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One-neutron knockout of ^{23}O

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Abstract. Breakup reactions were used to study the ground-state configuration of the neutron-rich isotope ^{23}O. The ^{22}O fragments produced in one-nucleon removal from ^{23}O at 938 MeV/nucleon in a carbon target were detected in coincidence with de-exciting γ rays, allowing to discern between ^{22}O ground-state and excited-states contributions. From the comparison of exclusive experimental momentum distributions for the one-neutron removal channel to theoretical momentum distributions calculated in an Eikonal model for the knockout process, and spin and parity assignment of $I^\pi = 1/2^+$ was deduced for the ^{23}O ground state. This result solved the existent experimental discrepancy.

PACS. 25.60.Gc Breakup and momentum distributions – 25.60.Dz Interaction and reaction cross-sections – 27.20.+n $6 \le A \le 19$

1 Introduction

Recent studies in neutron-rich oxygen isotopes near the neutron dripline have shown very exciting issues.^{22}O [1] with its first excited state at 3.17 MeV and ^{24}O [2] with no excited states below 4 MeV seem to be double magic nuclei. In addition, ^{24}O is today accepted to be the last bound oxygen isotope reinforcing the idea of the $N = 16$ magic number replacing the $N = 20$ gap for *sd*-shell dripline nuclei. In this context, ^{23}O is a key nucleus to understand the structure of light neutron-rich isotopes. Consequently, it has been subject of interest and several experiments have been dedicated to its study during the last years.

The main experimental tool used in these investigations are high-energy knockout reactions of single neutrons from near-dripline nuclei. Brown *et al.* [3] have shown that the residue momentum distributions and the corresponding cross-sections can be analyzed in such a way that both the l-values and the single-particle occupation probabilities of the levels can be deduced.This, however, requires that the level from which the breakup occurred is identified uniquely by measuring γ-rays in coincidence with the residue [4,5,6].

The first dedicated ^{23}O experiments could not profit from this γ-tagging and were limited to measure inclusive observables. Two experiments were performed. The first one, done at GANIL by Sauvan *et al.* [7,8] who measured a relatively narrow longitudinal momentum distribution of ^{22}O after one-neutron knockout from ^{23}O, led to a ground-state spin and parity of $I^\pi = 1/2^+$ for ^{23}O.

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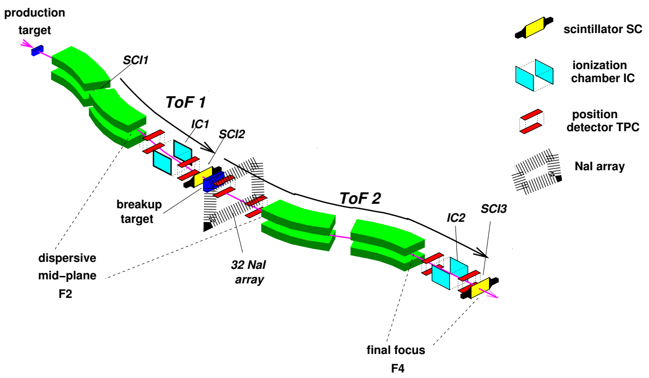

Fig. 1. A schematic view of the FRagment Separator (FRS) with the detection set-up. The complete identification was possible in both sections of the spectrometer by time-of-flight (TOF) measurements between scintillators (SCI) and energy-deposition in ionization chambers (IC) measurements. Several position-sensitive detectors (TPC) allow tracking of projectiles and fragments and momentum measurements of the fragments. γ-rays coincident with fragments where measured with a NaI-array.

In contrast, the other performed at RIKEN by Kanungo *et al.* [9], attributed $I^\pi = 5/2^+$ to the ^{23}O ground state. If confirmed this would have significant implications on our understanding of the shell structure in the vicinity of $N = 16$. This controversy prompted a comment by Brown *et al.* [10] and calculations by Sauvan *et al.* [8]. Both papers give a consistent analysis of the available *inclusive* data in terms of a $(d_{5/2})^6(s_{1/2})^1$ configuration for ^{23}O.

This discrepancy was at the origine of the experimental study presented in this paper where an exclusive one-neutron knockout experiment of ^{23}O was performed. In this work, the individual levels are identified by measuring the deexciting γ-rays in coincidence with the inclusive observables.

2 Experimental set-up

A 938 MeV/nucleon ^{23}O secondary beam was produced by fragmentation of a ^{40}Ar primary beam with an energy of 1.0 GeV/nucleon, delivered by the heavy-ion synchrotron SIS, in a 4 g/cm^2 Be target. The Fragment Separator (FRS [11]) at GSI was used in its energy-loss mode to transmit the ^{23}O secondary beam to the breakup carbon target at the intermediate focal plane (F2) and the ^{22}O fragments to the final focal plane (F4). We used a special ion optics that ensured the measurement of the complete momentum distribution in one single setting. The average intensity of the primary beam was $1.5{\cdot}10^{10}$ particles/spill, whereas only 50 ^{23}O/spill and 1 ^{22}O/spill reached the breakup target and final focus, respectively. The detector set-up at the FRS, shown in fig. 1, included position sensitive time projection chambers (TPC) for particle tracking and longitudinal momentum measurements, ionization chambers (IC) for determining the fragment charge, and scintillators (SC) that gave the time of flight between the different parts of the FRS. Using the magnetic rigidity and the time-of-flight information together with the energy loss data from the ICs, a complete particle identification was available throughout the spectrometer. For the present experiment, the most significant addition to the set-up was an array of 32 NaI crystals for the detection of γ rays emitted by the fragments around the reaction target in F2. This array has an average energy resolution ($\Delta E/E$) of (12.0$\pm$0.8)% and a total efficiency of (5.0$\pm$0.4)% for the case of γ-rays emitted by relativistic moving sources (obtained from a GEANT [12] simulation for $E_\gamma = 3.2$ MeV in the rest frame of the fragment [13]).

The intrinsic momentum resolution for ^{23}O was evaluated to be 19$\pm$1 MeV/c (FWHM). This experimental value includes the ion optical properties of the FRS plus straggling in the target, optical misalignment and any other secondary effects.

3 Experimental results

We measured in this experiment inclusive fragment longitudinal momentum distributions and cross-sections after one-neutron removal on a large number of neutron-rich oxygen isotopes. We only present in this paper results relative to ^{23}O.

The inclusive one-neutron removal cross-section ($\sigma_{-1\text{n}}$) was measured by directly counting ^{23}O and ^{22}O in front of, and behind the carbon breakup target. This ratio was corrected for the experimental transmission evaluated with the code MOCADI [14] after adjusting the simulated fragment longitudinal momentum width to the measured one. The value obtained was $\sigma_{-1\text{n}}$= 85$\pm$10 mb. The error includes statistical and transmission errors. This data does not show a significant increase when compared with the same quantity measured for other neutron-rich oxygen isotopes. In consequence, it does not support the idea of ^{23}O being a halo nuclei as it was proposed by Ozawa *et al.* [15].

The technique employed for fragment longitudinal momentum distributions measurements is described in ref. [6, 16]. The differential cross-section with respect to longitudinal momentum p_{long} (in the projectile center-of-mass frame) is shown on the left frame of fig. 2 for the one-neutron removal reaction. The solid curve corresponds to a double Gaussian fit to the experimental data from which a width of 134$\pm$10 MeV/c (FWHM) was obtained. A minor correction for the intrinsic momentum resolution gives a final width of 133$\pm$10 MeV/c. This result can be directly compared to the corresponding value of 114$\pm$9 MeV/c (FWHM) obtained at 47 MeV/nucleon [7] and of 73$\pm$15 MeV/c at 72 MeV/nucleon [9].

The γ-rays emitted during de-excitation of ^{22}O were recorded with the NaI detectors described in sect. 2. The high-energy γ-rays and the emission of γ-rays in cascade made it necessary to apply add-back corrections. Subsequently we performed a Doppler shift correction. The analysis of the γ-ray spectrum reveals three γ-ray energies at 1.3, 2.6, and 3.2 MeV corresponding to the known transitions in ^{22}O [10, 1, 2] (see the level scheme in ref. [17].) They correspond to de-excitation of the 2^+ and 3^+ states at 3.2 and 4.5 MeV, respectively, resulting from a $1d_{5/2}$

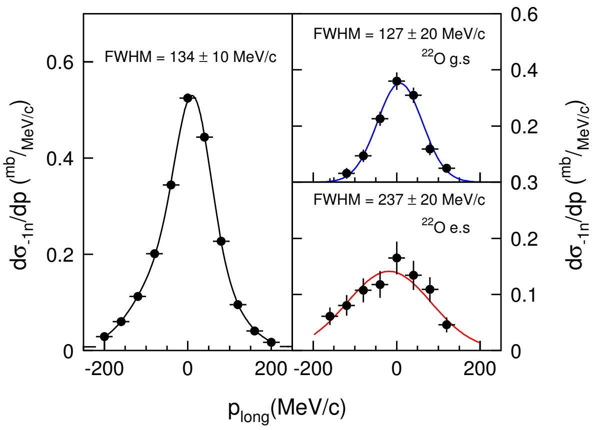

Fig. 2. Left: Inclusive longitudinal momentum distribution ($p_{\rm long}$) for ^{22}O fragments after one-neutron removal from ^{23}O. Right top: Exclusive longitudinal momentum distribution for ^{22}O in its ground state. Right bottom: Longitudinal momentum distribution for ^{22}O in any excited state.

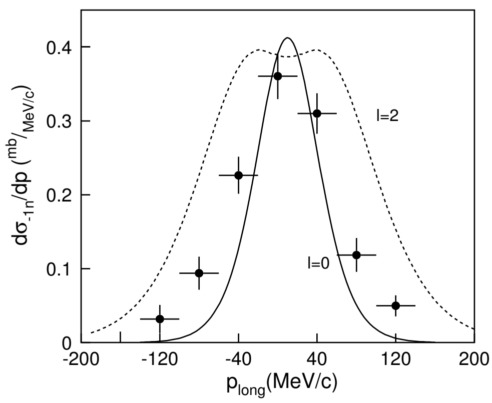

Fig. 3. Ground-state exclusive momentum distribution for ^{22}O fragments after one-neutron knockout reaction from ^{23}O compared with calculations assuming $l = 0$ and $l = 2$ (see text).

hole coupled to a $2s_{1/2}$ particle. The 5.8 MeV state could be due to the 0^- or/and 1^- states proposed in [10](see ref. [17] for details). The broad peak observed at higher energy is assumed to be due to the 3.2 MeV and the 2.6 MeV transitions that our NaI detectors cannot resolve. This peak is, therefore, used to gate the longitudinal momentum distribution in order to obtain the exclusive distribution.

The result, after efficiency correction of the γ array evaluated with a GEANT simulation and proper background subtraction, is shown in the right-bottom part of fig. 2, where the solid line corresponds to the Gaussian fit performed to obtain the width of the distribution. This results in a FWHM of 236±20 MeV/c for the momentum distribution leaving the core in any excited state.

The longitudinal momentum distribution for ^{22}O in its ground state could be obtained by subtracting from the inclusive measurement the exclusive one involving ^{22}O in any of its excited states. The resulting spectrum is shown in the upper part of fig. 1. We obtain a FWHM of 126±20 MeV/c (after correcting for the intrinsic momentum resolution). The corresponding integrated cross-section amounts to 50±10 mb. A summary of the experimental results obtained for ^{23}O is given in table 1 (third column). The associated error bars include statistical errors, assumptions for the level scheme of ^{22}O, and uncertainties in the γ-efficiency simulation. The relative weight of the exclusive one-neutron removal cross-section involving ^{22}O in any excited states to the inclusive measurement amounts to (41±10)%.

4 Discussion

The experimental momentum distribution for the one-neutron removal-channel leaving the ^{22}O core in its ground state is compared in fig. 3 to theoretical momentum distributions calculated in an Eikonal model for the knockout process. Two calculations are shown for angular momenta $l = 0$ and $l = 2$. Clearly, the distribution assuming a $2s_{1/2}$ neutron coupled to the ^{22}O(0^+) core is in much better agreement with the data. We can thus conclude that the ground-state spin of ^{23}O is $I^\pi = 1/2^+$. This result has been recently confirmed in another exclusive experiment performed by C. Nocciforo *et al.* [18]. They have measured exclusive differential cross-sections $\mathrm{d}\sigma/\mathrm{d}E^*$ for electromagnetic excitation of ^{23}O projectiles at 422 MeV/nucleon incident on a lead target, probing its ground-state configuration ($I^\pi = 1/2^+$) by an independent method.

We note, however, that the experimental distribution is slightly wider than the prediction for $l = 0$. This might be due to a slightly incomplete subtraction of the excited-state contribution. The large width of 237±20 MeV/c observed for the distribution involving excited states is in line with the expectation that in this case, most of the cross-section is related to knockout of neutrons from the d shell.

We now turn to the one-neutron removal cross-sections, which are calculated separately for the individual single-particle configurations adopting the Eikonal approach [19,20], which is well justified at the high beam energy used in the present experiment. The neutron-core relative-motion wave functions are calculated for a Woods-Saxon potential with geometry parameters of $r_0 = 1.25$ fm and $a = 0.7$ fm [4,5]. Further input to the calculations are free nucleon-nucleon cross-sections and harmonic-oscillator density distributions for the target and the core, which were chosen to reproduce the measured interaction cross-sections at high energy [15].

Neutron-knockout cross-sections were calculated for the configuration $(d_{5/6})^6$ $(s_{1/2})^1$, and are summarized in the fourth column of table 1. For the neutron knockout from the $2s$ shell the calculated cross-section is equal to 51 mb and thus in agreement with the experimental value of 50±10 mb. This result confirms the large spectroscopic factor for the s-neutron ($C^2S = 0.8$) obtained by Brown *et al.* [10]. Another experimental confirmation to this result is provided by C. Nocciforo *et al.* [18] that have reported

Table 1. The experimental one-neutron removal cross-sections are presented for $^{23}O \rightarrow {}^{22}O + n$ in the different final state configurations considered. Calculated cross-sections are shown for comparison.

E (MeV)	I^π	σ_{exp} (mb)	σ_{sp} (mb)
0	0^+	50±10	51
3.2	2^+	10.5±4.5	20
4.5	3^+	14.0±5.0	18
5.8	$(1^-,0^-)$	10.5±4.5	15
Total		85±10	104

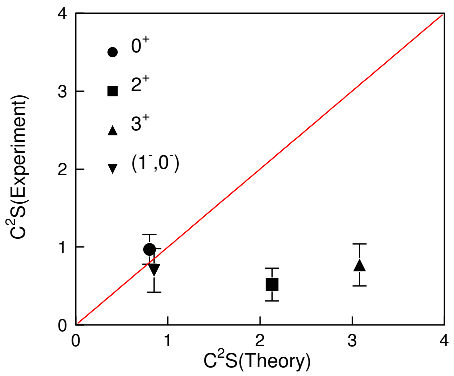

Fig. 4. Experimental *vs.* theoretical spectroscopic factors for the particular cases studied in this experiment. The experimental values represent the measured partial cross-section divided by the single particle cross-section (eikonal model), whereas the theoretical values correspond to many-body shell-model calculation. The diagonal line indicates a correlation factor between both quantities equal to one.

a spectroscopic factor of 0.78(13) for the $2s_{1/2} \otimes {}^{22}O(0^+)$ configuration.

The knockout of a neutron from the 1d-shell in this calculation results in ^{22}O either in the 2^+ state (20.0 mb), or in the 3^+ state (18.3 mb). The contribution of knockout of neutrons from deeper p shells $(1^-, 0^-$ state) amounts to 15 mb. A comparison with the experimental data shows that the contribution involving excited states is smaller by a large factor (see table 1). This fact is reflected in fig. 4, where we represent experimental *versus* theoretical spectroscopic factors for the particular cases studied in this experiment. The experimental spectroscopic factors are evaluated from the ratio between measured partial cross-section and single-particle cross-section calculated in an eikonal model. The theoretical spectroscopic factors correspond to many-body shell-model calculation [10]. The diagonal line represent a perfect correlation between these quantities and would evidence that the knockout technique is an adequate tool to provide spectroscopic information [21].

We can observe a very good correlation for the $^{22}O(0^+)$ configuration but an important discrepancy is observed for configurations involving ^{22}O excited states. This discrepancy might to a large extent be related to the fact that the experiment is only scanning the external part of the wave function, together with deficiencies related to the theoretical description used. Shell model calculations do not include short-range correlation and only many-body correlations within the reach of the basis are considered. These deficiencies point as well towards the need of more elaborate reaction models for calculating knockout cross-sections from the deeply bound core states. This result is not fully understood and further theoretical and experimental investigations are certainly needed.

5 Conclusion

We have measured the ^{22}O momentum distribution after one-neutron knockout from high-energy ^{23}O projectiles differentiated according to states populated in ^{22}O observed by a coincident measurement of the ^{22}O γ de-excitation. The experimental observations are evidence for a ground-state spin $I^\pi = 1/2^+$ for ^{23}O with a large spectroscopic factor for the $s_{1/2} \otimes {}^{22}O(0^+)$ single particle configuration, thus providing support for the existence of the $N = 16$ shell closure for $Z = 8$.

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