EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Report to the ISOLDE and Neutron Time-of-Flight Committee

^{18}N: a challenge to the shell model and to ab initio models of the nuclear structure of light nuclei

[new title]

^{18}N: a challenge to the shell model and a part of the flow path to r-process element production in Type II supernovae

[old title]

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with the T-REX and MINIBALL collaborations

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Abstract

The light nuclei up to the nitrogen region can have their structure calculated by state of the art *ab initio* calculations and these face the challenge of matching the accuracy of the predictions using large-scale shell model calculations. A particularly interesting case is ^{18}N, at the frontiers of *ab initio* work, where it is possible that the new approach might resolve the long-time unresolved problem of simultaneously explaining the level ordering in ^{16}N and ^{18}N. We plan to study of the spectroscopy of ^{18}N using the (d,p) reaction at 5.5 MeV/A in inverse kinematics with the T-REX array and Miniball. The proton angular distributions measured using T-REX will allow us to deduce the orbitals and spectroscopic strengths associated with the bound and unbound excited states in ^{18}N. The measurement of coincident gamma rays is absolutely essential in resolving and determining the precise excitation energies for bound states in ^{18}N.

Requested shifts: 21 shifts, (1 run)

Beamline: MINIBALL + T-REX

Previous Experimental Programme

This experiment forms a natural part of our established programme to study neutron rich light nuclei via single-neutron transfer. In a series of studies [1, 2, 3, 4], we have addressed the evolution of the neutron magic numbers which sees the classical magic numbers of N = 20 and 28 replaced by N = 16. An important theme has been the relative rise in energy of states based on the $0d_{3/2}$ orbital for neutron-rich nuclei. This is also important in considering ^{18}N, where the strong states of this structure are predicted to lie in the low-energy neutron resonance region. Also at GANIL, we previously studied the interaction of 0p-shell protons with sd-shell neutrons in ^{12}Be [5] and also ^{17}C via the (d,p) reaction [6]. The techniques in our previous (d,p) studies are exactly those that we propose to apply at HIE-ISOLDE using T-REX and MINIBALL. The best choice for this experiment is T-REX since it has been established as a standard piece of equipment to be operated with MINIBALL. The beam intensities that we have used at SPIRAL match the intensity that we anticipate for 17N, and we have used energies of both 5 and 10 MeV/u.

Motivation

The present state of knowledge of bound states in ^{18}N is summarised in Fig.1 and compared with ^{18}Na from ^{17}Ne+p [7]. Note that the second doublet in ^{18}N is labelled (0^-), (1^-) as suggested in the original study [8]. The two states 0^-_1 and 2^-_2 are then almost degenerate. Similarly the 1^-_2 and 3^-_1 states are almost degenerate. The NNDC data base misassigns the 0^- and 1^- states [9]. However the arguments for all four states are strong and can be understood in terms of the reaction selectivity. The experimental spectrum of ^{18}N is compared in Fig. 2 to two published shell model calculations [10] and our spsdpf calculations with NuShell [11] using the WBP interaction. None of the shell model calculations can reproduce the ordering of the two low-lying states and the deviations from the experimental energies are as high as 400 keV, which is larger than the typical 100 keV. In addition, the WBP calculations predict many bound positive parity states which are absent in the experimental spectrum. Such deviations reflect poorly understood features of the $\pi(p_{1/2})\otimes\nu(sd)$ coupling or of the evolution of nuclear levels in odd-odd nuclei with increasing neutron excess. The present experiment can clarify this.

Which of the ^{18}N states should be populated in the (d,p) reaction? Firstly, the 2^-_1 and 3^-_1 states can be populated. As discussed by Putt [8], the shell model of Millener indicates that these have a structure of $\pi(0p_{1/2})^{-1}$ coupled to $\nu(^{19}\mathrm{O}\ 5/2^+)$ and can be populated by adding a neutron to the pair already coupled to spin zero in $0d_{5/2}$ in ^{17}N. The ground state 1^-_1 and 2^-_2 states are $\pi(0p_{1/2})^{-1} \otimes \nu(^{19}\mathrm{O}\ 5/2^+)$ and will be suppressed as they require a recoupling of the $0d_{5/2}$ neutrons. The 0^-_1 and 1^-_2 should be strongly populated via transfer of a neutron to the $1s_{1/2}$ orbital. Our full shell model calculations support all these expectations (see Table 1 for spectroscopic factors).

Thus, via (d,p) we can populate both states in the 742/747 keV doublet of $3^-/1^-$ and the 0^-state around 580 keV (cf.Figure 2). There may be weak population also of the 587 keV 2^- state. In addition, the 121 keV 2^- state should be populated. It may be possible to determine lifetime information by the shadowing technique for this state (which is measured as $\tau = 0.58 \pm 0.17$ ns). The γ-rays from the decay of the state near 580 and 740 keV should allow the energies of the separate states in each doublet to be determined.

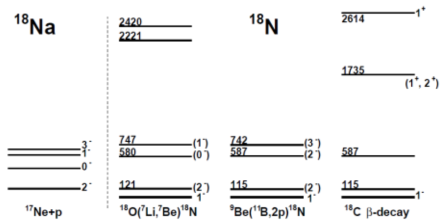

Figure 1: ^{18}N level schemes from previous experiments in comparison to the ^{18}Na spectrum. For the various experiments, we include only the spin information that is discussed in that particular work. For ^{18}Na, the first 2^- is plotted at the position of the first 2^- in ^{18}N states observed in [8] and the spacings between all the ^{18}N states are to scale.

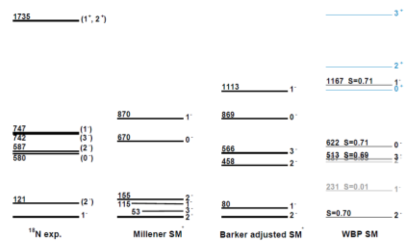

Figure 2: Comparison of the experimental level scheme in ^{18}N (in our interpretation) with the shell model. For the WBP SM calculations, the spectroscopic factors of negative-parity states are also included. The neutron separation energy is 2.825 MeV. *Ref.[10]

Note that the γ-decay pathway for the different spins will be quite different. It should also be noted that the differential cross sections will be very different for the two members of each doublet. For example the 3^- at 742 keV will have d-wave transfer and the 1^- at 747 keV has s-wave transfer. Therefore, the 3^- cross section will be greatest nearer to 90° in the laboratory frame and the 1^- differential cross section will be greatest closer to 180° in the laboratory. We should not rule out the possibility that the (d,p) transfer will populate positive parity bound states as well. They would be populated through admixtures of $\nu(1p_{3/2})$ and $\nu(1p_{1/2})$ configurations. According to the WBP shell model presented here, which incidentally fails to predict the energies correctly for either negative or positive parity states, the spectroscopic factors for the positive parity states are very small. However, these same calculations predict that the lowest $(0p)^{-1}$ neutron states ($1/2^-$, $3/2^-$) in ^{19}O should not be seen in (d,p), whereas experimentally the admixtures of $\nu(1p_{3/2})$ and $\nu(1p_{1/2})$ are sufficient that the lowest states are easily measured [15].

In summary, the (d,p) transfer measurements provide a unique opportunity to disentangle the details of the ^{18}N structure. In the case of the positive parity states, the present ^{17}N(d,p) measurement should also allow a limit to be set, at least, on the contributions from positive parity states to the (n,γ) astrophysical process of potential interest in supernovae. This is important, because the direct neutron capture into such states is not inhibited by any centrifugal barrier. The capture can be via direct E1 capture from the s-wave continuum, into a p-wave orbital in ^{18}N.

The present proposal will benfit from the close interaction and collaboration with reaction theorists. The measured angular distributions will be analysed using the latest developments in the theory of (d,p) reactions published in ref.[16]. These developments are based on non-local interactions of nucleons in deuteron with the target and an ongoing program of further development of these ideas is being pursued at the University of Surrey. For a preliminary estimation of the reaction yields, in order to calculate the beam time requirements, we have performed ADWA calculations of d(^{17}N,p)^{18}N and these are shown in Fig. 5.

E (keV)	J^π	$S_{1s_{1/2}}$	$S_{0d_{3/2}}$	$S_{0d_{5/2}}$	E (keV)	J^π	$S_{1p_{1/2}}$	$S_{1p_{3/2}}$	$S_{0f_{5/2}}$	$S_{0f_{7/2}}$
0	2_1^-		0.0004	0.6997	1119	0_1^+	0.0037			
231	1_1^-	0.0054	0.0118		1324	2_1^+		0.0005	0.0005	
487	2_2^-		0.0324	0.0012	1787	3_1^+			0.0002	0.0013
513	3_1^-			0.6890	1855	1_1^+	0.0051	0.0033		
622	0_1^-	0.7148			2511	2_2^+		0.0034	0.0053	
1167	1_2^-	0.7051	0.0104		2692	1_2^+	0.0004	0.0050		
2240	2_3^-		0.0001	0.0216	2781	4_1^+				0.0031
2545	3_2^-			0.0023						

Table 1: Spectroscopic factors from the ground state of ^{17}N for negative parity (left) and positive parity (right) bound states in ^{18}N as given by our spsdpf shell model calculations.

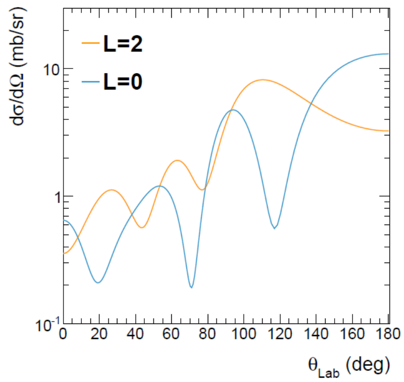

Figure 5: *ADWA cross sections in the laboratory frame with zero range approximation assuming S=1: (a) L=2, 742 keV 3⁻, and (b) L=0, 745 keV 1⁻. E_{beam}=5.5 AMeV*

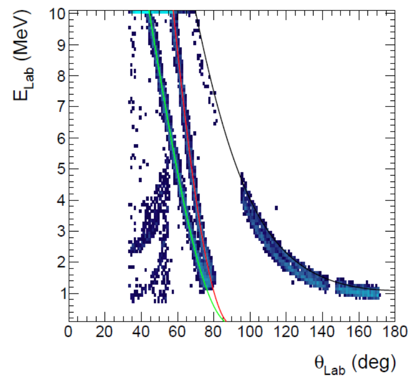

Figure 6: *Kinematic lines at 5.5 AMeV plotted over the Geant4 simulation. Black: (d,p) line for $^{18}N_{g.s.}$. Red: $^{17}N(d,d)$. Green: $^{17}N(p,p)$*

Impact

To clarify the impact of our experiment on the shell model structure studies we have contacted John Millener, Alex Brown and Furong Xu. The most interesting, unexpected and intriguing news came from Furong Xu who is the co-author of the new shell model interaction published in [18]. In [18] the energies were given for only the four lowest ^{18}N states because only these states were considered to be known. In our proposal we argue that two of these states are degenerate and actually 6 states are potentially known. We were particularly interested in the 0⁻/1⁻doublet. On our request, Cenxi Yuan and Furong Xu have calculated all the ^{18}N states below the neutron decay threshold and the new calculations are shown in Fig. 6 in comparison with other shell model calculations by Millener and using WBP. One can immediately notice that the Yuan interaction provides the correct ordering of the 1⁻ and 2⁻ lowest states which all other shell model calculations failed to achieve. However, at the same time the ordering of the 0⁻ and 1⁻ levels is also reversed. On the other hand, the ordering of the 0⁻ and 1⁻ levels, seen in the mirror nucleus ^{18}Na as populated in ^{17}Ne + p scattering, is the same as in the older versions of the shell model interaction. So, are these levels reversed in ^{18}N at all? What part of the interaction causes this inversion? Which shell model interaction is correct? Is it possible to have the correct ordering of the first two levels in ^{18}N without inversion of the 0⁻/1⁻ states? Nobody can answer these questions until the positions of these levels are pinned down by experiment.

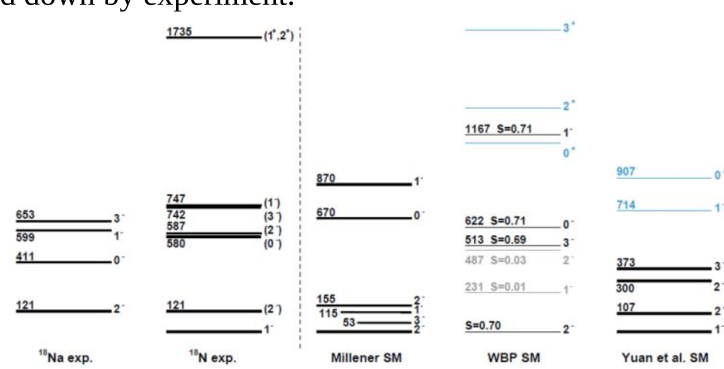

Figure 6: Comparison with new shell model calculations from ref.18 using an a priori interaction

The case for a new study of ^{18}N is also supported by Alex Brown and John Millener. From our discussion with them it became clear that in the past the ^{18}N energies were excluded from the fitting procedure of the shell model interactions because of the poor knowledge of the ^{18}N spectrum. Also, in the past the WBP and WBT effective interactions were derived in a truncated space including three interaction : a 0*p*-shell interaction, a cross-shell 0*p*1*s*0*d* interaction and a 1*s*0*d* interaction. Today, much larger model spaces can be and are used, requiring the development of a realistic interaction for these spaces. Including the ^{18}N spectrum is these developments will provide a strong test case for two-body matrix elements (TBME) in this mass region. In particular,

- Alex Brown mentions that he is now starting to develop a new interaction that can be used for calculations in the full p-sd model space, and that the simple nuclei are important input and ^{18}N is *one of the most important remaining to be determined"*. He identifies the simultaneous description of ^{16}N and ^{18}N with TMBE as an interesting matter to be resolved, but requires new data for ^{18}N, which we can provide.
- John Millener mentions that the Millener-Kurath interaction gets the ^{16}N order of levels wrong and that it attempts to fix this with adjustments to the TBMEs, resulting in a worse fit for some other nuclei and a particularly bad result for ^{18}N. Thus, ^{16}N by itself is not sufficient to define the relevant TBME. Also, he points out that the ^{18}N states have mixing, which has not been quantified and which could contribute to the challenge of describing these states. The transfer experiment should assist in quantifying this mixing. Finally, he mentions that *"the 0^- and 1^- energies especially are sensitive to the details of the interaction"*, which indicates that it is particularly important to know both of these energies.

Experimental Details

The T-REX detector allows the detection of the proton from the (d,p) reaction at backward angles using four 500μm silicon box detectors and a complete 500μm annular detector. The Si segmentation is sufficient to achieve an acceptable resolution in excitation energy. In order to resolve the closely spaced states in ^{18}N we plan to measure the γ-rays coming from the beam-like ejectile, using the Miniball array. We assume an efficiency of 5% at 1.3 MeV [17]. Doppler shift corrections will be applied. In addition, we plan to use the forward box detector of T-REX, comprising four telescopes of 140 μm ΔE and 500μm E, in order to measure the elastic scattering of the beam on both protons and deuterons in the target. This measurement allows an accurate normalisation of the measured differential cross section in the transfer channel. We plan to employ a device such as the Trifoil detector in the beam at zero degrees, beyond the target chamber. Immediately in front of the trifoil, the use of an appropriate thickness of aluminium, typically a few tens of micrometers, allows the products from compound nuclear reactions to be stopped, and lets the beam and transfer reaction products pass. The Trifoil then comprises a 10 μm thick plastic scintillator foil coupled to three photomultipliers. In use with beams of 5 MeV/u at TRIUMF [4] this layout has proven to be essential to eliminate background in the gamma ray spectra and suppress a large part of the carbon induced background in the proton spectra (improving signal to background ratio by an order of magnitude).

Summary of requested shifts:

According to the yield data base of the Isolde facility we assume a production rate of ^{17}N at 105 pps using a CaO target. Following the guide line for beam intensity we estimate an efficiency of 10% for the Trap+EBIS+ REX mass separator, giving around 10^4 pps on the reaction target. The estimated counts for 7 days of beam time, using a 0.5 mg/cm^2 thick CD_2 target can be found in Table 4. According to this estimate, it is necessary to run for a total of 7 days on the (d,p) reaction.

The expected energy resolution and detected count rate are estimated from a Geant4 simulation taking into account the target thickness and the geometry of the detection setup, as well as the angular distribution. The estimated count rate gives us confidence in our ability to extract useful angular distributions for the states with spectroscopic factors greater than 0.1. The gamma-rays can be used for gating, subject to statistics, but in any case will define very accurately the energies of states and their relative intensities, as for example was done in ref. [1].

Summary of requested shifts: We are requesting 21 shifts of ^{17}N beam at 5.5 MeV/u and 10^4 pps on the reaction target. The beam should be delivered at the T-REX + Miniball setup. We have initiated a liaison with the spokespersons of T-REX regarding this proposal.

Detector	Reaction	θ_{Lab}	Thickness
QQQ2	(d,p)	5-35°	500μm
X1	(d,p)	25-80°	500μm
X1	(d/p,d/p)	100-155°	140μm-500μm
QQQ2/1*	(d,^{3}He/t)	145-175°	140μm-500μm

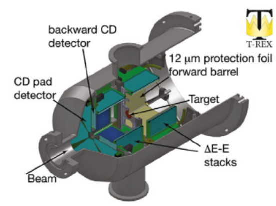

Table 2: *Layout of the detection for the T-REX array. Detectors marked with an asterisk are optional. Engineering drawing taken from [17]*

E (keV)	J^π	ℓ	S	$\sigma_{DWBA}(mb)$	Total count	Count per 1° bin	FWHM (keV)
0	1^-	2	0.01	15.14	10	0-1	275
121	2^-	2	0.70	28.91	1050	10-25	350
580	0^-	0	0.71	11.84	350	5-30	430
742	3^-	2	0.69	47.20	1650	20-40	360
747	1^-	0	0.71	34.85	1050	10-50	450

Table 3: *Expected counting rates and resolutions for states populated via $^{17}N(d,p)^{18}N$.*

Beam	Min.Intensity	Target Material	Ion Source	Shifts
^{17}N	1.10^4	nano-CaO	Helicon	30

Table 4: *Summary of the beam production informations*

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *(name the fixed-ISOLDE installations, as well as flexible elements of the experiment)*

Part of the	Availability	Design and manufacturing
MINIBALL + T-REX	☒ Existing	☒ To be used without any modification

HAZARDS GENERATED BY THE EXPERIMENT

(if using fixed installation) Hazards named in the document relevant for the fixed [MINIBALL + only CD, MINIBALL + T-REX] installation.

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	[material]		
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		

• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the environment	[chemical agent], [quantity]		
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]		

0.1 Hazard identification

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above):

Nothing additional to the standard setup of T-REX and MINIBALL.