Experimental Evidence of Core Modification in the Near Drip-Line Nucleus ^{23}O

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The longitudinal momentum ($P_{\|}$) distributions of one- and two-neutron removal fragments (^{21,22}O) of ^{23}O from the reaction with a C target at 72*A* MeV have been measured for the first time using a new direct time-of-flight method with nearly full acceptance for the breakup fragments. The unexpectedly narrow width of ^{21}O (115 ± 34 MeV/c in FWHM) is consistent with two neutrons occupying the $2s_{1/2}$ orbital in ^{23}O. This indicates modification of core (^{22}O) structure for neutron halolike *sd* shell nuclei near the drip line. This also suggests the lowering of the *s* orbital providing a justification for the $N = 16$ magic number.

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Recent studies of $N = 15$, N, O, F, isotopes show an abrupt rise in interaction cross section [1] which are underpredicted even with 100% *s*-wave probability of a valence neutron in a "core-plus-neutron" halo model [1,2]. It was proposed that a core modification takes place in these nuclei [2]. In this Letter we investigate the cause for this through the simultaneous $P_{\|}$ distribution measurements of one- and two-neutron removal fragments of ^{23}O, with a new direct time-of-flight (TOF) technique. This allowed us for the first time to explore the structure of the so-called "core" nucleus ^{22}O. The results, as will be discussed in details later, show the first clear evidence of a change of the core structure.

The experiment was performed using the RIKEN projectile fragment separator (RIPS) in the RIKEN Ring Cyclotron facility. The secondary beam of ^{23}O was produced by fragmentation of the ^{40}Ar primary beam on a Be target at 92*A* MeV. The ^{23}O beam with a typical intensity of 5–10 pps and energy of 72*A* MeV was subsequently incident on a 370 mg/cm^2 C target.

Measurements of momentum distribution so far have been based on a magnetic spectrometer technique that makes fragment identification quite simple. However, a finite acceptance of the spectrometer makes the derivation of the momentum distribution complicated specially in the tail regions. The present experiment is the first one to demonstrate a nearly full acceptance measurement of momentum distribution without transporting the fragments through any dipole magnet.

An advantage of this type of measurement becomes visible as the ^{21}O fragment from ^{23}O can also be detected with the same geometry along with the ^{22}O fragment. Furthermore, this method allows measurement of interaction cross section, proton pickup, and knockout reactions to be studied at the same time.

The momentum of ^{23}O was determined by TOF between two scintillators placed at the dispersive and the first achromatic foci of RIPS about 10 m apart. Additionally, position information, derived from the parallel-plate-avalanche counters placed at these foci, was used to derive the incident momentum. The momentum of the breakup fragments was determined by TOF between two plastic scintillators placed 5.5 m apart downstream of the reaction target. The transportation of the breakup fragments between these two scintillators was made only by focusing quadrupole magnets having nearly full angular acceptance (99%). The momentum acceptance is wide and flat because no momentum dispersive elements were used in between the target and the detector. The breakup fragments were identified by using the TOF information after the reaction target and the pulse height information from the NaI(Tl) E detector and the ΔE silicon detectors (placed after the scintillators at the final achromatic focus of RIPS). Ultrafast timing scintillators with intrinsic time resolution of 30 ps in σ and good energy resolution by NaI(Tl) ($\sigma = 0.2\%$ for 75*A* MeV ^{12}C) allowed for a very clear separation of the ^{23}O and ^{22}O fragments as shown in Fig. 1.

The main source of background as seen in Fig. 1 arises from the unreacted ^{23}O reacting in the NaI(Tl). The background was carefully estimated, in several ways, by considering fitting of the background by several different methods and also from data without a reaction target. The TOF spectrum of this background is identical to the unreacted ^{23}O peak as the background originates after the plastic scintillators, in the NaI(Tl) detector. The background can thus be subtracted by scaling down the ^{23}O peak in the TOF spectrum by the estimated background counts. The use of 17 silicon solid state ΔE detectors (SSD) helped in removing the reaction background both in the SSD as well as in the NaI(Tl). Fragments of different Z were identified by ΔE and TOF.

The momentum resolution of fragments was $\sim$20 MeV/c in σ. The reaction target thickness contributed mainly to this resolution as the resolution

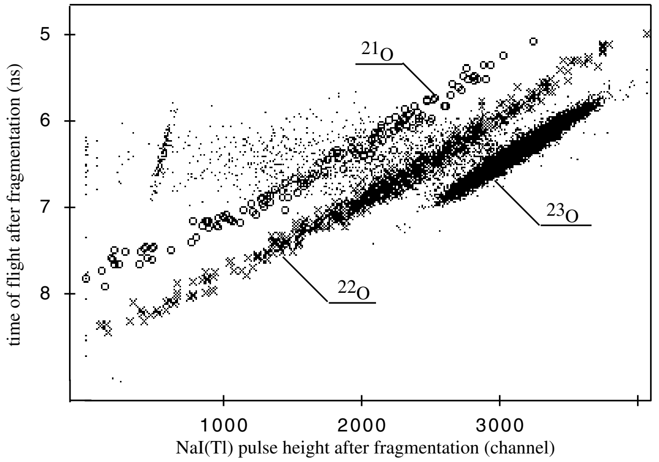

FIG. 1. The particle identification of the fragments after the C target using time-of-flight information between plastic scintillators, and pulse height information from the NaI(Tl) E detector. The unreacted ^{23}O together with one- and two-neutron removal fragments, ^{22}O and ^{21}O, respectively, are clearly identified. Fragments with different Z were already subtracted.

obtained without a reaction target was found to be ~10 MeV/c in σ. The experimental momentum resolution was determined by detecting the unreacted ^{23}O nuclei.

The momentum spectrum of one-neutron removal fragment ^{22}O converted to the projectile rest frame is shown in Fig. 2. The width of the measured distribution by a Lorentzian fitting (Fig. 2a) was, FWHM(Γ) = 94 ± 12 MeV/c. After unfolding the experimental resolution of Gaussian shape, $\Gamma = 73 \pm 15$ MeV/c was obtained. Unfolding was done by numerical integration of Lorentzian and Gaussian functions. The width appears to be slightly smaller than the value reported in Ref. [3], using a magnetic spectrometer technique, but both the data are in fair agreement (Fig. 2a). Fitting the data of Ref. [3], which contains the experimental resolution, by a Lorentzian distribution one obtains $\Gamma = 100 \pm 10$ MeV/c which is consistent with the present value.

For additional verification of the background subtraction, the momentum distributions shown in Figs. 2a and 3a were fitted by a sum of Gaussian and Lorentzian functions. The width and the peak position of the Gaussian distribution in this case were fixed as those of the unreacted ^{23}O distribution in the TOF spectrum. The strength of the Gaussian distribution from such a fit was found to be close to zero confirming that the proper subtraction of the background has been done.

The error bars in Figs. 2 and 3 include statistical errors as well as errors arising due to background subtraction. The theoretical curves shown in this Letter are few-body Glauber model calculations following Ref. [4].

The ground state spin of ^{23}O is yet to be experimentally determined, which makes it possible to consider $J^{\pi}_{gs} = 1/2^+$ or $5/2^+$. In a ^{22}O-plus-neutron model the probable ground state configuration can then be a mixture of ($0^+ + 2s_{1/2}$) and ($2^+ + 1d_{5/2}$) for $J^{\pi} = 1/2^+$ or ($2^+ + 2s_{1/2}$) and ($0^+ + 1d_{5/2}$) for $J^{\pi} = 5/2^+$. The 2^+ state of free

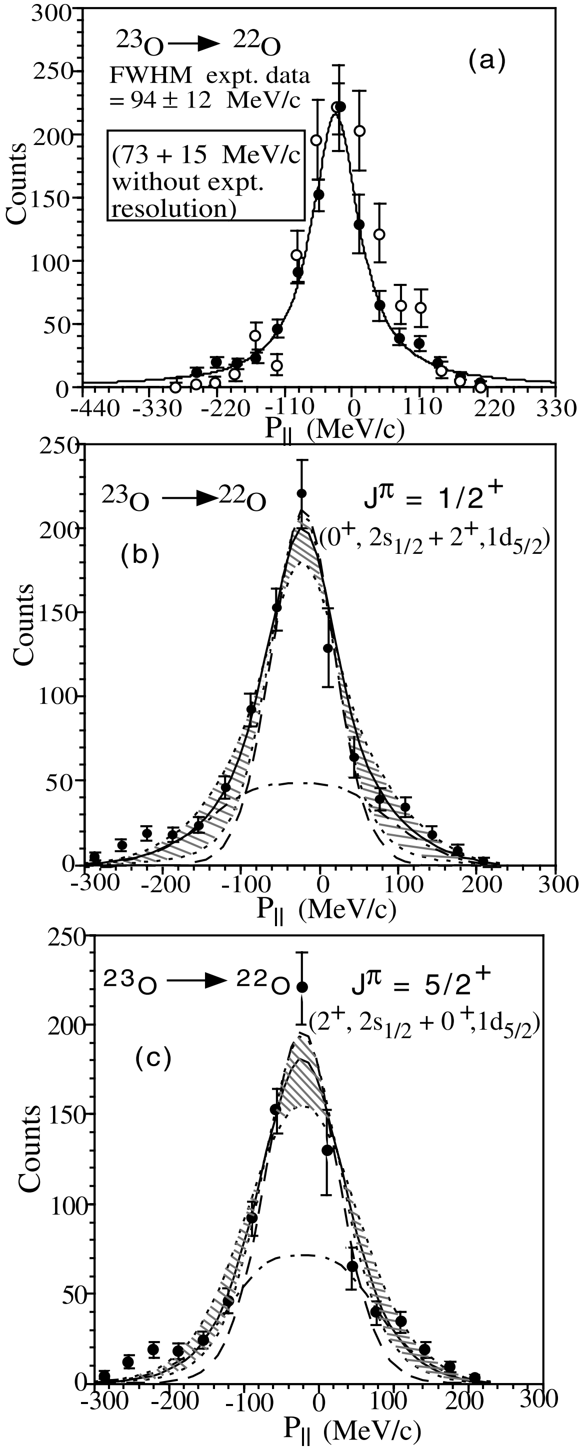

FIG. 2. $P_{\parallel}$ distribution data of ^{22}O from fragmentation of ^{23}O with a C target at 72A MeV (filled circles). (a) The solid line represents a Lorentzian fit to the data. The open circles are the data of Ref. [4]. (b) The curves represent Glauber model calculations in a core-plus-neutron ($^{23}\mathrm{O} = {}^{22}\mathrm{O} + n$) picture with J^{π}_{gs} for $^{23}\mathrm{O} = 1/2^+$. The curves are explained in the text. (c) Same as (b), with J^{π}_{gs} for $^{23}\mathrm{O} = 5/2^+$. The curves are explained in the text.

^{22}O at 3.2 MeV [5] is considered for calculation. However, this may not be true in reality when ^{22}O is inside ^{23}O and the single particle s orbital may lie very close to the $d_{5/2}$ orbital or even cross it.

Figure 2b shows the calculated results assuming $J^{\pi} = 1/2^{+}$ configuration. The solid line shows results of Glauber model calculations with 30% s-wave occupancy of the neutron which is the best χ^2 fit to the experimental data. The shaded region shows the 18% to 68% s-wave neutron occupancy which is the 1σ region of chi-square fit to the data following the method of maximum likelihood. The individual s- and d-wave fits are shown by the dashed and dashed dotted lines, respectively.

The results assuming $J^{\pi} = 5/2^{+}$ configuration are shown in Fig. 2c. An equal amount of s- and d-wave mixing is found to yield a minimum chi-square fit to the experimental data (solid line). The 1σ region of fit is shown by the shaded region (20%–70% s-wave probability).

The $P_{\parallel}$ distribution of ^{21}O from two-neutron removal of ^{23}O is shown in Fig. 3. The width of the experimental distribution by fitting to a Lorentzian (Fig. 3a) is $\Gamma = 130 \pm 30$ MeV$/c$. After unfolding the experimental resolution it reduces to 115 ± 34 MeV$/c$. Background subtraction was verified with fit by a sum of Gaussian and Lorentzian functions (as explained earlier), and the bin selection yielding Gaussian strength zero is chosen.

To interpret this experimental observation we estimate the ^{21}O momentum distribution to be a random addition of the momenta of $^{23}\text{O} \rightarrow {}^{22}\text{O}$ and $^{22}\text{O} \rightarrow {}^{21}\text{O}$. These momentum distributions are calculated following Ref. [4]. It should be noted here that such a random sum does not imply only a two-step process but also includes one-step simultaneous emission of two neutrons either from different or the same orbitals. We consider several possibilities of breakup through the ^{22}O ground state and the ^{22}O excited state leading to the final product ^{21}O which could also be in its ground or excited states. These possibilities are shown in Fig. 3b. The results of relevant folding are displayed in Fig. 3c.

For $J^{\pi} = 1/2^{+}$, the dashed [dotted] line represents case (a) [case (b)]. Case (c) and case (d) yield the same distributions as case (b). This is because the folded distribution is essentially guided by the width of the $^{23}\text{O} \rightarrow {}^{22}\text{O}(2^{+})$ distribution which is much wider compared to the $^{23}\text{O} \rightarrow {}^{22}\text{O}(\text{ex})$ s-wave distributions. It is clearly seen that any combination of the cases for $J^{\pi} = 1/2^{+}$ always leads to a distribution much wider than the observed one.

It is important to note here that the one-neutron removal momentum distribution of bare ^{22}O and its interaction cross section can both be consistently explained with the valence neutron having 80% probability of occupying the $d_{5/2}$ orbital. The dash-dotted line in Fig. 3c shows the result of folding this free ^{22}O momentum distribution with $^{23}\text{O} \rightarrow {}^{22}\text{O}$ s-wave momentum distribution. This is also much wider than the observed distribution.

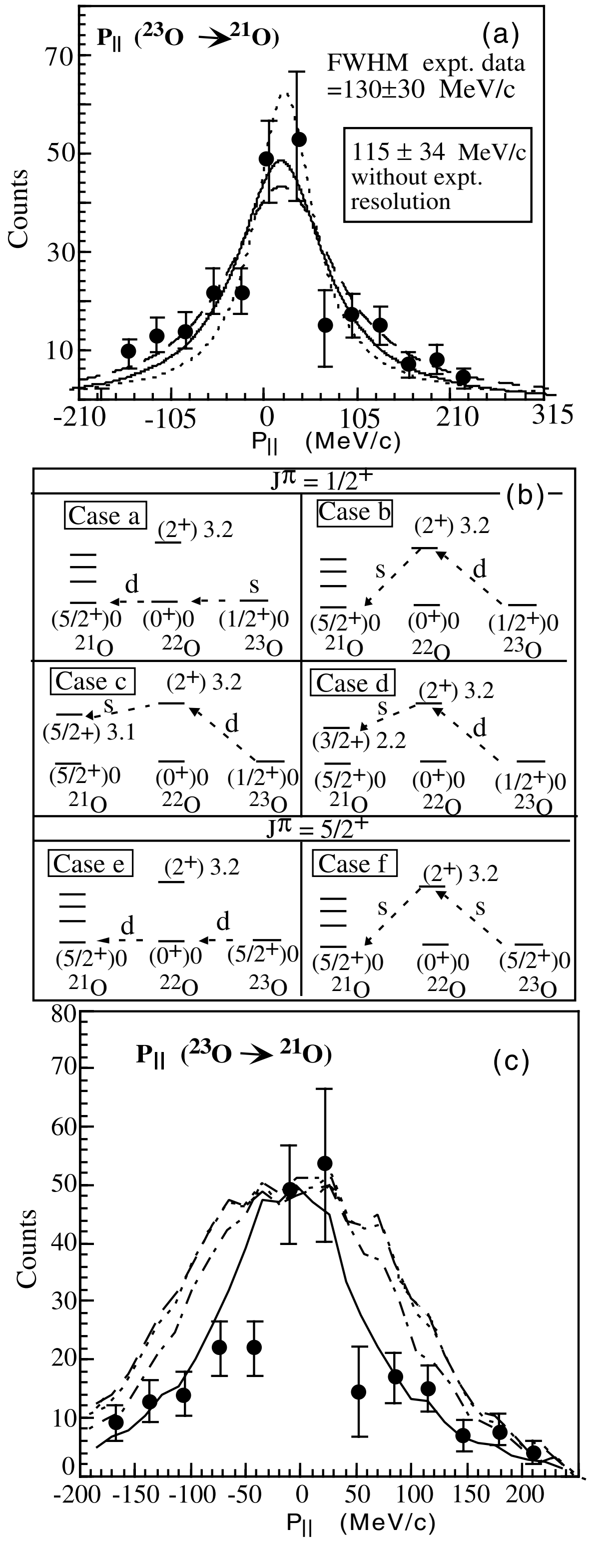

FIG. 3. $P_{\parallel}$ distribution of ^{21}O from fragmentation of ^{23}O. (a) The solid line represents a Lorentzian fit to the data. The dashed (dotted) line shows the 1σ limit of fitting. (b) Possibilities considered for two-neutron removal from ^{23}O. (c) The curves represent random addition of momenta (see text).

Consideration of $J^{\pi} = 5/2^{+}$ with the 10% case (e) + the 90% case (f) yields the best fit to the data (solid line). The results (Fig. 3c) clearly indicate that the possibility of two neutrons occupying the $2s_{1/2}$ orbital in ^{23}O can provide a consistent understanding of the two-neutron removal momentum distribution. The exact value of the spectroscopic factor remains uncertain at present in the absence of proper reaction theory.

This clearly indicates that the ^{22}O structure inside the ^{23}O nucleus is largely modified compared to the bare ^{22}O nucleus. The cause for this modification can be observed to be due to the probability of two neutrons occupying the s orbital. The present data show that the s orbital tends to get filled up before the d orbital, which suggests that it may be lower than the $1d_{5/2}$ orbital. Such a rearrangement can then account for the observed shell gap at $N = 16$ in this region. These data also indicate that the ^{22}O fragments from ^{23}O are not in the ground state and most likely are in the $d_{5/2}$ hole + $s_{1/2}$ particle excited state (2^+ or 3^+).

This is an interesting new situation where the valence nucleon, which determines J^π of the nucleus, is in the d orbital. On the other hand, valence nucleons participating in the nuclear reaction are in the s orbital because they have extended wave function. This can happen for sd shell nuclei when the s and the d orbital are very close to each other and the s orbital is lower, which also causes the valence nucleons to have a mixed configuration.

This experimental Letter does not attempt at making any theoretical model interpretation of the two-neutron removal $P_\parallel$ distribution a general treatment of which including neutron correlations is an involved theoretical project in itself.

The one-neutron removal cross section of ^{23}O obtained in this experiment is 233 ± 37 mb, while the two-neutron removal cross section of ^{23}O is 82 ± 25 mb. The transmission and detection efficiency of unreacted ^{23}O were used in the estimation of these values. The small change in the transmission between ^{23}O and ^{22,21}O is within the error bars. The background was estimated from the target out condition.

In conclusion, this Letter reports the first measurements of momentum distribution using a new technique which allows several fragmentation reactions to be studied in the same condition. The two-neutron and one-neutron removal $P_\parallel$ distributions of ^{23}O were measured simultaneously for the first time. The $^{23}\mathrm{O} \rightarrow {}^{22}\mathrm{O}$ $P_\parallel$ distribution in a core-plus-neutron model is consistent with mixed occupancy of a neutron in $2s_{1/2}$ and $1d_{5/2}$ orbitals, under the assumption of ^{23}O having $J^\pi = 1/2^+$ or $5/2^+$.

The $^{23}\mathrm{O} \rightarrow {}^{21}\mathrm{O}$ $P_\parallel$ distribution has a narrower width than that expected if the two neutrons emitted are one from the $2s_{1/2}$ orbital and the other from the $1d_{5/2}$ orbital or both from the $1d_{5/2}$ orbital considering $J^\pi = 1/2^+$. On the contrary, the data are consistent with two neutrons being emitted from the $2s_{1/2}$ orbital in a $J^\pi = 5/2^+$ configuration. This makes it the first direct experimental observation of core modification in near drip line nuclei.

The possibility of two neutrons occupying the s orbital also suggests its lowering compared to the d orbital and would be consistent with the emergence of the $N = 16$ shell gap. This would suggest that ^{23}O cannot be described in a core-plus-one neutron model as one cannot distinguish between two neutrons in the $2s_{1/2}$ orbital. Such a structure may then be able to explain the large interaction cross section.

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