decay. The kinematics of these break-ups could carry information about the correlations of the nucleons inside the Coulomb barrier, or in the tunneling process through the barrier. More than 30 years ago B.A. Brown estimated the branching ratio for direct two-proton emission from decay of the isobaric analog state of ^{22}Al in ^{22}Mg to be only a factor of 40 smaller than the already observed sequential emission [Bro1990]. With the new RIB production rates of ^{22}Al, this can now finally be tested. Correlated two-proton emission has until now only been studied in the ground state two-proton emitters ^{6}Be and ^{45}Fe [Bla2008, Pfu2012]. No published beta-decay studies have provided evidence for direct two-proton emission because the production rates have been too low to reach the sensitivity required to find this decay mode at the level it is predicted. As will be explained below, this is now possible with FRIB. For ^{31}Ar the β-delayed 2p and 3p-emission (β2p) have been extensively studied [Fyn2000, Kol2014b], see figure 1 and 2, and shown to take place sequentially through isolated levels in the daughters, which has led to a new way of studying decay properties of resonances populated after βp [Fyn2000, Kol2013]. Note, these studies at CERN-ISOLDE have been completed with yields of the order of 1-5 pps. **The second theme** is the mapping of the distribution of the strength of the β-decay in the large energy window open in the daughter nucleus. Most of the beta-strength is expected at high energy, but this is challenging to measure due to weak branching ratios and many open decay channels [Kol2014a, Kol2014b]. **The third theme** is the study of properties of resonances placed in the first MeV above the proton separation energy in the daughter nuclei. This includes their energy, spin, and partial decay widths for gamma-, and proton-emission. Measurement of these quantities makes it possible to estimate astrophysical reaction rates for capture reactions, which presently cannot be directly measured for these exotic nuclei [Ber2010, Chi2016].

We have pursued all these themes in our previous studies along the proton dripline for ^{8}B [Kir2011], ^{9}C [Ber2001], ^{12}N [Fyn2005, Dig2009], ^{13}O [Knu2005], ^{20,21}Mg [Lun2015a, Lun2015b, Lun2016], and ^{31}Ar [Fyn2000, Kol2013, Kol2014a, Kol2014b, Fyn2017] at the ISOLDE and IGISOL facilities in Europe. These studies demonstrate that we have the experience to complete studies such as the ones proposed here. With this proposal we wish to fill the gap between Mg and Ar.

The decay of ^{22}Al has been studied in four experiments previously, two at Berkeley and two at GANIL. A decay scheme is shown in Figure 4. It was first discovered and studied at Berkeley in the 1980s [Cab1982], where β2p from the isobaric analogue state (IAS) in ^{22}Mg was identified [Cab1983], but the statistics was too limited to say anything about the mechanism of the two-proton emission. At GANIL, beta-delayed alpha-emission was identified and branching ratios for βa-, βp, and β2p-emission were deduced [Bla1997]. That experiment, however, suffered from substantial contamination with ^{22}Al only being 30% of the beam delivered to the setup. In the latest experiment at GANIL in 2006 a cleaner beam was produced, and a setup including efficient gamma-detectors applied [Ach2006]. This experiment provided a rather complete measurement of the decay of ^{22}Al with the exception that it did not provide a measurement of the mechanism of the two-proton emission. Note, the observed βa via the IAS in the decay of ^{22}Al observed by [Bla1997] was within a factor 2 of the prediction in [Bro1990], which lends support to the predicted branching ratios for direct two-proton emission in that work.

The decay of ^{26}P has been studied in four experiments previously. A decay scheme is shown in Figure 5. It was studied at Berkeley in the 1980s [Hon1983, Cab1984], where β2p from the isobaric analogue state (IAS) in ^{26}Si was identified and sequential decay via at least one intermediate state in ^{25}Al established. This is still the only experiment to provide any information on the β2p mechanism in ^{26}P. In 2004, results from GANIL were published including delayed p, γ, pγ, γγ spectra [Tho2004]. This work identified more than 30 βp transitions including proton emission from the 3^{+} resonance at 5.93MeV in ^{26}Si which is believed to be determining the rate of the ^{25}Al(p, γ)^{26}Si reaction at the highest nova temperatures. In 2013 the decay was measured at the NSCL, where the γ-decay of the 5.93MeV resonance was identified and the Γ_γ/Γ_p ratio estimated by using information from the mirror level in ^{26}Al and other data [Ben2013]. Finally, in 2017 a study using an optical TPC at Dubna [Jan2017] found a smaller branching ratio to the 5.93MeV resonance of 12(2)% compared to 18(1)% measured by [Tho2004], a change that directly modify the Γ_γ/Γ_p ratio estimated by [Ben2013].

II. Goals of the proposed experiment

For each nucleus we will measure clean spectra of p, 2p , 3p, γ, βp, γp, βγp, and βγ. This will be achieved by using a compact array of double sided Silicon strip detectors (DSSDs). The βs will be measured in thicker detectors enabling βp spectra, while thin DSSDs will enable measurement of low energy protons.

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By surrounding the Silicon detectors by an array of Germanium detectors, γp, βγp, and βγ spectra can also be measured. The combined information from the charged particle- and γ-detectors will provide the decay schemes for each of ^{22}Al and ^{26}P. From systematics [Lun2015b] βαp and βα are also expected from ^{26}P, and if the branching ratios are favorable, these decay modes will also be measured by the proposed setup. Absolute branching ratios will be determined using the ratios $N_{\beta\gamma}$ / N_{β}, and $N_{\beta p}$ / N_{β}.

In particular this experiment will deliver the following:

- The first measurement of the mechanism of β2p from the decay of ^{22}Al, and a much deeper look into β2p from the decay of ^{26}P including spin determinations of levels in the βp daughter using pp angular correlations [Kol2014b]. The goal is to collect a sample of two-proton coincidences large enough to be well within the predicted range for correlated, direct two-proton emission.
- A search for βα from ^{26}P.
- An accurate determination of the β-strength distribution in the decays of both ^{22}Al and ^{26}P including the strength at high energy which is likely to be distributed over several decay channels [Kol2014a, Lun2015b].
- An accurate determination of the population of the 5.93MeV state in ^{26}Si in the decay of ^{26}P thereby resolving the existing disagreement [Tho2004, Jan2017] and potentially leading to a revised value of the Γ_γ/Γ_p ratio.
- An accurate determination of the ^{22}Al and ^{26}P half-lives using a new method [Fyn2014].

III. Experimental Details

Production The estimated rates of ^{22}Al and ^{26}P at the stopped beam general purpose beamline are:

- ^{22}Al 9×10^{3} pps (half-life: 91.1 ms)
- ^{26}P 5×10^{3} pps (half-life: 43.7 ms)

The chemistry factors for Al and P, and decay losses in the gas cell are included to these rates, which are at least a factor 10^{3} higher than the corresponding rates estimates at the NSCL. Note, if these rates can be confirmed, and the expected yields at the NSCL are scaled with similar factors for ^{22,23}Si, ^{27}S, ^{31}Ar and ^{35}Ca, then a very rich research programme of decay studies along the proton drip line becomes feasible.

Beam-time estimate: The branching ratios for β2p from ^{22}Al and ^{26}P are estimated to be 1-3% [Ach2006, Jan2017]. Our goal is to measure of the order of 5×10^{5} β2p events for each of ^{22}Al and ^{26}P, which will allow us to reach well into the predicted range of direct two-proton emission [Bro1990]. With the suggested detection setup this can be achieved in two days of beamtime for each of ^{22}Al and ^{26}P assuming a conservative yield of 10^{3} pps. We also ask for time for tuning of the stable beam and tuning of the radioactive beams in the gas cell and to the experimental station. To tune the chemistry of aluminum in the gas cell we will use ^{25}Al. A study of the chemistry of phosphorus in the gas cell has already been done.

The experimental setup for charged particles will be similar to the Si-cube [Mat2009] also used for the study of ^{31}Ar at CERN-ISOLDE [Kol2013, Kol2014a, Kol2014b]. Our setup is shown in Figure 3. It provides a total solid angle of 54% for one-proton and 29% for two-proton detection. The setup has already been used at an experiment at IGISOL in Finland in the fall of 2020. The data acquisition system for the charged particles is VME based using ADCs and TDCs from CAEN.
For γ-ray detection we will rely on the SeGA array in the betaSeGA configuration. Clock synchronization of the event type data from the two parts of the detection system will be required.

Readiness Most parts of the setup are available already. We request help from FRIB with setting up the SeGA array including mechanical support, electronics, and data acquisition. For the charged particle setup we require from MSU help with integrating the data acquisition computer to the network, and of course access to electrical power for NIM and VME bins. If possible, access to pumps for evacuating the small chamber holding the DSSSDs, 2 NIM bins and 1 VME bin would ease transport of the experimental equipment.

Supplemental Information (Figures, Tables, References, etc., including one figure that depicts the layout of the experimental apparatus)

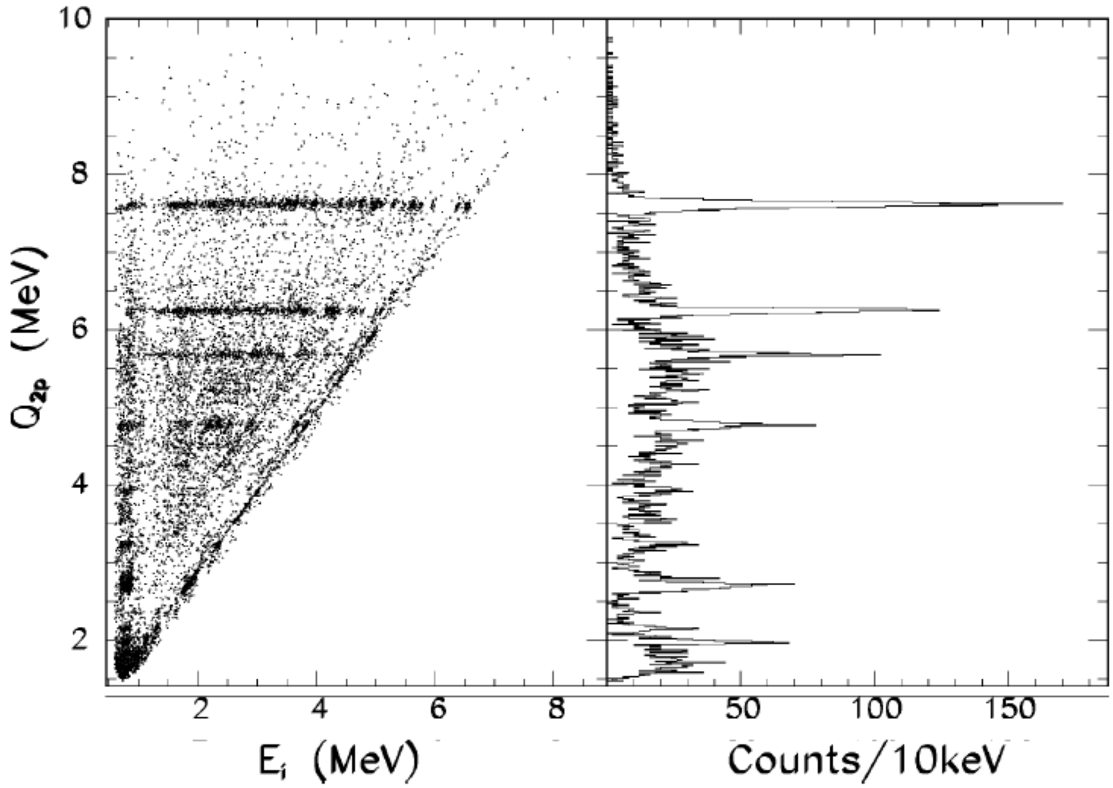

Figure 1 Beta-delayed two-proton emission from ^{31}Ar. To the left is shown a scatter plot of the Q-value for two-proton emission, Q_{2p}, against the energy, E_i, of the individual protons. Each event is represented by two points lying on the same horizontal line. The right part is the projection onto the Q_{2p}-axis. Two-proton emission from many states in ^{31}Cl is identified. From [Fyn2000].

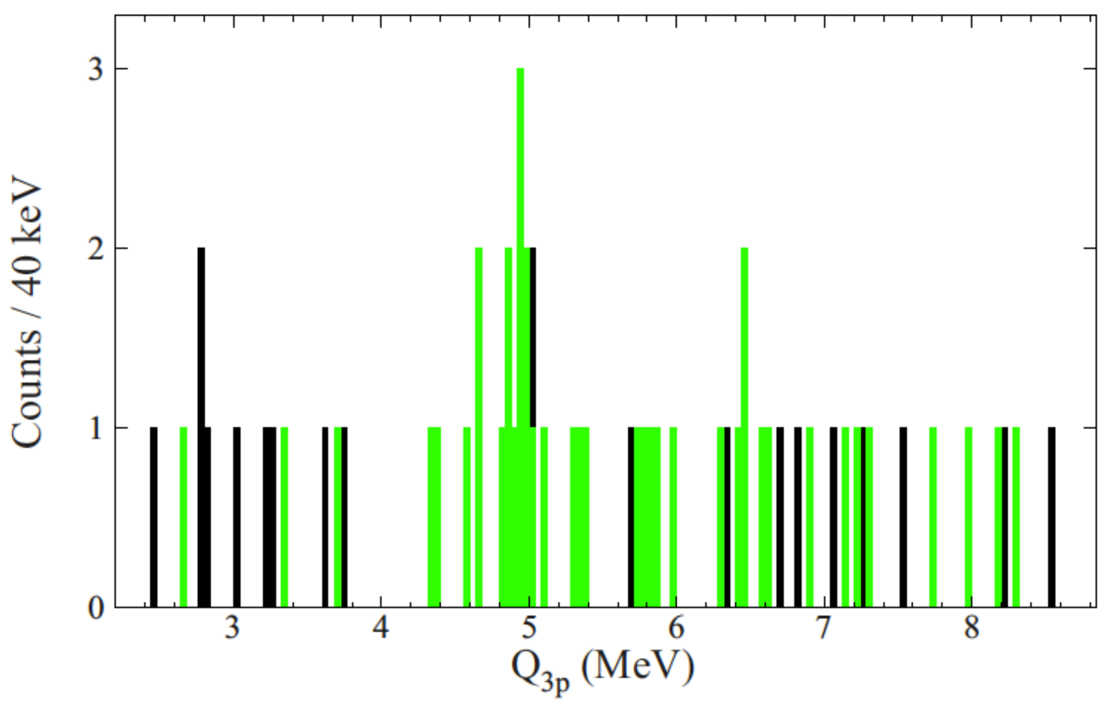

Figure 2 Beta-delayed three-proton emission from ^{31}Ar. Three-proton emission from many states is observed. The difference between the green and black events is related to which detectors the individual protons are observed in. From [Kol2014b].

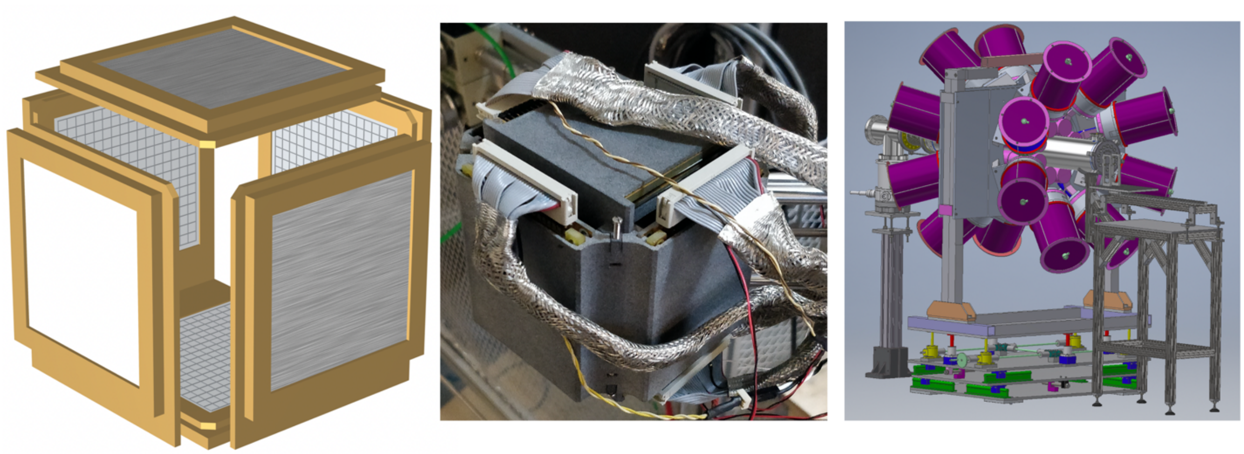

Figure 3 Si-detector setup of six DSSSDs backed by thick PAD detectors for punch-through protons and beta-particles. Left: detector configuration; center: photo of the setup in an experiment in Finland, September 2020; right: Setup including the SeGA in beta-decay configuration.

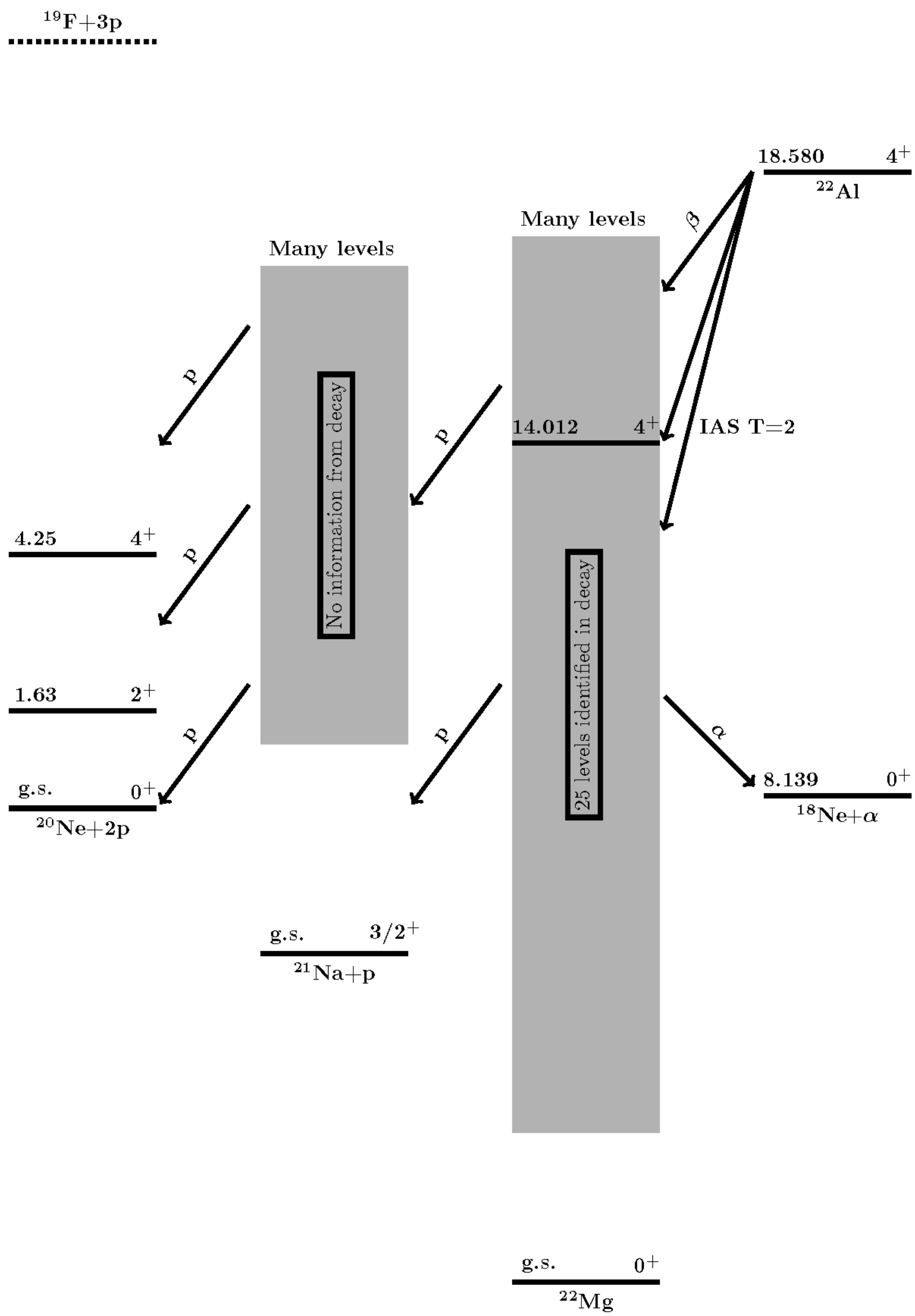

Figure 4 Schematic decay scheme for ^{22}Al. All energies are in MeV. [Ach2006] has identified more than 20 levels populated in ^{22}Mg after the beta-decay of ^{22}Al. Beta-delayed α-decay to ^{18}Ne was observed by [Bla1997].

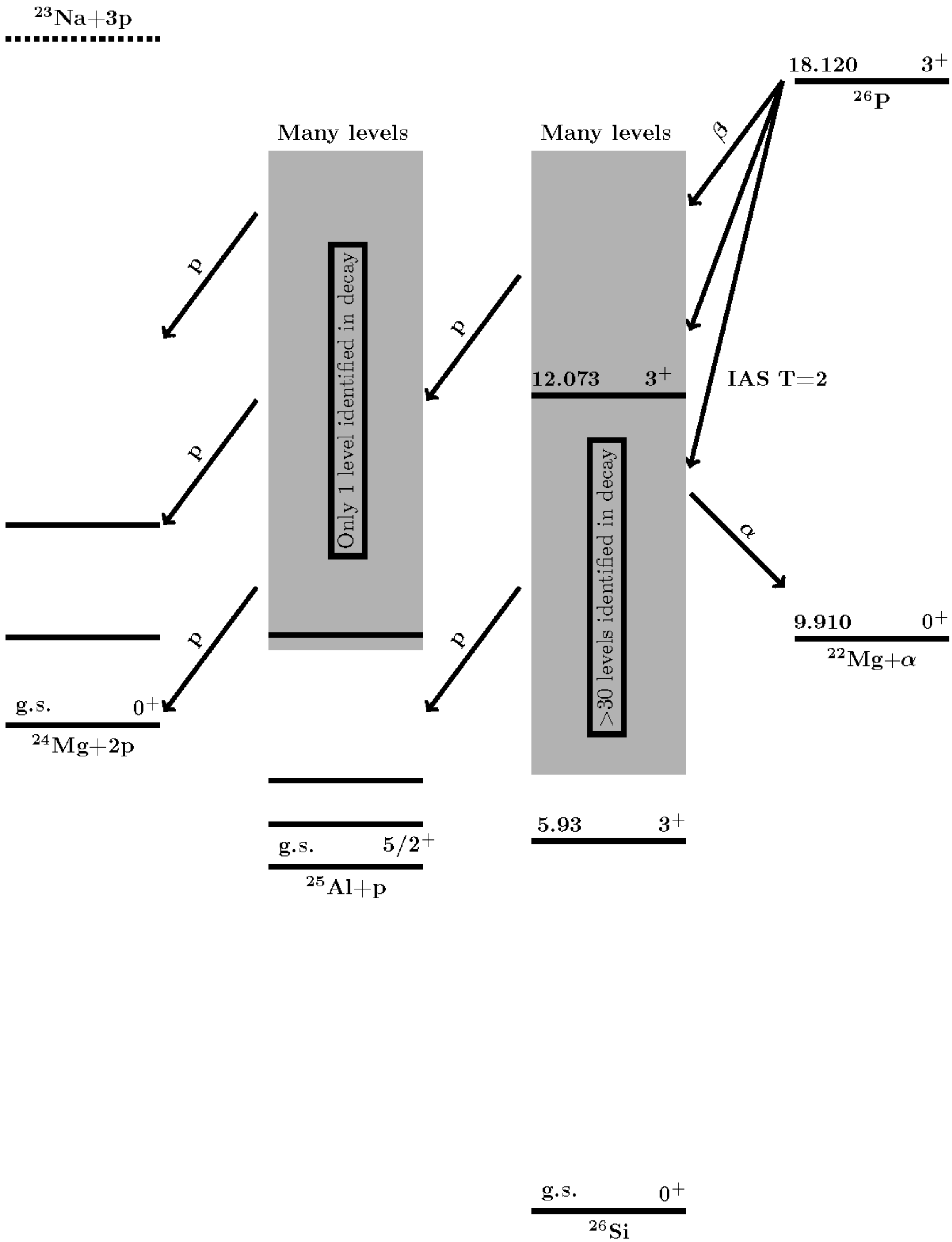

Figure 5 Schematic decay scheme for ^{26}P. All energies are in MeV. [Tho2001] has identified more than 30 levels populated in ^{26}Si after the beta-decay of ^{26}P, and [Cab1984] has identified one level in ^{25}Al populated after beta-delayed proton emission of ^{26}P. Beta-delayed α-decay to ^{22}Mg has not yet been seen.

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