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RIKEN ACCELERATOR RESEARCH FACILITY

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The Institute of Physical and Chemical Research (RIKEN)
2-1 Hirosawa, Wako, Saitama 351-0198, Japan
TEL (048)462-1111 FAX (048)462-4642
e-mail *username*@rikvax riken go jp

The first experimental evidence of core modification in near drip-line nucleus ^{23}O

Rituparna Kanungo, Masami Chiba, Naohito Iwasa[1], Shunji Nishimura, Akira Ozawa, Chhanda Samanta[2 3], Toshimi Suda, Takeshi Suzuki [4], Takayuki Yamaguchi, Tao Zheng and Isao Tanihata

The Institute of Physical and Chemical Research (RIKEN), 2-1,Hirosawa, Wako-shi, Saitama 351-0198, Japan

[1] *Department of Physics, Tohoku University, Miyagi 980-8578, Japan*

[2] *Physics Department, Virginia Commonwealth University, West Main Street, Richmond, VA-23284*

[3] *Saha Institute of Nuclear Physics, 1/AF, Bidhannagar, Calcutta 700064, India*

[4] *Department of Physics, Niigata University, Niigata 950-218, Japan*

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The longitudinal momentum distributions of the two neutron removal as well as the one neutron removal fragments of ^{23}O from reaction with a C-target at $72A$ 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$\pm$34 MeV/c in FWHM) from fragmentation of ^{23}O is the first direct evidence of a change of structure of ^{22}O inside ^{23}O compared to the bare ^{22}O nucleus This observation indicates a strong modification of core structure for neutron halo like *sd* shell nuclei near drip line The probability of two neutrons occupying the *s*-orbital in ^{23}O also suggests the lowering of the $s-$orbital providing a reason to the $N = 16$ magic number The ^{22}O momentum distribution from ^{23}O fragmentation shows a width of 73$\pm$ 15 MeV/c in FWHM

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Study of neutron rich nuclei has resulted in the discovery of nuclear halo [1] The simplest evidence of this structure is an abrupt enhancement in the interaction cross section Such measurements for the N, O, F, isotopes [2] indicated abrupt rise in interaction cross section for the $N = 15$ nuclei However, these enhanced cross sections failed to be interpreted by the usual "core-plus-neutron" model To understand this anomaly it was proposed that a core modification takes place in these nuclei [3] The reason for modified core could not however be understood due to lack of any further experimental information

The valence neutron momentum distribution of a neutron-rich nucleus is a reflection of the nuclear structure as its shape is strongly determined by the orbitals occupied by the valence neutrons In this letter we report the investigation of the neutron rich ^{23}O nucleus through the simultaneous measurements of the longitudinal momentum distributions of one and two-neutron removal fragments, 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, from the fragmentation of the ^{23}O nucleus The results, as will be dicussed in details later, show the first clear evidence of a change of the core structure

The experiment was performed using the fragment separator RIPS in the RIKEN Ring Cyclotron facility The secondary beam of ^{23}O was produced by fragmentation of ^{40}Ar primary beam on a Be target at 92A MeV The ^{23}O beam with a typical intensity of 5-10 pps and energy of 72 4 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, in particular of the tail part of the distribution 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 full acceptance type of measurement without using any spectrometer, 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 scintillation counters placed one at the dispersive and the other at first achromatic foci of RIPS about 10m apart Additionally, position information, derived from the parallel-plate-avalanche counters (PPAC) placed at these foci, were used to derive the incident momentum The momentum of the breakup fragments were determined by TOF between two plastic-scintillators placed 5 5m apart downstream of the reaction target The transportation of the breakup fragments between these two scintillators was made only by focussing 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 NaI(Tl) E-detector and the ΔE, silicon detectors (placed after the scintillators at the final achromatic focus of RIPS) Ultra-fast timing scintillators with intrinsic time resolution of 30 ps in σ and good energy resolution by NaI(Tl) (σ=0 2% for 75A 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, arise, 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 reaction target The TOF spectrum of this background is identical to the unreacted ^{23}O peak as the background originates after the plastic scintillators and in the NaI(Tl) detector The background can thus be subtracted by scaling down the ^{23}O peak in TOF spectrum by the estimated background counts The use of a stack of 17 silicon ΔE detectors 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

In the present measurement, the momentum resolution of fragments was $\sim$ 20 MeV/c in σ The reaction target thickness contributed mainly to this resolution as the resolution obtained without a reaction target was found to be $\sim$ 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) of ^{23}O converted to the projectile rest frame, is shown in Fig 2 The width of the measured distribution, Γ, was found to be 94$\pm$12 MeV/c in Γ, from fitting by a Lorentzian curve as shown in Fig 2a The width of this distribution after unfolding the experimental resolution of Gaussian shape yields a value of 73$\pm$ 15 MeV/c (Γ) Unfolding was done by numerical integration of Lorentzian and gaussian functions This observed width appears to be slightly smaller, than the value reported in a recent measurement by Sauvan *et al* [4] using a magnetic spectrometer technique, but the data is in fair agreement with that of Ref [4] as shown in Fig 2a Fitting the data of Ref [4], which contains the experimental resolution, by a Lorentzian distribution one can obtain an FWHM of 100$\pm$ 10 MeV/c which is consistent with the present observed value

For additional verification of the background subtraction, the momentum distribution shown in Figs 2a and 3a were fitted by a sum of Gaussian and Lorentzian function The width and the peak position of the Gaussian distribution in this case was fixed as those of the unreacted ^{23}O ditribution 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 all the experimental data in the figures 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 the formalism by Ogawa *et al* [5]

The ground state spin of ^{23}O is yet to be experimentally determined, which makes it possible to consider J^{π}_{gs}=1/2$^+$ or 5/2$^+$ The possibility of 3/2$^+$ is rather small and thus will not be discussed in this letter 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^π = 1/2$^+$ or (2$^+$ + 2s$_{1/2}$) and (0$^+$ + 1d$_{5/2}$) for J^π = 5/2$^+$ The 2$^+$ state of ^{22}O is known to exist at 3 2 MeV [6] and we consider this excitation energy in our 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^π=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^π=5/2$^+$ configuration are shown in Fig 2c An equal amount of *s*- and *d*− wave mixing is found to yield a minimum chisquare fit to the experimental data (solid line) The 1σ region of fit is shown by the shaded region (20% - 70% *s*-wave probability)

The momentum 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 is 130±30 MeV/c in (Γ) shown in Fig 3a After unfolding the experimental resolution it reduces to 115±34 MeV/c The fitting was done with 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}O→ ^{22}O and ^{22}O→ ^{21}O These momentum distributions are calculated in a few body Glauber model framework following Ref [5] It should be noted here that such a random sum does not imply only a two-setp process but also includes one-step simultaneous emission of two neutrons either from different or same orbitals In doing this, we consider two cases for the ground state spin of ^{23}O, i e J^π=1/2$^+$ in a normal shell ordering and J^π=5/2$^+$ for re-ordering of orbitals We consider several possibilities of breakup through ^{22}O ground state as well as ^{22}O excited state leading to the final product ^{21}O which could also be in its ground or excited states These possibilties are shown in Fig 3b The results of relevant folding are displayed in Fig 3c

For J^π=1/2$^+$, the dashed(dotted) line represents case(a)(case(b)) Case(c) and case(d) yield distributions same as case(b) This is because, the folded distribution is essentially guided by the width of ^{23}O→^{22}O(2$^+$) distribution which is much wider compared to the ^{23}O→^{22}O(ex) *s*-wave distributions It is clearly seen that any combination of the cases for J^π=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, both can be consistently explained with the valence neutron having 80% probability of occupying the $d_{5/2}$ orbital The dashed dotted line in Fig 3c shows the result of folding this free ^{22}O momentum distribution with ^{23}O → ^{22}O *s*-wave momentum distribution This is also much wider than the observed distribution

The consideration of J^π=5/2$^+$ with 10%case(e) + 90%case(f), yields the best fit to the data (solid line) The results (Fig 3c) clearly indicate that 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 is clearly indicative of the fact 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 shows that the *s*- orbital tends to get filled up before the *d*-orbital, which suggests that it maybe lowered than the 1$d_{5/2}$ orbital Such a re-arrangement can then account for the observed shell gap at N = 16 in this region This data also indicates that the ^{22}O fragments from ^{23}O is not in its ground state and most likely in the $d_{5/2}$ hole + $s_{1/2}$ particle excited state (2$^+$ or 3$^+$)

This is an extremely interesting new situation where the so-called valence nucleon, that determine 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 when the *s*- and the *d*− orbital are very close to each other and *s*- orbital is lower, which also causes the valence nucleons to have a mixed configuration

This experimental paper does not attempt at making any theoretical model interpretation of the two neutron removal fragment momentum distribution Such general treatment of two-neutron momentum distribution 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 was 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 of one and two neutron removal fragments of neutron-rich nuclei, using a new nearly full acceptance technique which allows several fragmentation reactions to be studied in the same condition The two-neutron and one neutron removal fragment momentum distributions of ^{23}O were measured simultaneously The width of the $^{23}O \rightarrow {}^{22}O$ momentum distribution was found to be 73$\pm$15 MeV/c in FWHM and is consistent with Glauber model calculations of the single neutron having mixed occupancy of the $2s_{1/2}$ and $1d_{5/2}$ orbitals, under the assumption of ^{23}O having $J^{\pi} = 1/2^{+}$ or $5/2^{+}$

The $^{23}O \rightarrow {}^{21}O$ $P_{||}$ distribution shows a width of 115$\pm$34 MeV/c in FWHM This width is found to be much smaller, 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^{π}=1/2^{+} Consideration of free ^{22}O momentum distribution also leads to a wider distribution On the contrary, the data, is consistent with the fact that two neutrons are emitted from the $2s_{1/2}$ orbital in a J^{π}=5/2^{+} configuration This makes it the first direct experimental observation of strong core modification in near drip line nuclei This introduces a possibility that in ^{23}O two neutrons occupy the $2s_{1/2}$ orbital Such a structure can then be able to explain the large interaction cross section

The possibility of two neutrons occupying the *s*- orbital also signifies its lowering compared to the *d*- orbital and would be consistent with the emergence of the $N = 16$ magic number in this region 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

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FIG 1 The particle identification of the fragments after the secondary C- target using time-of-flight information from the plastic scintillators, and pulse height information from 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

FIG 2 Momentum distribution data of one neutron removal fragment (^{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}O=^{22}O+n) picture with J^{π}_{gs} for ^{23}O = 1/2^{+} The curves are explained in the text (c) same as (b), with J^{π}_{gs} for ^{23}O = 5/2^{+} The curves are explained in the text

FIG 3 Momentum distribution data of two neutron removal fragment (^{21}O) from fragmentation of ^{23}O with a C-target at 72A MeV (a) The momentum distribution data for $^{23}O \rightarrow {}^{21}O$ The solid line represents a Lorentzian fit to the data The dashed/dotted lines show the lorentzian curve with upper/lower error bar of width (b) Different possibilies considered for two neutron removal from ^{23}O (c) The $^{23}O \rightarrow {}^{21}O$ parallel momentum distribution data The curves representing random addition of momenta are explained in the text

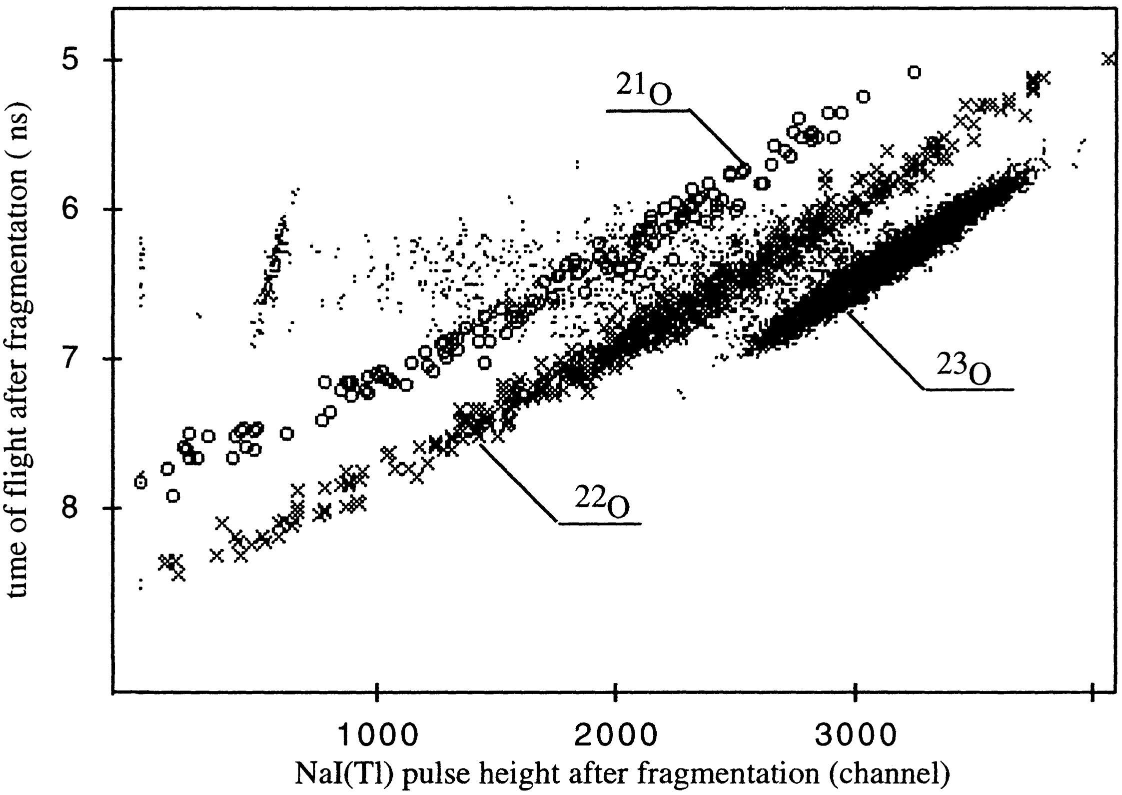
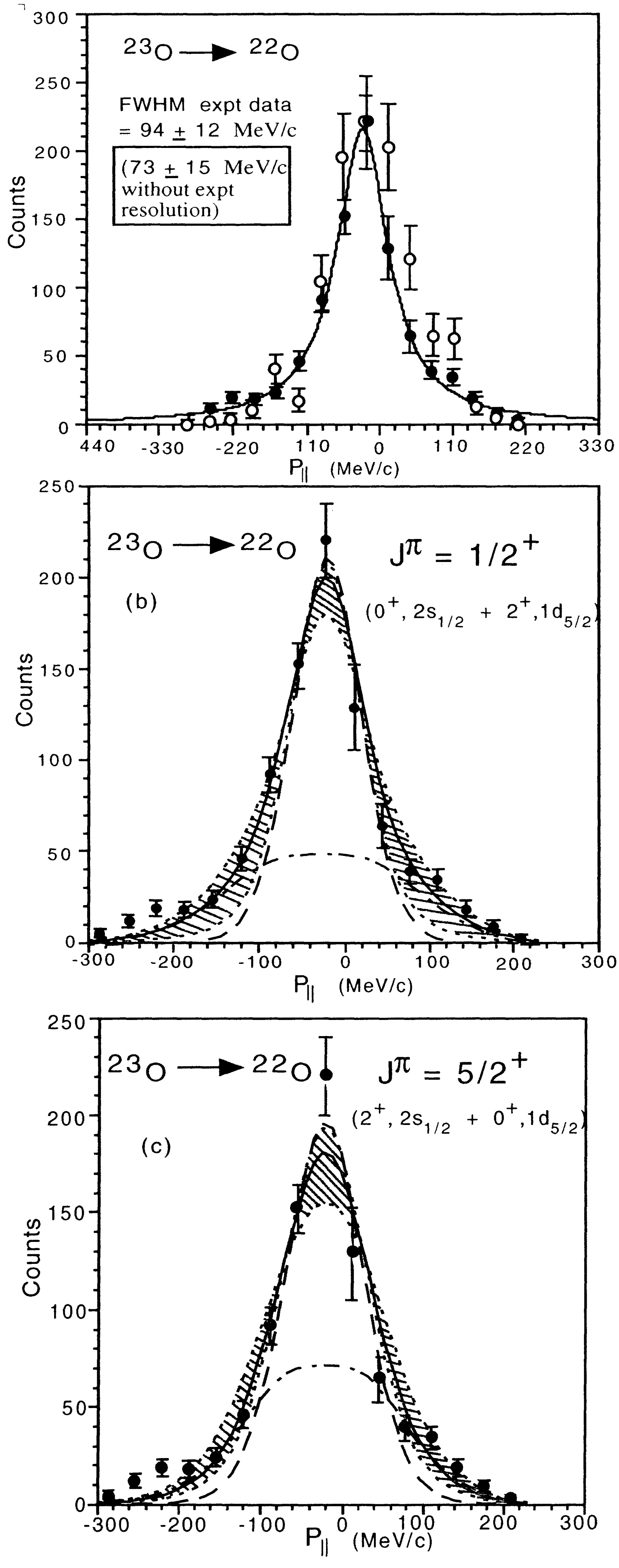

5
6
7
8
time of flight after fragmentation (ns)
21O
22O
23O
1000
2000
3000
NaI(Tl) pulse height after fragmentation (channel)

Fig 1



23O ⟶ 22O
FWHM expt data
= 94 ± 12 MeV/c
(73 ± 15 MeV/c
without expt
resolution)
Counts
P|| (MeV/c)
23O ⟶ 22O
J^π = 1/2+
(b)
(0+, 2s1/2 + 2+,1d5/2)
Counts
P|| (MeV/c)
23O ⟶ 22O
J^π = 5/2+
(c)
(2+, 2s1/2 + 0+,1d5/2)
Counts
P|| (MeV/c)

Fig 2

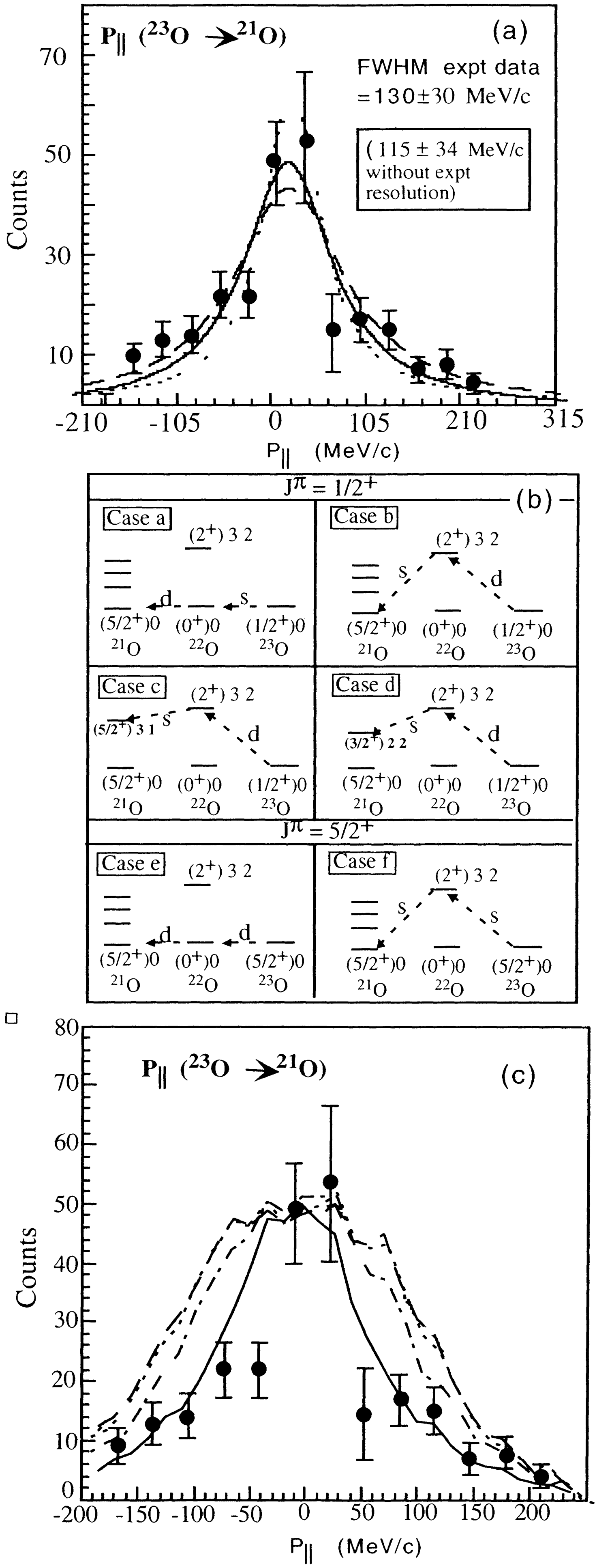


Fig 3 (revised)