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Matter radii of ^{22,23}O

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Abstract. The anomaly in the interaction cross section of ^{23}O is discussed through a new experiment performed at the FRS, GSI. The matter radius of ^{23}O is derived through a Glauber model analysis. Results using *ab initio* coupled cluster theory as well as densities from mean field models are presented.

1. Introduction

The structure of neutron-rich nuclei are an intriguing subject of investigation as we learn about unexpected deviations from our well-established model of nuclei. The presence of neutron-halo and skin in neutron-rich nuclei have opened a wealth of new information [1]. These exotic forms have been discovered through the measurement of matter radii and charge radii. Since the discovery of the neutron halo in ^{11}Li, the matter radii of neutron-rich nuclear isotopes have been quite effectively derived from measurement of interaction cross sections [2]. A nuclear halo, is manifested by an abrupt large increase in the cross section and hence the matter radius of a nucleus compared to its preceding isotopic neighbour. The radius therefore deviates greatly from the well known $r_0A^{1/3}$ rule. Such a structure has been pictured a one or two valence neutrons that are very weakly bound, extend to large distances from the neighbouring isotope, core, thereby forming a low-density neutron halo around the core.

One and two neutron halos have been identified in the light nuclei from helium to carbon. Extending further, a clear confirmation on halos in the isotopic chains of nitrogen and oxygen are not firmly established. The first measurement of interaction cross section for these isotopes reported quite an astounding observation of enormously large radii for the N=15 isotopes, namely, ^{22}N and ^{23}O [3]. In a conventional shell model arrangement of the nuclear orbitals the odd neutron in these nuclei should occupy the $2s_{1/2}$ orbital. Such a configuration can lead to the largest possible size in the framework of the adopted core+neutron halo model. The valence neutron in ^{23}O however is not very weakly bound. This leads to a calculated cross section within the $^{22}O_{gs}$(core) + neutron ($2s_{1/2}$) being much smaller than the experimental data. It was therefore a mystery as to what new additional effect might lead to such an enhancement. Subsequently it was proposed that the large interaction cross section, and matter radius, arises due to an enlarged size of ^{22}O as a core than the bare ^{22}O [4].

On the other hand, one-neutron removal reaction from ^{23}O, measuring the momentum distribution of the fragment ^{22}O, was described by ^{23}O having the structure dominated by ^{22}O in the ground state and valence neutron with spectroscopic factor of 0.97±0.19 [5] in the $2s_{1/2}$ orbital. The Coulomb dissociation measurement arrived at a similar conclusion with the $2s_{1/2}$ spectroscopic factor of 0.78±0.13 [6].


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The momentum distribution measured form one-neutron knockout from the neighbouring drip-line nucleus ^{24}O was explained with solely neutrons being knocked out of the $2s_{1/2}$ orbital with a spectroscopic factor of 1.74±0.19 [7]. Theoretical interpretation of the removal cross section from a more *ab initio* standpoint using coupled cluster theory [8] also predicted a spectroscopic factor consistent with Ref.[6]. Therefore it appears that the two valence neutrons in ^{24}O occupy the $2s_{1/2}$ orbital and each of them couple to ^{23}O in its ground state, which means the ground state spin of ^{23}O is $1/2^+$. This is therefore not favourable of a picture with ^{23}O ground state having a strong component with ^{22}O core in an excited state, which was thought to be one of the reasons for its possible enlargement.

2. Experiment

The situation was therefore inconclusive with the discrepancy between the interaction cross section measurement and the neutron removal reactions regarding the configuration of ^{23}O. A re-investigation of the interaction cross section of ^{23}O was therefore important and was undertaken at the fragment separator FRS at GSI. The details of the experimental setup is described in Ref.[9]. The layout of the experimental setup is shown schematically in Fig.1.

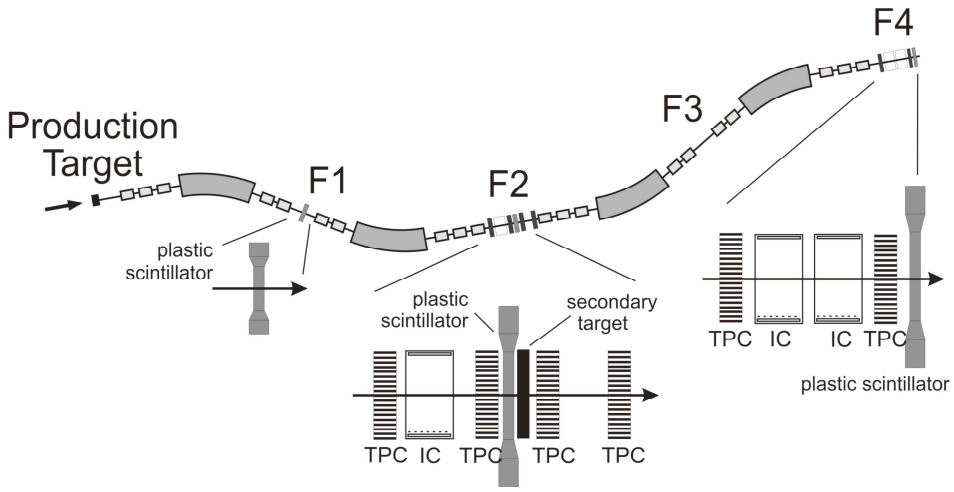

Fig.1 Experimental setup at the FRS, GSI. IC represents multi sampling ionization chamber and TPC represents, time projection chambers.

The measurement was done using the method of transmission, where ^{23}O before and after the reaction target needs to be identified and counted event by event. This was done by using the Bρ-ΔE-TOF technique. The identification before the target was done using the section F1 to F2 of the FRS. Two plastic scintillators located at these foci were used to measure the time of flight (TOF). Time Projection Chambers were used as beam tracking detectors to determine the beam profile on the target. The position measurement combined with the magnetic field information provided the magnetic rigidity (Bρ). The TOF and Bρ information determines the mass/charge (A/Q) of the incident beam species. A multisampling ionization chamber was used for the charge (Q = Z for fully stripped nuclei) identification. The beam energy at the reaction target was ~ 900*A* MeV. The carbon reaction target of 4 g/cm^2 was located at the dispersive second focus, F2. Two tracking detectors located after the reaction target provided the beam profile of the outgoing beam particles before they passed through the second stage of the FRS spectrometer. This allowed an assessment of any transmission losses. The unreacted ^{23}O nuclei after the target were transported from F2 to the final focus F4 using the second half of the FRS. The identification at F4 followed the same method as used before the target.

The open symbols in Fig.2 show the interaction cross section from Ref.[3]. The interaction cross section for ^{22,23}O measured in this new experiment is shown by the filled circles. They are found to be smaller than the earlier measurements.

3. Results and discussion

The root mean square matter radii of ^{22,23}O were derived through a Glauber model analysis of the data including the higher order terms that are missing in the optical limit approximation [10]. The calculations were done using two different parametric forms of the density distributions. The root mean square matter radius derived with a Fermi type density resulted in 2.75±0.15 fm for ^{22}O and 2.95±0.23 for ^{23}O [9]. A conservative approach was taken in this determination by searching for all combinations of half-radius and diffuseness of the Fermi density profile that reproduced the experimental cross section. The results using the harmonic oscillator density distribution were consistent with those derived with the Fermi densities giving values of 2.75±0.07 fm for ^{22}O and 2.97±0.11 fm for ^{23}O [9]. This shows that the root mean square radii extracted from the interaction cross sections are largely independent of the choice of the form the density distribution. It maybe mentioned here that one can place further restrictions on the radii by measuring the cross sections with different targets and/or beam energies.

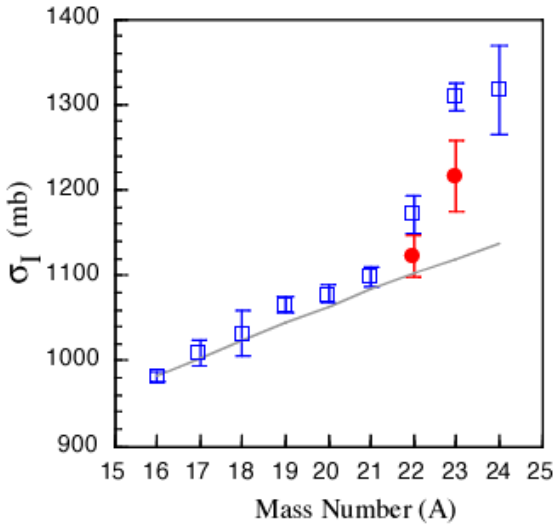

Fig.2 The interaction cross section of ^{A}C+^{12}C. The open squares are from Ref.[3] and filled circles are from Ref.[8].

In order to investigate what information on ^{23}O structure we can obtain from the present data, few body Glauber model calculations were performed which describes ^{23}O in a ^{22}O(core) + neutron model. The resulting cross section with two different possibilities of the valence neutrons being in the $2s_{1/2}$ or $1d_{5/2}$ orbital is shown in Fig.3. It is seen that within the lower limit of the experimental uncertainty, the data can be consistently described with the valence neutron occupying the $2s_{1/2}$ orbital. Such a description would be consistent with the observation from the knockout reaction. A potential model calculation of the oxygen isotopic chain [11] also is in agreement with the data within the uncertainty. We note however, that the central value of the interaction cross section is higher than the results of a few-body Glauber model or the potential model.

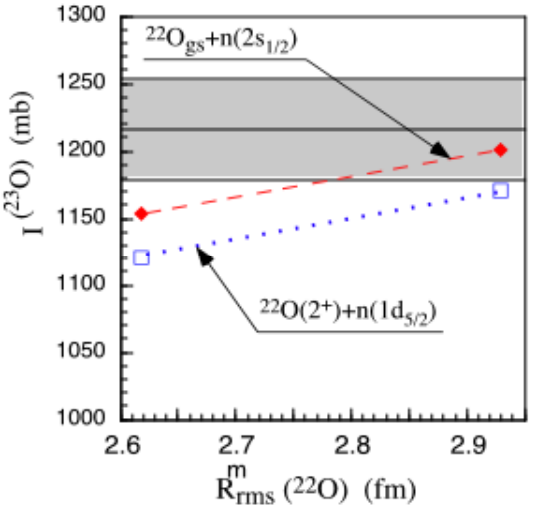

Fig.3 The interaction cross section of ^{23}O+^{12}C at 900*A* MeV shown by the horizontal shaded area. The lines are few-body Glauber model calculations with the configurations as labeled in the figure.

Coupled cluster calculations were also performed

by Hagen et al., which described the ground state of ^{23}O as a super- position of 1h and *1p2h* excitations on top of the correlated ground state of ^{24}O [12]. The first set of calculations were performed using the low-momentum version of the nucleon-nucleon interaction from chiral effective field theory. Fig. 4 shows the results with density distributions from coupled cluster theory with different momentum cutoff parameters λ [13] that were used in the Glauber model analysis. The cross sections with λ = 4.0 and 3.8 fm^{-1} are in good agreement with the data. The variation of the cross section magnitude with λ probably shows the contributions of the neglected three-nucleon forces. A later coupled cluster calculation was performed including the effects of the three-nucleon forces and of the continuum [14]. The three-nucleon forces were approximated as density-dependent nucleon- nucleon forces. The results of such a calculation are consistent with the matter radii derived from the present experiment as shown in Fig.3 of Ref.[14]. It is noted however that this calculation predicts ^{22,23}O slightly more overbound compared to experimental findings from mass measurements. The effect of overbinding might relate to calculated radii being therefore slightly smaller. Calculations with other *ab initio* approaches in the future may provide us with further information.

Figure 4 also shows the Glauber model calculations using density distributions from mean field potentials. Both the calculations agree with the present experimental data for ^{23}O but are higher for ^{22}O. In general, we notice that the evolution pattern of matter radii from ^{21}O to ^{22}O and from ^{23}O to ^{24}O shows an increasing trend in the mean field calculations while the coupled cluster calculations show an almost constant flat trend. It will be interesting to explore with further precise measurements of the cross sections the odd-even pairing effect, as observed from the coupled cluster results. In this context, it is noteworthy to mention a recent investigation of odd-even staggering from the interaction cross sections of $^{22\text{-}24}$O isotopes that was studied by Hagino and Sagawa [17]. The present data for ^{23}O was found to lead to a consistent description of the staggering parameter compared to theoretical systematics. Ref.[17] employed the optical limit approximation of the Glauber model. The density of ^{24}O was constructed with Hartree-Fock-Bogoliubov method using a Woods-Saxon mean field potential together with a density dependent zero-range pairing interaction. The density distributions of $^{22\text{-}23}$O did not take into account the pairing interaction. It was shown that the staggering parameter depends very weakly on energy based on which it is discussed that it could be a useful way to study pairing correlations in neutron-rich nuclei.

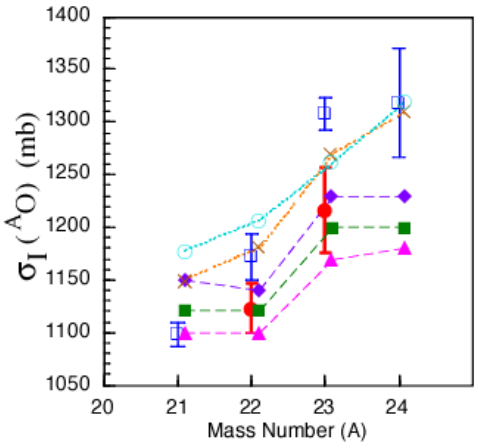

Fig.4 The interaction cross section of oxygen isotopes from Ref.[3] open squares and Ref.[9] filled circles. Results with densities from mean field potentials are shown by cross marks (Ref.[15]) and open circles (Ref.[16]). The filled diamond/squares/triangles are coupled cluster calculations with λ = 4.0/3.8/3.6 fm^{-1}.

It will be interesting to look into the matter radii predictions of monte carlo shell model calculations such as by Otsuka and collaborators in understanding the evolution of structure of the oxygen isotopes.

References

[1] Tanihata I, Savajols H and Kanungo R 2013 *Prog. Part. Nucl. Phys.* **68** 215
[2] Ozawa A, Suzuki T and Tanihata I 2001 *Nucl. Phys.* A **693** 32
[3] Ozawa A et al. 2000 *Phys. Rev. Lett.* **84** 5493

[4] Kanungo R, Ozawa A and Tanihata I 2001 *Phys. Lett.* B **512** 261
[5] Cortina-Gil D et al. 2004 *Phys. Rev. Lett.* **93** 062501
[6] Nociforo C et al. 2005 *Phys. Lett.* B **605** 79
[7] Kanungo R et al. 2009 *Phys. Rev. Lett.* **102** 152501
[8] Jensen Ø et al. 2011 *Phys. Rev.* C **83** 012305R
[9] Kanungo R et al. 2011 *Phys. Rev.* C **84** 061304R
[10] Horiuchi W et al. 2007 *Phys. Rev.* C **75** 044607
[11] Fortune H T and Sherr R 2013 *Eur. Phys. J.* A **49** 26
[12] Hagen G, Papenbrock T, Dean D J and Hjorth-Jensen M 2010 *Phys. Rev.* C **82** 034330
[13] Bogner S K, Furnstahl R J and Perry R J 2007 *Phys. Rev.* C **75** 061001
[14] Hagen G et al. 2012 *Phys. Rev. Lett.* **108** 242501
[15] Abu-Ibrahim B et al. 2009 *J. Phys. Soc. Jpn.* **78** 044201
[16] Brown B A et al. 2001 *Phys. Rev.* C **65** 014612
[17] Hagino K and Sagawa H 2012 *Phys. Rev.* C **85** 037604