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Experiments with the newly available Carbon beams at ISOLDE

Resonance scattering and beta decay studies

M. Alcorta[1)], M.J.G. Borge[1)], C.Aa. Diget[2)], L.M. Fraile[3)], H. Frånberg[3)],[4)]
H.O.U. Fynbo[2)], H.B. Jeppesen[3)], B. Jonson[5)], H.H. Knudsen[2)], U. Köster[3)],[6)]
M. Madurga[1)], T. Nilsson[5)], G. Nyman[5)], S.G. Pedersen[2)], K. Riisager[3)], G. Schrieder[7)]
M. Turrion[3)], O. Tengblad[1)] and E. Tengborn[4)]

Spokesperson: H.O.U. Fynbo and H.B. Jeppesen
Contactperson: H. Frånberg

Abstract

Recent target-ion-source developments at ISOLDE providing significantly increased yields for Carbon isotopes, open up for new and intriguing experiments. We propose to exploit this in two different ways.
In particular we wish to do an elastic resonance scattering experiment of ^{9}C on a proton target to gain information on the particle unbound system ^{10}N. Furthermore we wish to perform decay experiments of the neutron rich Carbon isotopes, with special focus on $^{17-19}$C but also including a test to see whether the even more neutron-rich isotopes ^{20,22}C are accessible at ISOLDE.

[1)] Instituto de Estructura de la Materia, CSIC, Madrid, Spain
[2)] Institut for Fysik og Astronomi, Århus Univ., Århus, Denmark
[3)] ISOLDE, PH Department, CERN, Geneva, Switzerland
[4)] Paul Scherrer Institute, Villigen, Switzerland
[5)] Fundemental Physics, Chalmers University of Technology, Göteborg, Sweden
[6)] ILL, Grenoble, France
[7)] Institut für Kernphysik, Technische Universität Darmstadt, Darmstadt, Germany

1 Introduction

The area of light exotic nuclei holds much interesting physics and has therefore been investigated at many laboratories, including ISOLDE [1, 2, 3, 4]. But unfortunately, until very recently ISOLDE could not produce efficiently the elements in the gap between Beryllium and Neon, so only experiments that could work with relaticely limited intensities, eg. ^{9}C [5], could be done. In-flight facilities has therefore done most of the work in this region with contributions also from IGISOL and TRIUMF for some specific isotopes. Recent target-ion-source developments [6, 7, 8] have made some of these chemically difficult elements accessible. Hence several experiments are now becoming feasible, we therefore propose to start off with two different lines of inquiry employing Carbon isotopes (if successful dedicated experiments on the neutron-rich Nitrogen isotopes would be the next step).

i) An elastic resonance scattering (ERS) experiment of ^{9}C on protons to investigate the low-lying states in the unbound nucleus ^{10}N which is of particular interest since it is the mirror nucleus of ^{10}Li.

ii) Beta-decay studies of the neutron-rich carbon isotopes. In particular we would search for beta-delayed particles from $^{17-19}$C. We would also like to investigate the possibility for going further away from stability by measuring the yields of ^{20}C and ^{22}C, to investigate whether decay studies of these nuclei would be feasible. In particular ^{22}C could be very interesting, it is the heaviest Carbon isotope, the lightest bound nucleus with N=16, and has as large a A/Z-ratio as ^{11}Li.

2 Elastic resonance scattering of ^{9}C on protons

ERS of ^{9}C on protons would give information on low-lying states in the unbound nucleus ^{10}N. This would be of great value both since ^{10}N is interesting on its own but indeed also since ^{10}N is the mirror nucleus of ^{10}Li. Knowledge on the low-lying states in ^{10}N could be used to extract information on low-lying states in ^{10}Li, which are indispensable for theory when describing ^{11}Li - the most pronounced halo nucleus. We have already performed experiments at REX-ISOLDE looking for states in ^{10}Li (IS367 [9, 10]) and their analogues in ^{10}Be (IS371 [9]), getting information also on ^{10}N will help to clarify the situation.

So far only one experiment has succeeded in obtaining information on ^{10}N. This was a four-nucleon transfer reaction , which showed evidence for a state at 2.6(4) MeV (Γ=2.3(16) MeV) above the ^{9}C+p threshold [11]. This only revealed a broad bump and was unable to determine whether it was a s- or p-wave resonance. Without this clarified it would be difficult to identify this as the ground state or as an excited state. Indeed calculations indicate that the observed state is the analogue state of the 0.24 MeV 1^{+} state in ^{10}Li [12]. Apart from this, an earlier attempt to measure ERS of ^{9}C on protons at GANIL, was unsuccessful [13]. Thus it seems reasonable to say that the situation is unsettled. Therefore we think that it would be only natural to perform a second experiment with the aim of extracting information on the low-lying states in ^{10}N.

From the mirror comparison (and in analogy to ^{11}N-^{11}Be [14]) one would expect that the ground state in ^{10}N is an s-state (as is the case for ^{10}Li) which theory places at a roughly 2 MeV excitation energy in the ^{9}C+p system (1.5 MeV [15] and 2.3(4) MeV see reference in [11]). The low one- and two-proton separation energy of ^{9}C implies that break-up processes can occur and produce low energy protons.

	$t_{1/2}$	S_p	S_{2p}
^{9}C	126.5(9) ms	1.300(2) MeV	1.438(2) MeV

At REX-ISOLDE we can presently produce a ^{9}C beam with 3.0 MeV/u, corresponding to a center-of-mass energy of 2.7 MeV, which means that we are able to scan the excitation energy in ^{9}C+p from 1.4 MeV to 2.7 MeV cleanly without contamination from break-up of ^{9}C. This is precisely the window in which the lowest s- and/or p-states should be present in ^{10}N. Furthermore the bunched beam structure at REX-ISOLDE allows to suppress the background from beta-delayed protons emitted in the decay of ^{9}C by three orders of magnitude.

In earlier ERS experiments at REX-ISOLDE [9] it has been shown that a resolution better than 100 keV, in the excitation energy spectra, can be obtained. This resolution should be sufficient to determine the spin of possible states seen in ^{10}N.

Carbon isotopes are released in form of CO and CO_2 from oxide targets. So far high losses occured in ISOLDE target and ion source units due to gettering of the CO and CO_2 on the hot tantalum surfaces of the target and ion source unit (container, part of the transfer line, ion source cathode). Thus, about 99% of all radioactive carbon isotopes are lost by gettering before being ionized [6]. In her PhD thesis (development of new ISOL beams of carbon), H. Frånberg has studied systematically the adsorption behaviour of CO and CO_2 and found that on quartz and alumina surfaces the adsorption times are negligible at room temperature and higher [8]. Thus, CO and CO_2 would be released equally rapidly and efficiently as noble gases when covering the tantalum surfaces by an inner layer of quartz (for use up to ca. 1200°C) or alumina (up to ca. 1800°C). As the standard ISOLDE plasma ion sources of the FEBIAD type require a hot metal cathode, instead a 1+ ECRIS should be used. The MiniMono ECRIS has already been tested off- and on-line at ISOLDE [16]. Reproducing the previously obtained on-line efficiencies (the off-line efficiencies are still higher) would immediately boost the radioactive carbon yields by about two orders of magnitude.

Previously measured ^{9}C yields from ISOLDE MgO and CaO targets combined with FEBIAD type ion sources vary between 700/μC and 4000/μC. Hence, we can expect conservatively a ^{9}C yield of $\geq 7 \cdot 10^{4}/\mu$C.

Moreover carbon release tests have been performed recently with various fiber and powder target materials [7]. The former (e.g. Al_2O_3, ZrO_2, HfO_2) showed clearly a faster release than the latter (MgO). Thus, an additional yield improvement is expected due to the faster release and reduced decay losses for short-lived carbon isotopes when using a fiber target.

We consider a ^{9}C yield of about $7 \cdot 10^{4}/\mu$C as reasonable minimum to perform the proposed REX experiment, since previous ERS experiments were successful with $1-10 \cdot 10^{3}$ ^{9}Li/s on target after the REX-LINAC [9].

It should be noted that the CO molecules need to undergo a break-up in the REX-EBIS, for which the efficiency is presently unknown. However, this efficiency is expected to be quite large since Oxygen is more electro-negative than Carbon, thus it is more probable that the Carbon stays ionized and thereby inside the electron beam. The break-up efficiency should be tested offline. To compensate for the break-up efficiency it should be noted that the 1% transmission through REX-ISOLDE is based on ^{9}Li experiments, which has a low trapping efficiency in REX-TRAP, due to the low mass. This, and the cooling in REX-TRAP, should be better for the heavier CO molecules.

2.1 Experimental setup

The experimental setup for the ^{9}C ERS at REX-ISOLDE will consist of a collimator shortly before the proton target (PolyEthylene target of 60 μm), in which the ^{9}C beam

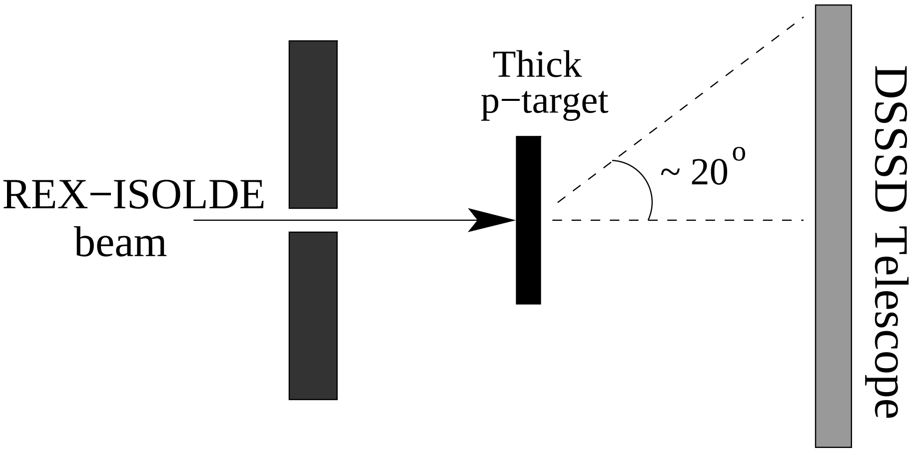

Figure 1: Setup for elastic resonance scattering of ^{9}C on protons.

will be fully stopped, and a Double-Sided Silicon Strip-Detector (DSSSD) of thickness 60 μm backed by a 1500 μm Si-pad detector, all centered at zero degrees. The setup is shown in fig. 1 and will be very similar to the setup used in earlier ERS experiments [9].

3 Beta-decay of neutron rich Carbon isotopes

Beta-delayed particle decay of exotic nuclei has long been studied at ISOLDE [1, 2, 3, 4] and with the advent of neutron-rich Carbon-molecular beams at ISOLDE we propose to measure the beta-delayed charged particle spectra of $^{17-19}$C. The open decay-channels are shown in tab. 1 together with the Q-values. We note that ^{22}C also has an open beta-delayed deuteron channel, ($Q_{\beta d}$=2.6(9) MeV), 4 neutron channel ($Q_{\beta 4n}$=7.9(9) MeV) and 5 neutron channel ($Q_{\beta 5n}$=5.05(90) MeV) which could be of interest to study in a future experiment.

3.1 Previous experiments on the neutron-rich Carbon isotopes

Due to the fact that these isotopes have mainly been produced at in-flight facilities little information on their beta decays are known. A summary of the known properties is given below:

^{17}C) The half-life of ^{17}C has been found to be 193(6) ms [18]. The P_n was in the same experiment found to be 10.8(2.7)%. Further this experiment also measured a neutron ToF spectrum, which exhibited four neutron groups below 2 MeV. Recently the ground state spin of ^{17}C was determined to 3/2$^+$ by β-NMR [19].

	^{17}C	^{18}C	^{19}C	^{20}C	^{22}C
Q_β	13.168(23)	11.816(36)	16.56(10)	15.79(25)	21.2(9)
$Q_{\beta t}$	3.069(17)	0.11(3)	3.8(1)	1.57(24)	5.9(9)
$Q_{\beta\alpha}$	2.052(17)	–	1.0(1)	–	–
$Q_{\beta n}$	7.284(17)	8.988(34)	11.2(1)	13.63(24)	20.0)9)
$Q_{\beta 2n}$	4.795(17)	3.103(30)	8.4(1)	8.30(24)	15.4(9)
$Q_{\beta 3n}$	–	0.615(30)	2.5(1)	5.48(24)	13.2(9)

Table 1: Open decay-channels and Q-values (in MeV) for some of the neutron-rich Carbon isotopes (nuclear masses from G. Audi *et al.* [17]).

^{18}**C)** The half-life has been measured to be 92(2) ms and the P_n was found to be 20(3)% [18]. As in the case of ^{17}C this experiment also measured a neutron ToF spectrum, which exhibited many neutron groups below 4 MeV, and several below 2 MeV.

^{19}**C)** This nucleus has been studied at RIKEN [20] where a half-life of 45.5(4.0) ms and a neutron ToF spectrum with many neutron groups below 3 MeV was measured. Earlier a P_n value of 62.4(2.6)% was reported [21]. The ground state spin of ^{19}C is believed to be $1/2^+$.

^{20,22}**C)** At present very little, except for half-lifes (6.1(1.4) ms and 16(3) ms, respectively) and P_n values, are known about the beta-decay of these very exotic nuclei, see [22] and references therein.

In several cases conflicting values of P_n have been measured, see [18] and references therein. A potential explanation of these discrepancies could be the presence of neutron lines at very low energy (as seen in ^{11}Li [1]), a measurement with ^{3}He neutron spectrometer could resolve this question.

Thus it seems reasonable to perform new decay experiments with these isotopes including charged particle detection, since these would give unique information about B_{GT}-distribution at high excitation energy, high-resolution neutron spectroscopy and gamma detection. Detection of gamma rays will aid in separating the different branches in the decay (possibly through analysis of line broadening [23]), note furthermore that the beta-decay daughter ^{18}N has a 12% beta-delayed alpha branch that gives a unique signature.

3.2 Experimental setup

The experimental setup for the beta-decay experiment would consist of a Gas-Si telescope to measure the beta-delayed charged particles. The radioactive beam would be stopped on the window of the gas cell. The gas-telescope would be composed of a 12 mm gas cell, with charge collection from 6 mm and a thin Si-detector (100 μm) backed by a thick Si-detector (700 μm), to allow for measurement of the emitted beta particle. Outside the thin transfer line, from the ISOLDE vacuum-system to the gas-telescope, two ^{3}He neutron spectrometers would be placed close to the collection point (3-4 cm). Furthermore a gamma detector would be placed just behind the gas-telescope to measure beta-delayed gamma rays. The setup is sketched in fig. 2.

The expected minimum yields for the neutron-rich Carbon isotopes from a HfO_2 target in combination with a MiniMono ECR ion-source are (the numbers are for CO^+ molecules):

	^{17}C	^{18}C	^{19}C
Yield	700/μC	170/μC	12/μC

These yields should be sufficient to measure branching ratios of the order of 10^{-4}-10^{-5} for charged particles, which generally for light nuclei can be large (10^{-3}-10^{-4} [1]). No estimates for ^{20,22}C yields are at present known but it would be very valuable to investigate this to see whether beta-decay experiments on these nuclei might be feasible. Again it should be kept in mind that these estimated yields are conservative and based on the release curve for a MgO target, and not for a HfO_2 target, which is known to be faster.

4 Summary and Beam-time request

We propose two experiments to exploit the newly available Carbon beams at ISOLDE. The first an ERS experiment of ^{9}C on protons to explore the low-lying states in ^{10}N, the mirror companion of ^{10}Li. The second a beta-decay study of the neutron-rich Carbon iso-

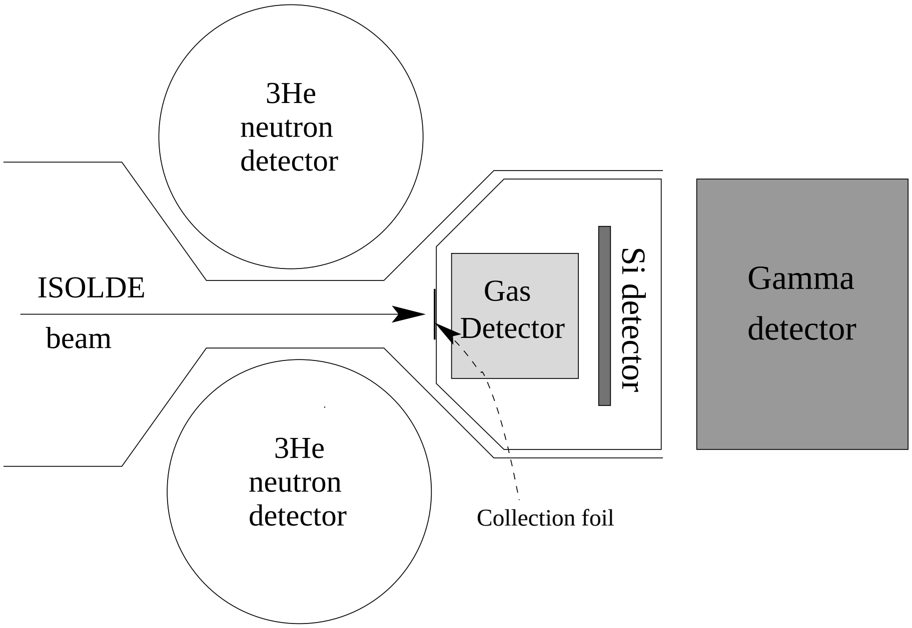

Figure 2: Setup for beta-decay experiments for the neutron-rich Carbon isotopes.

topes $^{17-19}$C and a feasibility test for future experiments on the even more neutron-rich carbon isotopes ^{20,22}C.

For the ERS experiment with ^{9}C at REX-ISOLDE we ask for a total of 15 shifts:

- Setup, beam changing and calibration with ^{12}C **3 shifts**.
- Radioactive beam ^{9}C on protons **9 shifts**.
- Radioactive beam ^{9}C on ^{12}C for background measurement **3 shifts**.

For the ERS experiment a MgO or HfO_2 fiber target with quartz- or alumina-coated target container and transfer line would be required in combination with the MiniMono ECR ion-source. Calculations show that a MgO target should have a slightly larger in-target production of ^{9}C as compared to a HfO_2 target, which in turn has a faster release. Thus either of the two targets would be equally good for this part.

For the beta-decay experiment of neutron-rich Carbon isotopes we ask for a total of 17 shifts:

- Setup and calibration with radioactive beam **1 shifts**.
- Beta-decay of ^{17}C **3 shifts**.
- Beta-decay of ^{18}C **5 shifts**.
- Beta-decay of ^{19}C **6 shifts**.
- Yield measurement of ^{20,22}C **2 shifts**.

For production of the neutron-rich carbon isotopes a HfO_2 fiber target with quartz or alumina–coated target container and transfer line combined with the MiniMono ECR ion-source would be needed.

Furthermore we would need the ISOLDE VME data acquisition and the CERN data storage system.

In total we ask for **32 shifts** for the two experiments.

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