EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

[Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Study of the β-delayed α decay of ^{16}N

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Abstract: We propose to study the β decay of ^{16}N at ISOLDE with the aim of determining the branching ratio for $\beta\alpha$ decay on an absolute scale. Presently, the $\beta\alpha$ branching ratio is known with an estimated uncertainty of 10%. This limits the precision with which the E1 contribution to the astrophysical ^{12}C$(\alpha,\gamma)^{16}$O rate can be determined. There are indications that the previously measured branching ratio is in error by an amount significantly larger than the quoted uncertainty.

Requested shifts: 15 shifts

1 Motivation

We propose a measurement of the β decay of ^{16}N with the goal of reducing the uncertainty on the astrophysical rate of ^{12}C$(\alpha,\gamma)^{16}$O, the key reaction in helium burning together with the triple-α reaction. It has been known since 1971 that the β decay of ^{16}N (see Fig. 1) can be used to restrict the dominating E1 contribution to the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate [2]. Basically, the shape of the $\beta\alpha$ spectrum is sensitive to the reduced α width of the sub-threshold 1^- state at 7.12 MeV in ^{16}O. Knowledge of this quantity is crucial to model the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate. Buchmann, Ruprect and Ruiz (BRR) have recently examined in detail the handful of measurements of the $\beta\alpha$ decay of ^{16}N reported in the literature [3]. The authors suggest that the measurements yield consistent spectral shapes provided the experimental differences are properly taken into account. A new measurement from Argonne also agrees with the shape determined by BRR [4]. BRR also suggest new measurements to improve the status quo. In particular, they argue that an improved measurement of the branching ratio to the 1^- state at 9.6 MeV is needed. The more precisely this branching ratio is known, the more precisely the reduced α width of the sub-threshold 1^- state can be determined. The TUNL evaluation [5] quotes a value of $1.20(5) \times 10^{-5}$ for the branching ratio to the 9.6 MeV state, but this value and the uncertainty is difficult to trace, see the discussion in Ref. [3]. The value appears to be based on one or at most two measurements [6, 7]. An uncertainty of 10% appears to be more realistic. Motivated by the circumstances outlined above we performed a new measurement of the $\beta\alpha$ decay of ^{16}N at the KVI facility in Groningen in 2013. A mass-separated ^{16}N beam was implanted in a finely segmented detector and the energy of the implanted ion and the combined energy of the decay fragments were measured. We have succesfully used this technique on two previous occasions to study the $\beta\alpha$ decays of ^{8}B, ^{12}B and ^{12}N [8, 9, 10]. The data suggest that the branching ratio to the 1^- state at 9.6 MeV might be 30% higher than the accepted value. The effect on the ^{12}C$(\alpha,\gamma)^{16}$O reaction rate is not easily determined, but preliminary estimates suggest that it could be comparable in magnitude, *i.e.*, an increase of 30% [11]. Unfortunately, we do not have complete confidence in our result due to concerns about the dead-time correction. The KVI facility has since closed down so we are unable to repeat the measurement.

Very recently (October 2014) our collaboration has studied the βp decay of ^{31}Ar at ISOLDE. On this occasion we also observed a significant number of $\beta\alpha$ decays from ^{16}N. Unfortunately, the setup did not allow an accurate determination of the branching ratio to the 9.6 MeV state (the setup was optmised with ^{31}Ar in mind), though this would clearly be possible with a dedicated setup.

2 Experimental setup

The mass-separated beam will have an energy of 30 keV and will be implanted in a thin carbon foil. The foil will be viewed by four DSSDs in a rectangular configuration as shown in Fig. 2. The DSSDs are 60 μm thick, have 16×16 strips and an area of 5×5 cm^2. At a distance of 5 cm the detectors will cover 26% of 4π and allow detection of $\alpha + {}^{12}$C coincidences with high efficiency. The DSSDs have a very thin deadlayer allowing
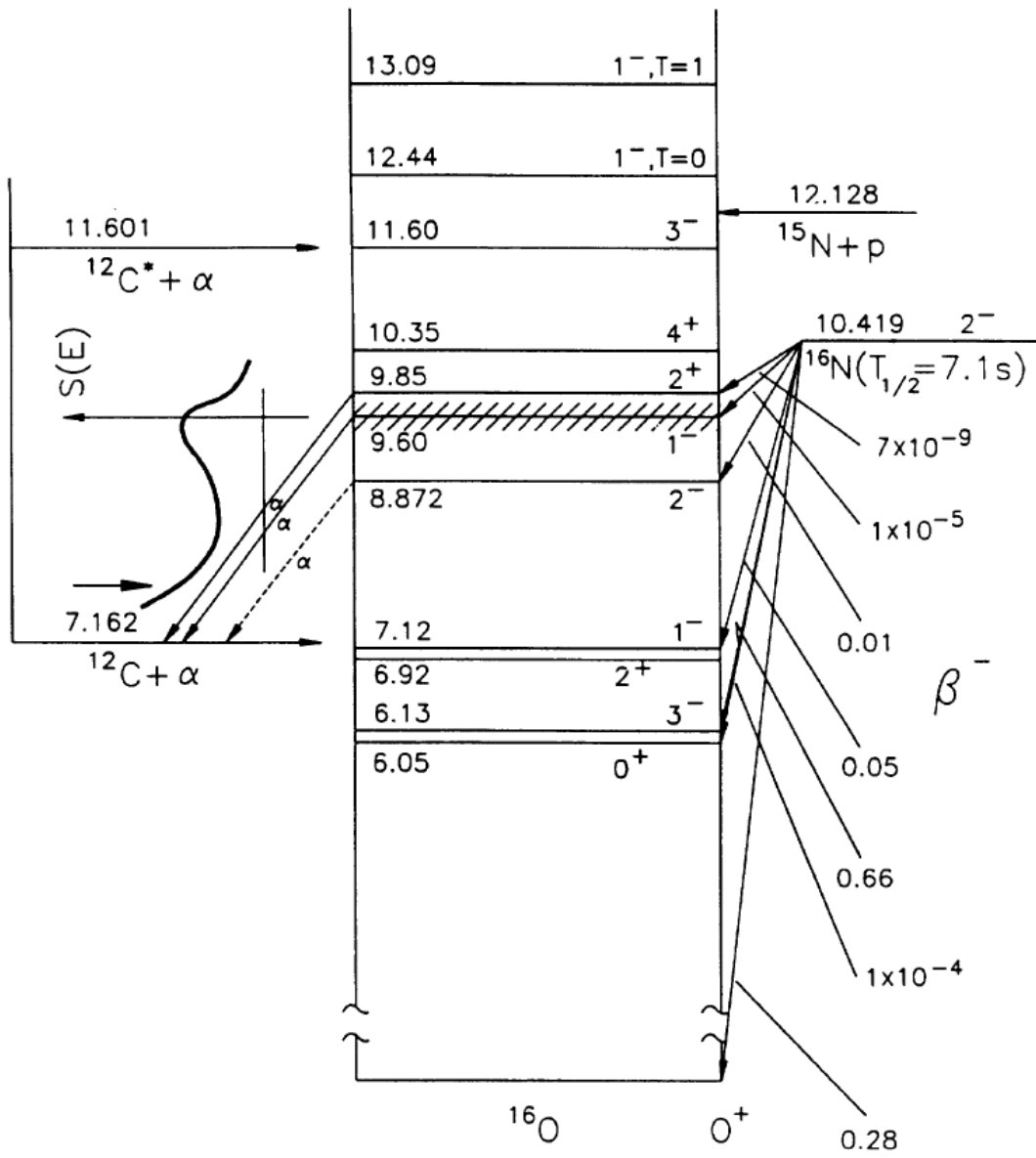
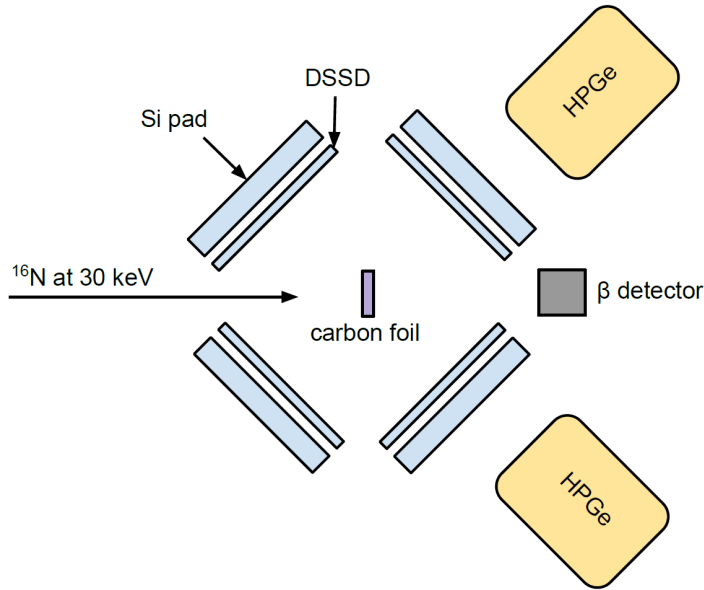Figure 1: Partial energy-level diagram for ^{16}O, from Ref. [1].

Figure 2: Schematic illustration of the detector setup.

detection of the low-energy ^{12}C ions [12]. The DSSDs will be backed by 1 mm Si pads to veto against β particles. A similar setup was succesfully used by our collaboration at IGISOL in 2008 to study the β-delayed α decays of ^{8}B and ^{20}Na [13, 14]. Additionally, a dedicated β detector will be employed to allow for the γ-ray detection effieciency to be determined by the β-$\beta\gamma$ ratio method (Section 3). Two Ge detectors will be used to detect $\beta\gamma$ transitions. The $\beta\gamma$ lines at 2.74 MeV and 6.13 MeV will be used for absolute normalisation.

Our collaboration has invested considerable effort in modelling energy-loss effects of low-energy charged particles, see for example Ref. [15]. We have developed an improved way of calibrating large segmented detectors when low energy particles are involved [16], and we have participated in the new design of a large, segmented detector with significantly reduced deadlayers [12]. We have also initiated a joint research project (DLEP) under the Integrated Infrastructure Initiative for EUROpean Nuclear Structure research (EURONS) within the Sixth Framework Programme of the European Commission aimed at optimising detection of low-energy charged particles. Thus, we feel that our collaboration should be able to make a significant contribution to the measurement of the ^{16}N $\beta\alpha$ decay, where α energies range between 0.5 and 2.5 MeV (and ^{12}C energies range between 0.17 and 0.83 MeV).

3 Energy and efficiency calibrations

BBR have stressed the importance of an accurate and precise energy calibration of the $\beta\alpha$ spectrum of ^{16}N [3]. We will calibrate the DSSDs online using the $\beta\alpha$ lines of ^{18}N at $E_\alpha = 1.081(1)$ and $1.409(1)$ MeV [17, 18] and offline using the 3.182 MeV α-decay line of ^{148}Gd. This gives us three calibration points which cover the main part of the

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$\beta\alpha$ spectrum (1.0–2.5 MeV). The efficiency of the Ge detectors will be determined in two ways:

Method 1. Absolutely calibrated γ-ray sources will be used to calibrate the efficiency of the Ge detectors on an absolute scale up to an energy of $E_\gamma = 1.5$ MeV. Online measurements of $\beta\gamma$ lines from ^{34}Ar at 0.67, 2.58 and 3.13 MeV will allow us to extend the efficiency calibration up to 3 MeV with a precision better than 3%. (Additional calibration points in this energy range could be obtained with ^{35}Ar.) The $\beta\gamma$ line of ^{16}N at 2.74 MeV, the intensity of which is known with a precision of 7.3%, can then be used to normalise the ^{16}N $\beta\alpha$ spectrum.

Method 2. A dedicated β detector will be included in the setup. The absolute efficiency of the Ge detectors at 6.13 MeV may then be determined from the ratio of β singles and β-$\gamma_{6.13}$ coincidences using the intensity of the 6.13 MeV line which is known with a precision of 0.9%. From the data obtained in October 2014 we have verified that ^{16}N is the sole activity on $A = 30$, which is necessary for this method to work.

Method 2 will allow us to normalize the $\beta\alpha$ spectrum to a precision of about 2% (0.9% at the very best). Method 1 has the advantage of being more robust, but only reaches a precision of about 10% (7.3% at the very best). This reduced precision would, however, still be of great interest in the sense that it would allow us to verify our KVI result.

4   Beam-time estimates

Our goal is to determine the branching ratio to the 9.6 MeV state with a precision of 2% which requires at least 2.5×10^3 events. Since our detection efficiency is close to the solid-angle coverage, *i.e.*, 26%, and the $\beta\alpha$ branching ratio is about 1.2×10^{-5}, we conclude that 0.8×10^9 implantations will be needed to achieve this goal.

In our recent ^{31}Ar experiment (Oct 2014) we achieved a ^{16}N yield (at our setup) of 2.0×10^3 μC^{-1} on mass $A = 30$ using a CaO production target heated to 500° C. When heated to 800° C the yield went up to 50×10^3 μC^{-1}. In a previous ^{31}Ar experiment (August 2009) we obtained a ^{16}N yield of 2.2×10^3 μC^{-1} on mass $A = 31$. Correcting for the relative yield of N_2^+ and N_2H^+ molecules, which we have determined to be 2:3 [19], we deduce a ^{16}N yield of 1.5×10^3 μC^{-1} on mass $A = 30$. Adopting the lower of the three ^{16}N yield estimates we determine the beam time required to achieve the desired statistical precision to be 3 days assuming a proton current of 2 μA.

To characterise the low-energy region of the $\beta\alpha$ spectrum of ^{16}N (0.5–1.0 MeV) we need of the order of 10^5 counts, *i.e.*, about a factor of 40 more than we need for the branching-ratio determination. If we achieve a ^{16}N yield of 50×10^3 μA^{-1} (the higher of the three yield estimates) this may be possible with 3 days of beam time assuming, again, a proton current of 2 μA.

The $\beta\alpha$ calibration lines of ^{18}N have branching ratios of 6.8% and 1.8%, respectively. The anticipated energy resolution is 40 keV (FWHM). Based on these numbers we estimate that 3×10^5 implantations are required to reach a statistal uncertainty of 1 keV on the energy determination. Data collected on mass $A = 32$ by our collaboration on a

previous occasion (August 2009) has been used to determine the relative yields of the nitrogen isotopes ^{16,17,18}N on mass $A = 31$, 32 and 33 from a CaO production target [19]. In particular, the ^{18}N yield on mass $A = 32$ was determined to be about 5 μC^{-1}. We conclude that about 8 hours of beam time are needed to reach the desired energy precision assuming a proton current of 2 μA.

The $\beta\gamma$ lines of ^{34}Ar, which will be used for efficiency calibration, have branching ratios of the order of a few percent. The ^{34}Ar yield from a CaO target is very high according to the ISOLDE yield database, at least 10^6 μC^{-1}. The necessary amount of statistics can therefore be obtained very quickly, within 1-2 hours or less.

5   Beam production and beam-time request

A CaO target will be used to produce the ^{16,18}N and ^{34}Ar isotopes needed for the experiment. The nitrogen isotopes form molecules (N_2 and N_2H). A cooled plasma ion-source will be used both for nitrogen and argon. ^{16}N can be obtained both on mass $A = 30$ and 31, but in our recent experiment at ISOLDE (October 2014) we found that only $A = 30$ is free of β contamination, as mass $A = 31$ suffers from the presence of ^{31}Ar. ^{18}N can be obtained both on mass $A = 32$ and 33 with similar yields, but $A = 32$ is preferable because it has the shortest-lived β-unstable contaminant. (^{32}Ar and ^{33}Ar have half-lives of 100 and 173 ms, respectively; the half-life of ^{18}N is considerably longer, 620 ms.) Accordingly, we will run ^{16}N on mass $A = 30$ and ^{18}N on mass $A = 32$.

We would like to point out that ISOLDE offers unique opportunities for realising the proposed experiment. Most importantly, it is possible to produce the necessary isotopes with high yields from the same target. This allows the experiment to be carried within a rather short time period of only 5 days.

Based on the estimates presented in Section 4, we ask for a total of 15 shifts:

- 3 shifts for the ^{18}N energy calibration (1.5 at the beginning and 1.5 at the end).

- 1 shift for the ^{34}Ar efficiency calibration (0.5 at the beginning and 0.5 at the end)

- 11 shifts for the ^{16}N measurement (10 shifts for the actual measurement and 1 shift to explore the temperature dependence of the production rate)

Calibrations will be performed both before and after the ^{16}N run to check if material has accumulated on the carbon foil and check for potential gain drifts. In previous experiments, notably the study of the $\beta\alpha$ decay of ^{8}B, we have seen that considerable amounts of material can accumulate within short time periods, even when oil-free pumps are used. It is important to quantify such effects which otherwise introduce significant systematic error in the energy calibration [13].

Summary of requested shifts: 15 shifts.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: 1 vacuum chamber, 4 DSSDs, 4 Si pads, 1 β detector, 2 HPGe detectors and associated electronics.

Part of the	Availability	Design and manufacturing
fixed ISOLDE installation not used	☐ Existing	☐ To be used without any modification
Detectors and electronics	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	Detectors and electronics		
Thermodynamic and fluidic			
Pressure			
Vacuum	10^{-6} mbar		
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LN$_2$ for 2 HPGe detectors, 1.2 Bar, 30 l		
Electrical and electromagnetic			
Electricity	max 4 kV for Ge detector		
Static electricity			
Magnetic field			
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	carbon		
Beam particle type	^{16,18}N, ^{34}Ar		
Beam intensity	$< 10^6$ ions/sec		

Beam energy	30 keV		
Cooling liquids			
Gases			
Calibration sources:	☐		
• Open source	☒ ^{148}Gd		
• Sealed source	☒ [ISO standard]		
• Isotope	^{60}Co, ^{137}Cs, ^{152}Eu		
• Activity	$< 10\mu$Ci		
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		

Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high work-places	[location]		
Obstructions in pas-sageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]