EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Clarification to the ISOLDE and Neutron Time-of-Flight Committee

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

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Abstract: We propose a 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 will assist in resolving and determining the precise excitation energies for bound states in ^{18}N.

Requested shifts: 30 shifts
Installation: Miniball + T-Rex in standard configuration

1 Motivations

This proposal was defended at the INTC meeting in June 2013 and the referees found the physics case interesting but would like to know how the outcome of this experiment will impact the Shell Model on the one hand and the astrophysics on the other hand. The full referees' report is provided below:

CERN-INTC-2013-012, INTC-P-377: *^{18}N: a challenge to the shell model and a part of the flow path to r-process element production in Type II supernovae.*

It is proposed to study the bound states in ^{18}N using the (d,p) reaction at 5.5 MeV/u in inverse kinematics with the T-REX and MINIBALL arrays. The data will be used to constrain the couplings between the $p_{1/2}$ proton and sd neutrons which are not well determined in the shell model, and will serve as an input to calculate the cross section of the n-capture by ^{17}N which is of astrophysical interest. In general the physics case is found to be interesting and important. However, the impact of the proposed study on the astrophysical calculations, on the shell model, and on the reaction theory was not clear. Therefore, a Letter of Clarification is requested where authors should further elaborate these points.

2 Impact on shell model structure

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 [1]. In [1] the energies were given for only the four lowest ^{18}N states because only these states were considered to be known. In our proposal submitted in May, we argued that two of these states were degenerate and actually 6 states were potentially known. We were particularly interested in the $0^-/1^-$ doublet that was expected to be populated with a significant strength due to them having large spectroscopic factors as predicted by shell model calculations using the WBP interaction. 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. 1 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 from (hopefully, our) experiment.
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 [2] were derived in a truncated space including three interaction : a $0p$-shell interaction, a cross-shell $0p1s0d$ interaction and a $1s0d$ 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,
(i) 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.
(ii) 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.
How can our experiment help to solve these questions? We expect that the 0^- and 1^- states should be populated in the ^{17}N(d,p)^{18}N reactions because of the larger spectroscopic factors (S $\sim$ 0.7). We also expect that we will be able to detect gamma-rays from their decays to the lower levels. We have estimated the decay probabilities of the 1^-_2 and 0^-_1 states for different assumptions about their positions corresponding to those given in Fig.1. When their energies are assumed to be given by the charge-exchange experiment [3] (Fig.1b) we have found that the 1^-_2 will decay mainly through an M1 transition to the $1^-_{g.s.}$ and to the 2^-_1 state emitting γ-rays of respectively $\sim$750 keV and $\sim$630 keV while the 0^-_1 state will decay directly to the ground state through an M1 transition emitting a γ-ray of $\sim$580 keV. Similar conclusions are made for other assumptions about the locations of 1^-_2 and 0^-_1. The large difference in energy of those gamma rays insure that we will be able to separate the two states from each other, and most likely obtain γ-gated proton differential cross section allowing a firm spin assignment and energy establishment.
Summarising, our experiment will have a strong impact on fixing the shell model interactions (especially cross shell interactions and n-p pairing due to the tensor force) in the neutron-rich region where the r-process path takes place. It will solve the level inversion puzzle revealed in the latest shell model calculations made especially in response to our request. The measurements we propose are not only relevant to determining the structure of light r-process nuclei, but also it is *timely to measure them now*, because Alex Brown and the Japanese/Chinese are both interested in refining the new interactions that they are in the process of developing.

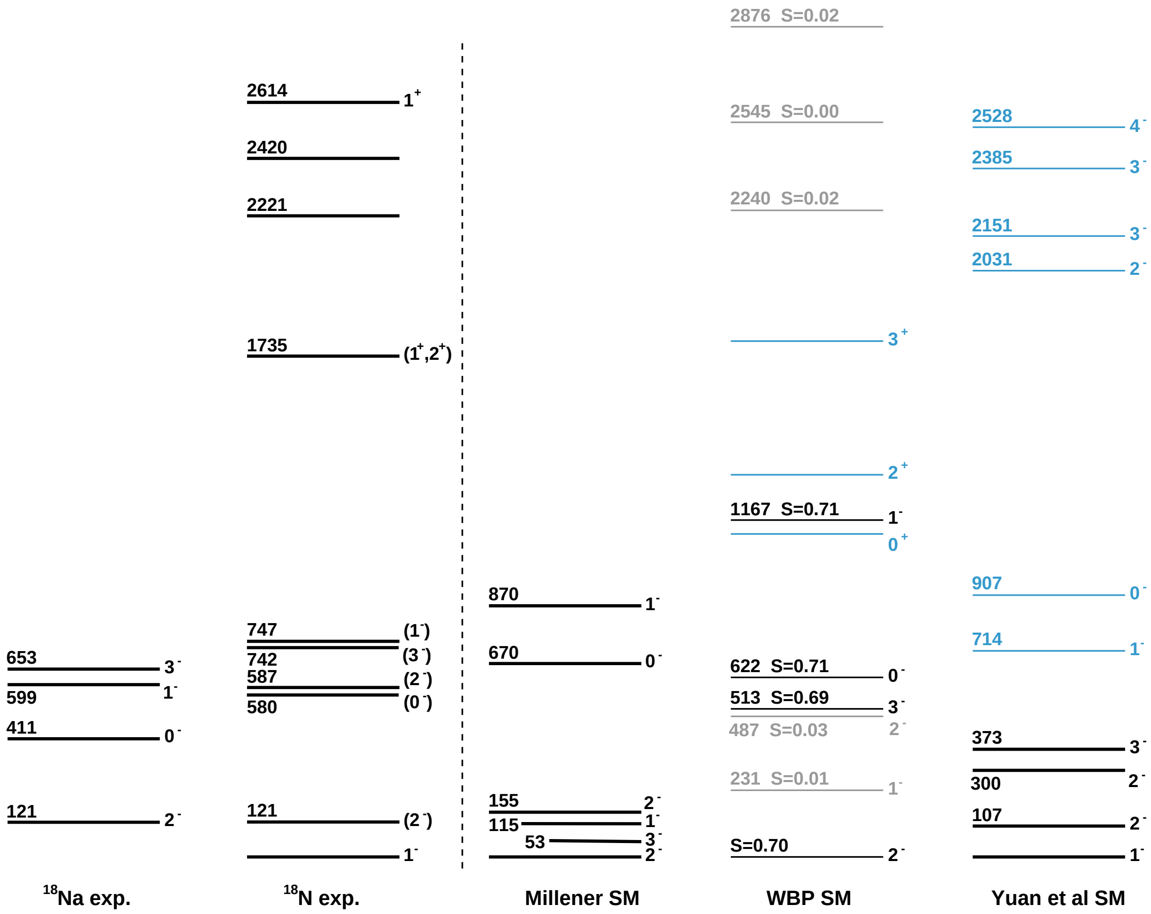

Figure 1: *^{18}N and mirror ^{18}Na experimental level schemes compared to various shell model calculations.*

3 Impact on nuclear astrophysics

To clarify the impact of our proposal on nuclear astrophysics research we have contacted Thomas Rauscher and Nobuya Nishimura. We have found out that neutron capture reactions on neutron-rich light nuclei, including ^{17}N$(n,\gamma)^{18}$N, are routinely used for all supernovae scenarios. The data for these reactions are taken from JINA REACLIB. We have checked this data base and were surprised to find that the data for ^{17}N$(n,\gamma)^{18}$N are referred to in that library as "experimental". This is of course not true as no such an experiment could have ever been done. We have checked that what is contained in REACLIB represents the results of potential model calculations based on old shell model calculations of spectroscopic factors and on an incomplete knowledge of the ^{18}N spectrum. Therefore, the most obvious impact of our experiment will result in the correction of REACLIB as used for numerous astrophysical purposes. It is difficult to say to what extent the outcomes of those calculations will be influenced. Nobuya Nishimura has performed a few restricted calculations for us which seems not to give any significant changes in the cases calculated. However, the full investigation of the importance of the ^{17}N$(n,\gamma)^{18}$N reaction needs the investment of much more time.
Apart from the supernova explosions, the ^{17}N$(n,\gamma)^{18}$N reaction also occurs in modern versions of the inhomogeneous Big Bang nucleosynthesis (IBBN) since it is still possible that density fluctuations are introduced into the Early Universe by some mechanism. These versions take account of observational constraints of the ratio of baryonic density to the critical density from the latest measurements of the Cosmic Microwave Background Radiation. The input data of the ^{17}N$(n,\gamma)^{18}$N reaction for IBBN calculations is available only from REACLIB and their quality is unverified.

4 Impact on reaction theory

As a clarification, no claim that this experiment can make any improvement in terms of reaction theory was made in our proposal. It is however stated that the latest developments performed at the University of Surrey, will be used to analyse the data that we obtain. These latest developments refer to the adiabatic theory of (d,p) reactions with non-local optical potentials as published in the Physical Review Letters and Physical Review C this year [4, 5]. Further advances in the development of (d,p) theory have been made at Surrey even since these publications, which will help to extract reliable spectroscopic factors and asymptotic normalization coefficients from the ^{17}N$(d,p)^{18}$N reaction.

Summary of requested shifts: We are requesting 30 shifts of ^{17}N beam at 5.5 MeV/A 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.

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

Table 1: *Summary of the beam production informations*

References

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