# Neutron Knockout Reactions from Proton–rich Carbon Isotopes

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(Dated: March 17, 2007)

## Abstract

We propose a single–neutron knockout experiment on the proton–rich light nucleus $^{10}$C to determine the absolute spectroscopic factor. By comparison of the experimental results with shell–model calculations, it is possible to extract a quenching factor for the deeply bound (21 MeV) neutron $p_{3/2}$ orbital which can be expected to be much smaller than unity. As the reaction residue, $^{9}$C, has only one bound state, it is possible to carry out a rather simple counting experiment at the fragment separator FRS which could even be carried out during nights in ion therapy treatment blocks because a $^{12}$C primary beam will be used. Experimental results will likely spark theoretical efforts studying the quenching of spectroscopic factors in deeply bound states. A complementing two–nucleon knockout reaction on $^{11}$C is foreseen. Such an experiment will provide precise data in order to quantitatively understand the interplay of stripping and diffraction dissociation in a direct two–nucleon knockout process.

PACS numbers: 21.10.Jx, 21.60.Cs, 24.50.+g, 25.60.Gc, 27.20.+n

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## I. INTRODUCTION

Single–nucleon knockout reactions involving secondary ion beams have been established as a spectroscopic tool for studying the structure of light and medium–mass exotic nuclei [1–3]. Analyzing knockout data on stable nuclei, it has been suggested [4] that knockout reactions provide information on spectroscopic factors on an absolute scale. In stable nuclei, the spectroscopic factors extracted from nuclear knockout from fast beams in inverse kinematics are about 30–40% smaller than predicted within state–of–the–art shell–model calculations [4]. This finding is in line with results from quasi–elastic electron scattering [5]. For weakly bound nucleons in exotic nuclei, this quenching factor

$$R_s = \frac{\sigma_{\rm exp}}{\sigma_{\rm th}} = \frac{\sigma_{\rm exp}}{\frac{A}{A-1}\, M\,(C^2S)_{\rm th}(\sigma_{\rm str}+\sigma_{\rm dif}+\sigma_{\rm C})} \tag{1}$$

is found to be closer to unity [4, 6], whereas for the deeply bound neutron in the knockout from $^{32}$Ar a quenching factor below 0.3 was deduced [7]. In Eq. (1) the experimental cross section is denoted by $\sigma_{\rm exp}$. The theoretical cross section, $\sigma_{\rm th}$, is calculated from the predicted spectroscopic factor as determined from a shell–model approach $(C^2S)_{\rm th}$ and a radial mismatch factor $M$ which takes the change of the potentials between the nuclei into account, cf. [8]. The factor $A/(A+1)$ is a center–of–mass correction valid for the $p$ shell, and $\sigma_{\rm str}$, $\sigma_{\rm dif}$, and $\sigma_{\rm C}$ stand for theoretical single–particle cross section for stripping, diffraction dissociation, and Coulomb–induced breakup, respectively. Recently, also from transfer reactions on stable nuclei quenching factors around 0.7 have been extracted [9].

As the nuclear knockout process probes the outer regions of the nuclear wavefunction only, deducing the absolute occupancy of specific orbitals from the measured spectroscopic factor is not necessarily straightforward. The uncertainties involved in this extrapolation, however, can be estimated from varying the parameters used in the reaction model. At high energies, eikonal models using a sudden approximation provide a reliable determination of the single–particle cross section, see [2, 10, 11] and Refs. therein. While the accuracy of the eikonal approximation appears to be surprisingly good even at energies down to about 30 MeV/nucleon [12], deviations from the eikonal description (especially in the momentum distributions) are documented for energies between 50 and 100 MeV/nucleon at large angular momenta [13] or finite binding energies [14].

In addition to one–nucleon knockout reactions, the knockout of two well–bound nucleons in an exotic nuclei has been studied [15, 16] using intermediate beam energies, establishing a novel sudden direct reaction process for studying far unstable nuclei. Stripping [17] and diffraction dissociation contributions [18] to the two–nucleon knockout cross section have been discussed, and values for a two–nucleon quenching factor have been extracted.

In nuclei located not immediately at the drip lines, there are usually several bound states that can be populated by a one- or two–nucleon knockout reaction. In order to disentangle the final state of the reaction, gamma–ray detection is needed [19–21]. This necessity disappears if the reaction residue has only one bound state (and no long–lived unbound states) as was the case, e.g., in the $^{9}$Be($^{32}$Ar,$^{31}$Ar)X reaction of Ref. [7] or the $^{12}$C($^{9}$C,$^{8}$B)X experiment described in Ref. [6].

## II. SCIENTIFIC GOALS

We propose to study one- and two–neutron knockout from proton–rich carbon isotopes in the inclusive reactions $^{9}$Be($^{10}$C,$^{9}$C)X and $^{9}$Be($^{11}$C,$^{9}$C)X at energies of about 370 MeV/nucleon. Within this experiment, we will address a number of questions related to our present knowledge of knockout reactions presented above:

- How large is the quenching factor for spectroscopic factors when deeply bound orbitals are involved? The binding energy of the last ($p_{3/2}$) neutron in $^{10}$C amounts to 21.3 MeV which is close to the value of 21.5 MeV for the case of $^{32}$Ar discussed in Ref. [7]. Initial and final state are well defined in the one–nucleon knockout from $^{10}$C as no isomeric states exist in $^{10}$C, and the residue has only one bound state. Therefore, the proposed experiment will improve our understanding of the quenching process in a nuclear region different from the one investigated by Ref. [7]. The high beam energy will allow the reaction cross section to be determined reliably, and within the $p$ shell various nuclear structure models exist that can be used for determining spectroscopic factors from theory. The relatively low mass of the particles involved may spark investigations using ab–initio models which for the example of electro–induced knockout from $^{7}$Li have been successful in describing spectroscopic factors on an absolute scale [22]. Ab–initio studies should be able to clarify, in how far short–range correlations in the nucleon–nucleon interaction are responsible for the quenching of spectroscopic strength.

- The experiment will provide new data for investigating parameter constraints in order to extract absolute occupancies of the $p_{3/2}$ neutron shell with reasonable accuracy. The extracted occupation numbers may be compared with experiments on quasi–free scattering where the model dependence is much smaller and whose feasibility has been demonstrated at GSI [23].

- Do we understand two–nucleon knockout reactions? The recent work by Tostevin and Brown [18] has studied the interplay of stripping and diffraction dissociation in the two–nucleon knockout process and has applied the model to experimental data in medium–mass nuclei. The reaction $^{9}$Be($^{11}$C,$^{9}$C)X at GSI would extend the available data to a different mass and energy region. The two–nucleon separation energy for the $^{11}$C$\rightarrow$$^{9}$C reaction is comparable to the data analyzed by [18]. However, this experiment would be the first to investigate a two–nucleon removal from an odd–mass nucleus where possible complex configurations in the ground states of $^{11}$C and $^{9}$C might play a role. In addition, the neutron separation energy in the intermediate $^{10}$C is – due to pairing – higher than in $^{11}$C.

In summary, the proposed experiment addresses current questions in nuclear structure physics and in the description of reaction dynamics that might serve as a benchmark for our understanding of light exotic nuclei. The experimental results are likely to spark theoretical interest, e.g., by the groups at GSI/TU Darmstadt, Surrey, Michigan State, or Arizona.

## III. EXPERIMENTAL DETAILS

The proposed experiment can easily be carried out at GSI's fragment separator (FRS) using a primary beam of $^{12}$C as specified for the therapy project. Therefore the experiment represents an opportunity for performing fundamental research without additional beam development during therapy blocks and without difficult demands on the accelerator.

### A. Count–rate estimate for the reaction $^{9}$Be($^{10}$C,$^{9}$C)X

Assuming a primary $^{12}$C beam of 400 MeV/nucleon with an intensity of $2 \cdot 10^{8}$ particles per second (e.g. from $1 \cdot 10^{9}$ particles per spill with a 5–second spill cycle) incident on a 10 mm thick beryllium target, about 700 $^{10}$C ions per second reach the S2 focus at the FRS center if the momentum acceptance is selected to be about 1%. This estimate has been obtained using the program LISE++ [24]. At the intermediate focus S2 of the FRS, a 3 mm thick beryllium secondary reaction target (550 mg/cm$^2$) is placed. The beam purity is likely to be not as good as predicted. However, even if the beam purity would turn out to be worse by a factor of five, the overall count rates would still be acceptable. Thus a scintillator for beam–line timing can be operated at S1 and tracking detectors at S2.

Using position–sensitive MWPCs or TPCs in the FRS beam line (e.g., four detectors at S2, two at S4) in addition to particle identification with MUSIC (one at S2 and one at S4) will allow one not only to detect and identify the reaction residues on an event–by–event basis, but will also provide a rough estimate on the width of the parallel momentum distribution of the knocked–out particle which is linked to the angular momentum value [25]. This method has been used in previous experiments (see the recent experiment S277 [21] or the earlier study by, e.g., Baumann et al. [26]).

With about 700 particles per second at S2, about 650 reaction residues are expected at S4 within one shift if one uses an extremely conservative cross–section estimate of 1 mb only. The statistical accuracy of $\pm 4\%$ is sufficient and much smaller than the expected systematic uncertainties that arise from target thickness determination, transmission through the fragment separator, acceptance corrections, and data analysis. Usual cross sections for one–neutron removal reactions are much larger than our estimate of 1 mb (e.g., 10 mb in the case of $^{32}$Ar$\rightarrow$$^{31}$Ar [7]), so even the smaller spectroscopic factor ($\sim$1 as compared to 4.1) and a quenching factor of below 0.24 would lead to a detectable result.

### B. Count–rate estimate for the reaction $^{9}$Be($^{11}$C,$^{9}$C)X

With the same primary beam specifications as above (which are defined by therapy) and a 10 mm thick production target, LISE++ [24] predicts 9000 $^{11}$C ions to arrive at S2 per second. Using again a secondary beryllium target with thickness around 3 mm, 750 breakup residues within an eight–hour shift are expected at S4. Here, the cross section was estimated to be of the order of 0.1 mb (a conservative estimate with respect to cross sections of around 0.4 mb given by Ref. [16]). The estimate includes a smaller transmission to S4 due to the wider momentum distribution generated by the two–neutron knockout process.

### C. Experimental set–up

The experiment uses detector equipment that has been used at the FRS before. For the measurement of the momentum distribution, the particle trajectories will be reconstructed from the positions measured with TPCs. The MUSIC detectors will serve for particle identification in combination with scintillators providing beam–line timing. In order to analyze the momentum distribution of the reaction residues with resolution of about $10^{-3}$, the target is located at S2, and the reaction residues are identified at S4 and their paths are tracked. As the S4 focal plane serves as main trigger for the experiment (in combination with significantly downscaled events at S2 to monitor the incident beam), the results are background–free.

Other options for possible set–ups include the ALADIN/LAND area at cave C, or using the S4 focal plane only. While the ALADIN/LAND site would provide information on the knocked–out neutron so that diffractive breakup contributions could be separated from stripping, the longitudinal momentum distributions could not be extracted with sufficient resolution in that set–up. In addition, the finite transmission to cave C would reduce the rate of incident particles and would increase the amount of necessary beam time further due to the time needed for beam tuning and optimization. Setting up the secondary target at S4 could improve the experimental situation only slightly with respect to beam purity, but the possibility to detect the momentum distributions of the residues would be lost.

### D. Beam–time request

For the experiment, we request 6 (six) eight–hour shifts of primary beam time and 1 (one) shift of parasitic beam time. We point out that the experiment can be carried out during the night breaks of the therapy blocks using a beam as specified for therapy, with typically 400 MeV/nucleon beam energy and about $10^9$ particles per spill at a spill cycle of about 5 seconds. As the experimental equipment has been in similar set–ups previously, the experiment also could run on relatively short notice. The requested beam time shall be used as follows:

- The shift with parasitic beam will be used to test the functionality of detectors and electronics.
- A first shift as primary user is foreseen for the tuning and identification of the exotic

ion beams.

- The second shift as primary user is needed for calibrating the detectors and for quantitatively studying the transmission through the FRS.
- Two shifts will be allotted for the ($^{10}$C,$^{9}$C) reaction. During the first shift, the central part of the momentum distribution with the main fraction of the statistics will be measured. The second shift is for scanning the residue distribution across the S4 focal plane.
- Two shifts will be assigned to studying the ($^{11}$C,$^{9}$C) two–neutron knockout reaction. In this case the momentum distribution is wide so that two settings of the second part of the FRS will be used.

In order to set up detectors for tracking and particle identification, the vacuum system especially at S2 needs to be modified. For this work we estimate about four days of full access to the FRS beam line prior to the experiment.

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