SC P

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/ISC 98-23
ISC/P105
14 April 1998

SW 9906

Proposal to the ISOLDE Committee

# Investigations of neutron-rich nuclei at the dripline through their analogue states: The cases of $^{10}Li$–$^{10}Be$ (T=2) and $^{17}C$–$^{17}N$ (T=5/2)

L. Axelsson[1], U. Bergmann[2], M.J.G. Borge[3], G. Chubaryan[4], G. Crawley[5], C. Forssén[1], L.M. Fraile[3], H.O.U. Fynbo[2], V.Z. Goldberg[6], P. Hornshøj[2], B. Jonson[1], T. Lönnroth[7], K. Markenroth[1], M. Meister[9], I. Mukha[2], T. Nilsson[8], G. Nyman[1], K. Riisager[2], G.V. Rogachev[6], M.V. Rojkov[6], G. Schrieder[9], I.N. Serikov[6], H. Simon[8], S. Tabor[10], O. Tengblad[3], W. Trzaska[11], F. Wenander[12], and M.V. Zhukov[1].

Spokesmen: V.Z. Goldberg, B. Jonson
Contactman: T. Nilsson

## Abstract

We propose to study the elastic resonance scattering reactions $^{9}Li$+p and $^{16}C$+p to investigate the energies, spins and parities of the lowest T=2 states in $^{10}Be$ and the T=5/2 states in $^{17}N$. These are analogue states of the ground states and first excited states in $^{10}Li$ and $^{17}C$. We request **12** shifts of $^{9}Li$ and **20** shifts of $^{16}C$ from REX-ISOLDE with maximum beam energy.



1) Chalmers University of Technology, S 41296 Göteborg, Sweden
2) Institut for Fysik og Astronomi, Aarhus Univ., DK 8000 Aarhus C, Denmark
3) Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
4) Cyclotron Institute, Texas A & M University, College Station, TX 77843-3366, USA
5) College of Science and Mathematics, University of South Carolina, SC 29208, USA
6) Russian Scientific Research Center "The Kurchatov Institute" R 123182 Moscow, Russia
7) Department of Physics, Åbo Akademi, FIN 20500 Turku, Finland
8) EP Division, CERN, CH 1211, Geneve 23, Switzerland
9) Institut für Kernphysik, Technische Universität, D 64289 Darmstadt, Germany
10) Physics Department, Florida State University, Tallahassee, Fl 32306, USA
11) Department of Physics, University of Jyväskylä, FIN 40351 Jyväskylä, Finland
12) PS Division, CERN, CH 1211, Geneve 23, Switzerland

# 1 Introduction

Studies of nuclei in the dripline regions continue to attract a large interest worldwide. This originated in the realization that the loose binding of nuclei near the border of stability and their large excess of neutrons or protons give rise to phenomena such as halo states, clusters and new shell structures. Both on the experimental and theoretical sides there is steady progress which has been summarized in several recent review articles, see for example Refs. [1, 2, 3, 4].

The analysis of available experimental data, as well as future advances in the theoretical understanding of dripline nuclei, are still hampered by the absence of information about the quantum characteristics of their nuclear states. For dripline nuclei above $^{9}$He (the unbound $^{8}$He+n system), there is essentially no reliable information about the non-zero spin states. It is well-known that the understanding of Borromean nuclei requires information about the structure of their binary sub-systems. Two examples are $^{10}$He and $^{11}$Li, where one needs knowledge of the $^{9}$He and $^{10}$Li ($^{9}$Li+n) structures. The typical approach to obtain this kind of information is to produce the needed nuclear species in some reaction. When the nuclei of interest are very far from both target and beam nuclear species, as is the case for dripline nuclei, using conventional stable beams for this production becomes increasingly difficult. This is exemplified in several recent experiments where complicated, largely unknown reaction mechanisms have been employed. In addition, these reactions are characterized by small reaction cross-sections resulting in low statistics, a large background and limited energy resolution. To draw unambiguous conclusions from such data is therefore complicated. The literature on different attempts to learn about the structure of $^{10}$Li provide examples of these problems, see the review [5].

One possible way to proceed is to use radioactive beams combined with simple, well understood reactions to populate the states in question. An illustrative example is provided by the unbound nucleus $^{11}$N which was studied by elastic resonance scattering of a radioactive beam of $^{10}$C ($T_{1/2}$=19.3 s) impinging on methane gas which acted as a proton target [7]. This technique, which is very successful for proton-rich nuclei, can be developed so that it can be used to obtain new information on very neutron-rich nuclei, where many different radioactive beams are now available.

The experiment we propose aims at obtaining direct evidence of the quantum characteristics of the lowest levels in $^{10}$Li and $^{17}$C by investigating the analogue states in $^{10}$Be and $^{17}$N belonging to the same respective isobaric multiplets.

The measurements proposed here are two of the most suitable at the present REX-ISOLDE beam energy. They are also very relevant in our program for investigations of dripline nuclei, concerning both the physics around the Borromean nucleus $^{11}$Li and the odd-mass neighbour of the heaviest known one-neutron halo nucleus $^{19}$C. We believe that this experiment will constitute an example of a type of experiments that may easily be extended to other interesting cases, for example $^{7}$He, $^{9}$He and $^{13}$Be, when higher REX-ISOLDE beam energy becomes available.

# 2 Resonance scattering applied to neutron-dripline nuclei

The neutron dripline can be defined as the line connecting the last bound neutron-rich member of each isobaric chain along the nuclear chart. At present there is no technical possibility to reach such nuclei in neutron resonance scattering reactions. For unbound systems one would need a neutron beam and a radioactive target. This opportunity is naturally excluded since the needed radioactive nuclei are very shortlived. On the other hand, bound systems cannot be reached in simple resonance scattering experiments since they are below the neutron threshold. But Nature gives us a helping hand: due to the isotopic-spin symmetry one can learn about the interesting states in very neutron-rich nuclei from a study of their isobaric-analogue states. The neutron-stable states in very neutron-rich nuclei and the corresponding isobaric analogue states when a neutron is replaced by a proton differ because of different charges. Due to the Coulomb interaction the analogue states on the proton-rich side are shifted upwards relative to isospin(T)-allowed proton decay. Thus, even if the corresponding neutron-rich nucleus is bound, the analogue state is proton unstable, which gives the possibility to study it in elastic resonance scattering on protons. This is illustrated for the case of $^{17}$C in Figure 1. Due to the Coulomb interaction, which violates isospin conservation, the energy difference between the two states in the isobaric multiplet is

$$S_p(^{17}N, T = 5/2) - S_n(^{17}C) = \Delta V_{Coul.} \tag{1}$$

In a simple uniform sphere model and with A~3Z it has been found [6] that the Coulomb shift can be well approximated by the expression

$$\Delta E_{Coul.} = 0.65 Z^{2/3} (MeV) \tag{2}$$

where Z is the charge of the neutron-rich nucleus. For $^{17}$C, $\Delta E_{Coul.}$ is 2.14 MeV, so that the lowest analogue state is expected to lie about 1.4 MeV above the T-allowed proton decay threshold, Figure 1. The expression 2 does not take into account the nuclear structure of the states and the precision of this estimate is a few hundred keV.

The example above was given to illustrate the principle of the study of analogue states in proton elastic resonance scattering, and their relation to the corresponding neutron-rich states. Generally, these measurements give the possibility to determine spins and parities of the populated states, as well as their excitation energies and decay widths. The experimentally determined excitation energies can be used for a direct evaluation of the Coulomb displacement energies which in turn are related to the charge distribution in the nucleus [8, 9]. The widths are directly related to the single-particle spectroscopic factors and can bring direct evidence on, for example, deformation.

Thus, investigation of analogue states can yield new knowledge on the spin-parity assignments, as well as information that can be directly related to structural features of neutron-rich dripline nuclei.

The next section will describe the experimental technique that we propose to use at REX-ISOLDE for these measurements.

## 3 Experimental method

The proposed experiment is technically very similar to the $^{11}$N experiment [7] performed at GANIL. The radioactive beam is brought to a scattering chamber filled with $CH_4$ gas via a thin window which is separating the scattering chamber from the vacuum in the beamline. The pressure of the target gas is regulated so that the beam from REX-ISOLDE is slowed down to a complete stop, which means that an energy range of about 2 MeV is continuously scanned. The scattered protons will then have energies ranging from zero energy up to about 8 MeV which will be measured in $\Delta$E-E telescopes placed in and around the direction of the incoming beam.

The high efficiency of the method was demonstrated in [7] where the excitation function of $^{11}N$ was measured with a beam intensity of about $7 \cdot 10^3$ $^{10}C$/sec. The effective energy resolution in the measurements was about 25 keV and we expect to have about the same at REX-ISOLDE. In the proposed study of analogue states there are, however, some important new experimental features:

- In the study of $^{11}N$ with the $^{10}C$+p interaction, only levels with T=3/2 could be excited. In the study of high-lying analogue states, on the other hand, both $T_>$ (our aim) and T< states may be excited. There are many $T_<$ states at high excitation energy and the population of them, and their subsequent decay, is a new source of background, not present in our earlier experiments. An example is the $^{10}Be$ case where we expect the T=2 states to lie above 20 MeV. At such high excitation there is of course a very high density of T=1 levels.
- There are many open decay channels for the $T_>$ states. This can give a general decrease in the elastic resonance-scattering cross-section.

None of these problems are expected to be critical for the measurement. Let us consider the Breit-Wigner expression for resonance cross-sections:

$$\sigma \sim \frac{\Gamma_i^2}{(E - E_r)^2 + \frac{\Gamma_t^2}{4}} \tag{3}$$

where $\Gamma_i$ is the width of the resonance in the elastic channel and $\Gamma_t$ is the total width of the resonance. Some consequences of expression (3) can be summarized as follows.

The $T_<$ states which can be excited in elastic resonance scattering are broad since there are many different decay channels open at about 20 MeV excitation energy. The partial width $\Gamma_i$ of the elastic channel should not exceed 10% of the total width due to the small penetrabilities (the c.m. energy is less than 2 MeV). This means that we expect a background from population of $T_<$ levels of maximum 1% of the population of states characterized by the ratio $\Gamma_i/\Gamma_t \sim 1$.

Most of the energetically open channels from the $T_>$ states are isospin forbidden, see Figures 1, 2 and 3. As a rule, only proton decay is allowed due to isospin conservation. This gives comparatively longlived $T_>$ states and we therefore expect to observe narrow states. The admixture of $T_<$ configuration in the $T_>$ states is related to violation of isospin conservation caused by Coulomb interaction, and usually results in a contribution of some keV to the widths of the $T_>$ states. As an example, the width of the lowest T=3/2 state in $^9Be$ at about 14 MeV excitation energy is about 0.4 keV since there are no T-allowed decays for the state. Thus we expect values of the $\Gamma_i/\Gamma_t$ ratio to be around 1 and correspondingly large cross-sections for excitation of the $T_>$ states in the elastic resonance scattering.

## 4 The $^9$Li+p reaction

As mentioned in the Introduction, no measurements with conventional beams have until now given a clear evidence for the lowest 1s resonances in the $^{10}Li$ spectra. However, most of the available data indicate that the supposed 1s ground state of $^{10}Li$ lies very close to the $^9$Li+n threshold. Therefore we should start our search for T=2 states in $^{10}Be$ at the threshold for zero binding energy of $^{10}Li$. The energy corresponding to the T=2 level was estimated using eq. 2 under the assumption that the binding energy of the odd neutron in $^{10}Li$ equals zero. Even if the level lies 0.7 MeV lower (due to the Nolen-Schiffer anomaly [11] and deviations from the prediction in eq. 2) the corresponding recoil protons in our measurement will have an energy of more than 1 MeV which is easy to detect.

There have been several attempts to observe T=2 states in $^{10}$Be using T-forbidden reactions (as for example t+$^7$Li → p+$^9$Li [5]). Indeed, some small (~20%), narrow anomalies were observed in the excitation functions which were interpreted as narrow T=2 states at 21.17 MeV and 21.23 MeV excitation energies in $^{10}$Be. The evidence is relatively weak and the results are not considered as reliable [10]. Figure 3 shows the possible positions of T=2 resonances in $^{10}$Be and the thresholds for different decay channels. The $^9$Li+p channel is the lowest T-allowed channel. As illustrated in Figure 3, the T-allowed neutron decay is possible above 21.2 MeV in $^{10}$Be. The maximum neutron-decay energy is about 0.4 MeV with the REX-ISOLDE energies. Therefore, we expect at most comparable partial widths related to T-allowed decays by protons (the investigated channel) and neutrons for the states close to the energy limit in the experiment proposed here. The effect of the presence of an open neutron-decay channel will result in a decrease of the proton cross-sections, but this is of minor importance at the present intensities of the $^9$Li beam. This means that we can investigate T=2 levels in $^{10}$Be corresponding to excitation energies in $^{10}$Li from zero (relative to the neutron threshold) up to about 0.9 MeV. Based on data with conventional beams, at least five levels are claimed to be present in this energy region. From the experiments we propose here we expect to be able to determine the position, widths of the levels and also to deduce the relative angular momentum between $^9$Li and the proton.

## 5 The $^{16}$C+p reaction

The spin of the $^{17}$C ground state is not known. The ground state wave function can be expected to have a $1s_{1/2}$ or a $0d_{3/2,5/2}$ neutron coupled to $0^+$ or the $2_1^+$ state of $^{16}$C. The measured momentum width of $^{16}$C fragments after a one-neutron removal reaction from $^{17}$C shows a value $\Gamma$ = 141±6 MeV/c while the $^{18}$C fragments after the same reaction with $^{19}$C gives a value of 69±3 MeV/c [12, 13]. Different possible spin values have been proposed (see discussion in ref. [12]) but the proximity of the $s$- and $d$-states makes the prediction of the ground state configuration based only on the measured momentum distributions difficult. There are also speculations about large deformation of neutron-rich nuclei such as $^{17,19}$C [14]. The measurements of the single particle widths of the IAS may resolve the ambiguities in this problem.

The Coulomb energy shifts are different for $1s_{1/2}$ and $0d_{3/2,5/2}$ due to the Thomas-Ehrman effect [15, 16]. We have calculated the positions of the lowest T=5/2 states in $^{17}$N assuming $1s_{1/2}$ or $0d_{5/2}$ using a Woods-Saxon potential. The results indicate that the $1s$ state should lie about 1 MeV above the proton emission threshold and the $d$-state about 0.6 MeV higher, see Figure 3. Their predicted single particle widths are also different, namely 0.4 and 0.15 MeV, respectively. Therefore, the two different configurations can readily be distinguished by measurements of cross sections, angular distributions, and positions and widths of the resonances.

## 6 Beam-time request

We propose to study the elastic resonance scattering reactions $^{9}$Li+p and $^{16}$C+p to investigate the energies, spins and parities of the lowest T=2 states in $^{10}$Be and the T=5/2 states in $^{17}$N with radioactive beams from REX-ISOLDE. We have assumed a beam intensity of $3.6 \cdot 10^{6}$ ions/s for $^{9}$Li and 400 ions/s for $^{16}$C and based on these numbers we request:

- 2 MeV/u beam of $^{9}$Li for **12** shifts.
- 2 MeV/u beam of $^{16}$C for **20** shifts.

We also request the use of the new ISOLDE Data Acquisition System.

## References


[1] M.V. Zhukov et. al., *Phys. Rep.* **231**, 151 (1993).

[2] P.G. Hansen, A.S. Jensen, and B. Jonson, *Annu. Rev. Nucl. Part. Sci.* **45**, 591 (1995).

[3] I. Tanihata, *J. Phys.* **G157** (1996).

[4] B. Jonson, and K. Riisager, *The Royal Society, Theme Issue on "Science with Radioactive Beams"*

[5] S.N. Abramovish, B.Ya. Guzhovskii, and L.M. Lazarev, Phys. Part. Nucl. **26**(4), 423 (1995).

[6] A. Baz et al., *in* "Light and Intermediate Nuclei at the Borders of Nuclear Stability" Moscow, Nauka, 1977 (in Russian).

[7] L. Axelsson et al., Phys. Rev. **C54**, R1511 (1996).

[8] T. Teranishi et. al., Phys. Lett. **B407**, 110 (1997).

[9] T. Suzuki and T. Otsuka, Nucl. Phys. **A635**, 86 (1998).

[10] F. Ajzenberg-Selove, Nucl.Phys. **A490**, 1 (1988).

[11] J.A. Nolen, J.P. Shiffer, Ann. Rev. Nucl. Sci. **19**, 471 (1969).

[12] T. Baumann et. al., Phys. Lett. **B439**, 256 (1998).

[13] D. Ridikas et. al., Nucl.Phys. **A628**, 363 (1988).

[14] Ren Zhongzhou et. al., Nucl. Phys. **A605**, 75 (1996).

[15] J.B. Ehrman, Phys. Rev. **81**, 412 (1951).

[16] R.G. Thomas, Phys. Rev. **88**, 1109 (1952)

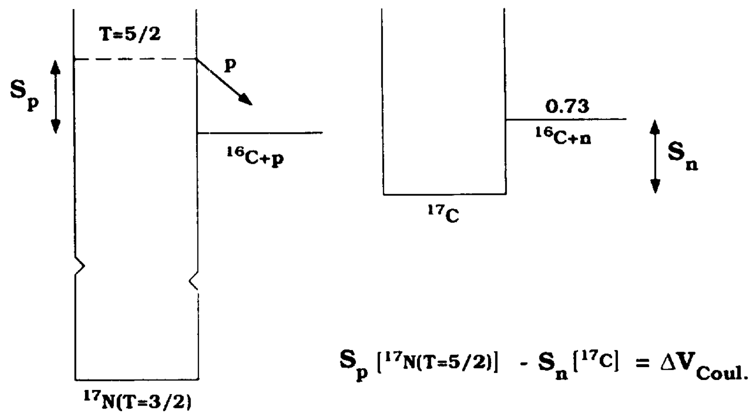


Figure 1:

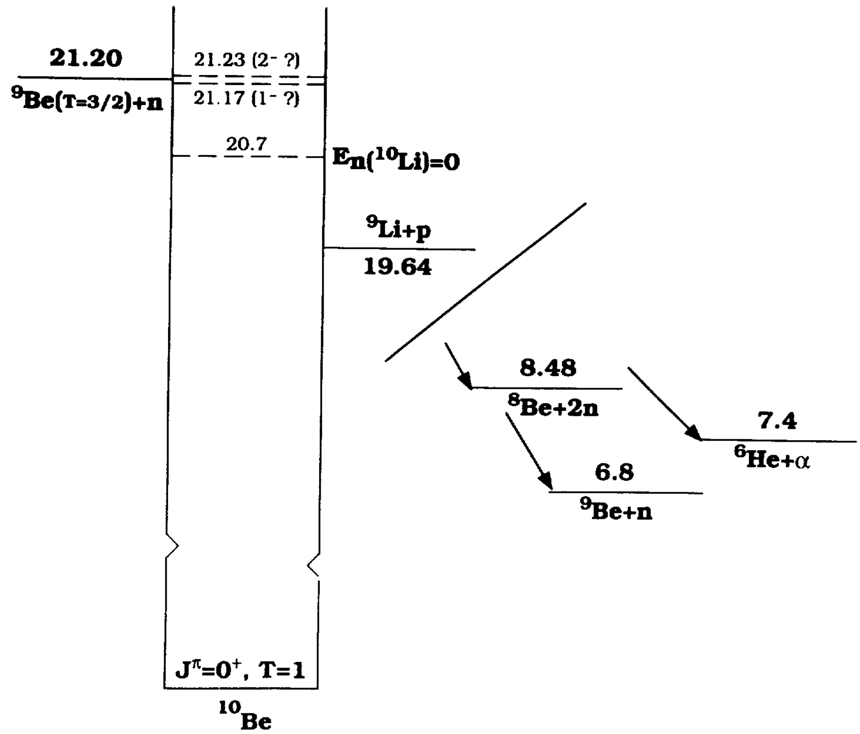


Figure 2:

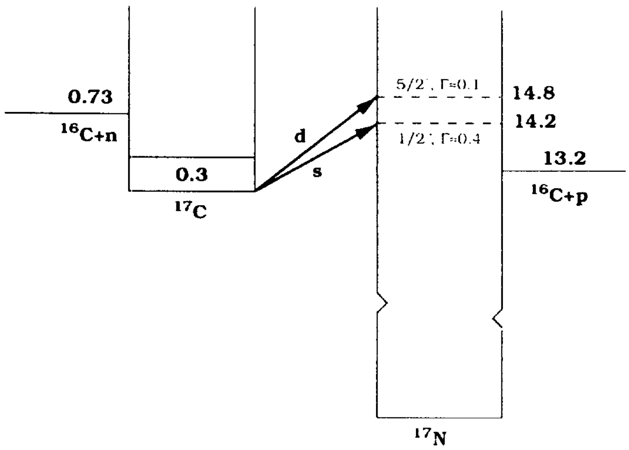


Figure 3: