EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Absolute measurement of the $\beta\alpha$ decay of ^{16}N

June 3, 2015

M.J.G. Borge[1], L.M. Fraile[2], H.O.U. Fynbo[3], A. Heinz[4], A.M. Howard[3], J.S. Johansen[3], H.T. Johansson[4], B. Jonson[4], O.S. Kirsebom[3], M.V. Lund[3], I.M. Alonso[5], M. Munch[3], E. Nacher[5], T. Nilsson[4], A. Perea[5], J. Refsgaard[3], K. Riisager[3], O. Tengblad[5], R. Thies[4] and V. Vedia[2]

[1] *ISOLDE, CERN, Geneva, Switzerland*
[2] *Grupo de Física Nuclear, Universidad Complutense de Madrid, E-28040 Madrid, Spain*
[3] *Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus, Denmark*
[4] *Fundamental Physics, Chalmers Univ. of Technology, S-41296 Göteborg, Sweden*
[5] *Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*

Spokesperson: O. S. Kirsebom, oliskir@phys.au.dk
Contact person: M. Madurga, miguel.madurga.flores@cern.ch

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. There are indications that the previously measured branching ratio is in error by an amount significantly larger than the quoted uncertainty. This limits the precision with which the S-factor of the astrophysically important ^{12}C(α,γ)^{16}O reaction can be determined.

Requested shifts: 12 shifts

1 Motivation

It has been known since the 1970s that the $\beta\alpha$ decay of ^{16}N (see Fig. 1) can be used to constrain the E1 component of the S-factor of the astrophysically important $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ reaction. While consesus appears to have been established regarding the *shape* of the experimental $\beta\alpha$ spectrum [2, 3], an improved measurement of the branching ratio to the 1^- state at 9.6 MeV is needed. The TUNL evaluation [4] quotes a branching ratio of $1.20(5) \times 10^{-5}$, but this value has been questioned by Buchmann *et al.* [2]. A precise measurement of the *position* of the maximum of the $\beta\alpha$ spectrum is also of considerable interest. Existing phase-shift data, capture data, and β-decay data are in good agreement, but only if the maximum of the $\beta\alpha$ spectrum is shifted by -5 keV compared to its measured value [3].

In 2013 our collaboration performed a new branching-ratio measurement at KVI. A mass-separated ^{16}N beam was implanted in a finely segmented Si detector and the energy of the implanted ion and the combined energy of the decay fragments were measured. The data suggest that the branching ratio is 25% higher than the accepted value. We have performed R-matrix fits to the spectrum of Ref. [3] to evaluate the effect on S_{E1}. The results are shown in Fig. 2. We find that S_{E1} increases proportionally to the branching ratio, as also observed by Azuma *et al.* [1]. A 25% increase in the branching ratio results in an 26% increase in S_{E1}, and a 15% increase in the total S-factor. Given the importance of this result, we believe it should be confirmed in an independent experiment.

In October 2014 our collaboration 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. While the setup was optimised with a view to ^{31}Ar, and thus did not allow us to determine the branching ratio to the 9.6 MeV state, this experiment clearly shows the feasibility of such a measurement.

Our collaboration has invested considerable effort in modelling the energy loss of low-energy charged particles [5]. We have developed an improved way of calibrating large segmented detectors [6], and we have participated in the design of a new, large-area, segmented detector with significantly reduced deadlayers [7]. We have also completed a joint research project (DLEP) under EURONS aimed at optimising detection of low-energy charged particles. Thus, our collaboration is able to make an improved measurement of the ^{16}N $\beta\alpha$ decay.

2 Setup and procedure

The mass-separated beam will have an energy of 30 keV and will be implanted in a thin carbon foil, viewed by four DSSDs as shown in Fig. 1. The DSSDs cover 50% of 4π and allow detection of $\alpha + {}^{12}\mathrm{C}$ coincidences with high efficiency. The DSSDs will be backed by 1 mm Si pads to veto against β particles. A similar setup has been succesfully used by our collaboration to study the $\beta\alpha$ decays of ^{8}B and ^{20}Na at IGISOL [8, 9] and ^{31}Ar and ^{20,21}Mg at ISOLDE (IS507, IS577). A dedicated β detector will be used to provide absolute normalisation. A HPGe detector and a CEPA detector, consisting of four 2.5×2.5 cm^2 $\mathrm{LaBr_3(Ce){:}LaCl_3(Ce)}$ crystals, will be used to measure $\beta\gamma$ transitions. The DSSDs will be calibrated on-line using the $\beta\alpha$ lines of ^{18}N at $E_\alpha = 1.081(1)$ and $1.409(1)$ MeV [10, 11]

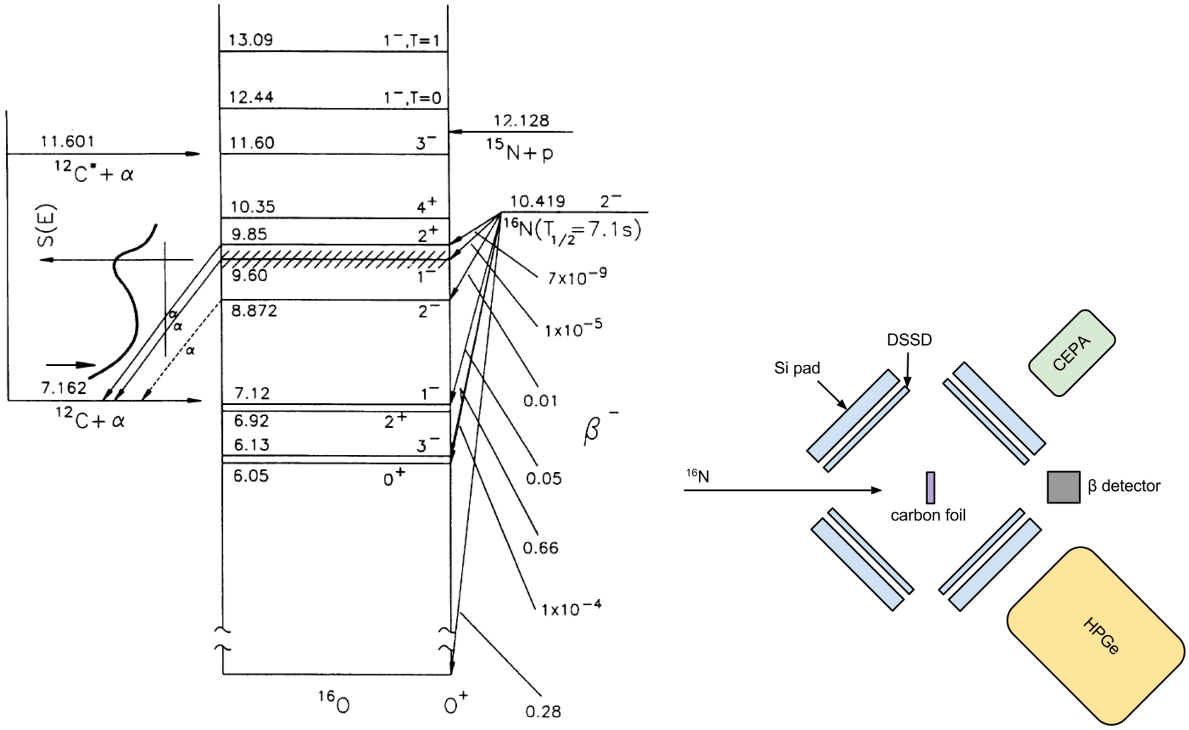

Figure 1: Left: Partial energy-level diagram for ^{16}O from Ref. [1]. Right: Schematic illustration of the detector setup.

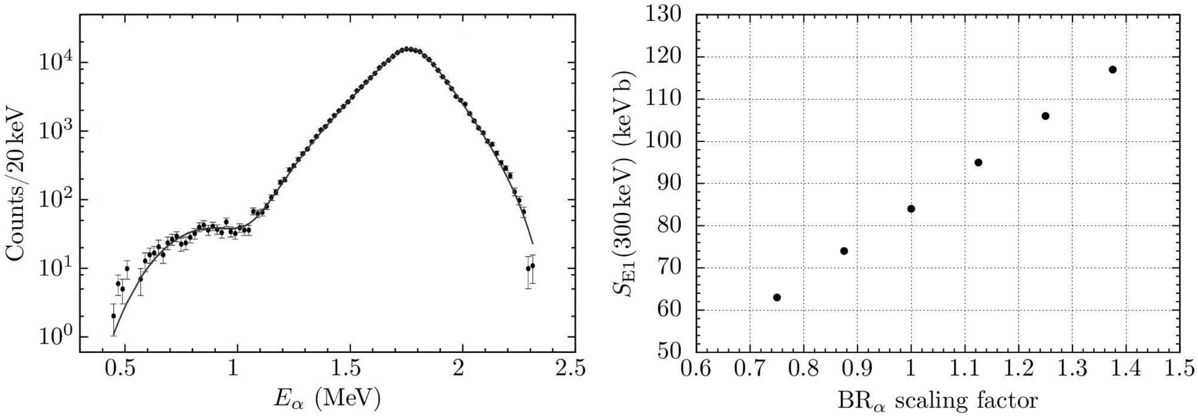

Figure 2: Left: R-matrix fit to the spectrum of Ref. [3]. Right: Effect on S_{E1} of varying the branching ratio to the 9.6 MeV state.

and off-line using the 3.182 MeV α-decay line of ^{148}Gd. This gives us three calibration points which cover the main part of the $\beta\alpha$ spectrum (1.0–2.5 MeV). The ^{18}N data will also be used as an important cross-check of the measured branching ratio. To this end we will use the known intensity of the 1.081 MeV $\beta\alpha$ line (6.8(5)% [10, 11]) and the known intensity of the 1982 keV $\beta\gamma$ line (72.0(25)% [11]).

3 Absolute normalisation

Absolute normalisation will be achieved using three different methods. This will allow us to perform important cross-checks and eliminate systematic errors. Note that these methods are all complemetary to the approach used at KVI.

Method 1. We will use absolutely calibrated γ-ray sources to calibrate the absolute efficiency of the γ-ray detectors up to 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 to a precision better than 3%. We can then use the 2.74 MeV $\beta\gamma$ line of ^{16}N to normalise the $\beta\alpha$ spectrum. The intensity of this line is known to a precision of 7.3%.

Method 2. In the βp decay of ^{17}Ne exited levels in ^{16}O are populated following proton emission from ^{17}F*, among them the 6.92 MeV level with a branching ratio of 2.4% [12]. By gating on the proton lines and counting the number of coincident γ-rays from the deexitation of the levels in ^{16}O, the absolute efficiency of the γ-ray detectors can be determined in the 6–7 MeV region using the known branching ratios. We can then use the 6.13 MeV $\beta\gamma$ line of ^{16}N to normalise the $\beta\alpha$ spectrum. The intensity of this line is known to a precision of 0.9%.

Method 3. The ratio of β-singles to $\beta\gamma$-coincidences, gated on the 6.13 MeV line, provides direct normalisation of the $\beta\alpha$ spectrum. 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 1 has the advantage of being very 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. Methods 2 and 3 will allow us to normalise the $\beta\alpha$ spectrum to an estimated precision of 2%.

4 Beam-time estimates

All beam-time estimates have been made assuming an average proton current of 1.6 μA. This corresponds to 20 pulses/minute and 3×10^{13} protons/pulse.

^{16}N. 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.*, 50%, and the $\beta\alpha$ branching ratio is about 1.2×10^{-5}, we conclude that 4×10^8 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 briefly 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 [13], we deduce a ^{16}N yield of 1.5×10^3 μC^{-1} on mass $A = 30$. Since the high yield (50×10^3) has been obtained only once and only for a brief time interval, we base our beam-time estimate on the low yield (1.5–2.0×10^3) which we know is reproducible. To achieve the desired statistical precision we thus need 6 shifts.

^{17}Ne. The yield of ^{17}Ne from a CaO target is of the order of 10^3 μC^{-1}. Assuming an absolute γ-ray efficiency of 0.5%, we will collect 5.5×10^3 γ-rays per shift in the strongest line. With a charged-particle solid angle of 50% this gives 2.8×10^3 coincidences. Thus 1 shift is needed to determine the absolute efficiency of the γ-ray detectors with a statistical precision of 2%.

^{18}N. The $\beta\alpha$ calibration lines of ^{18}N have branching ratios of 6.8% and 1.8%, respectively. Assuming an energy resolution of 40 keV (FWHM) we estimate that 1.5×10^5 implantations are needed to reach a statistical precision of 1 keV on the energy calibration. This high level of precision is needed to resolve the discrepancy between the phase-shift data and the capture and β-decay data. The statistical uncertainty on the $\beta\alpha$ branching-ratio determination is estimated to be 3%. 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 [13]. In particular, the ^{18}N yield on mass $A = 32$ was determined to be about 5 μC^{-1}. We conclude that 1 shift is needed for the ^{18}N measurement.

^{34}Ar. 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, ^{17}Ne 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 ^{15}C and ^{17}N [13]. ^{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 4 days.
Based on the estimates presented in Section 4, we ask for a total of 12 shifts:

- 2 shifts for the ^{18}N calibration (1 at the beginning and 1 at the end).
- 2 shifts for the ^{17}Ne calibration (1 at the beginning and 1 at the end).
- 1 shift for the ^{34}Ar calibration (0.5 at the beginning and 0.5 at the end).
- 7 shifts for the ^{16}N measurement (6 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 [8].

Summary of requested shifts: 12 shifts.

References

[1] R. E. Azuma *et al.*, Phys. Rev. C **50** (1994) 1194.
[2] L. Buchmann, G. Ruprecht, and C. Ruiz, Phys. Rev. C **80** (2009) 045803.
[3] X. D. Tang *et al.*, Phys. Rev. C **81** (2010) 045809.
[4] D. R. Tilley, H. R. Weller, and C. M. Cheves, Nucl. Phys. **A564** (1993) 1.
[5] O. S. Kirsebom *et al.*, Nucl. Instr. Meth. **A758** (2014) 57.
[6] U. C. Bergmann, H. O. U. Fynbo and O. Tengblad, Nucl. Instr. Meth. **A515**, (2003) 657.
[7] O. Tengblad *et al.*, Nucl. Instr. Meth **A525** (2004) 458–462.
[8] O. S. Kirsebom *et al.*, Phys. Rev. C **83** (2011) 065802.
[9] K. L. Laursen, Eur. Phys. J. A **49** (2013) 79.
[10] K. I. Hahn, C. R. Brune, and P. R. Wrean, Phys. Rev. C **48** (1993) 914.
[11] D. R. Tilley, H. R. Weller, C. M. Cheves, and R. M. Chasteler, Nucl. Phys. **A595** (1995) 1.
[12] A. C. Morton *et al.*, Nucl. Phys. A **706** (2002) 15 (Table 1).
[13] J. H. Kusk, Master thesis, Aarhus University (2011).

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, ^{17}Ne, ^{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 workplaces	[location]		
Obstructions in passageways	[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]