Measurement of unbound excited state of $^{24}$O

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R405n collaboration


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New Magic number

\[ S_n(N,Z) = B(N,Z) - B(N-1,Z) \quad N=\text{odd}, \ Z=\text{even} \]


Traditional magic number
Disappear traditional magic number
Appear NEW magic number
No $\gamma$-transitions have been observed for $^{23-24}$O.


The first excited state of $^{23-24}$O lies above the neutron separation energy (unbound state).

The relative high excited energy, which has the lower limit of $4.09\pm0.13$ MeV, in the neighboring even-even nuclei provides a signature of the magic property at $N=16$.

Theoretical predictions

The first excited state of $^{24}$O will be attributed to the promotion of a neutron from the $\nu_1 s_{1/2}$ orbital to the $\nu_0 d_{3/2}$ orbital, and the possible spin-parity values are $1^+$ and $2^+$ with the configuration of $(\nu_1 s_{1/2})^1 \otimes (\nu_0 d_{3/2})^1$.

The theoretical calculations predict that the first $2^+$ excited state will lie below the $1^+$ state.

The shell model code : NUSHELL@MSU, B.A. Brown and W.D.M. Rae, MSU-NSCL report (2007)
Recently, the first excited state of $^{24}$O was studied by C. R. Homan in the nucleon removal reaction of a radioactive $^{26}$F beam. (C.R. Homan et al., Phys. Lett. B, 672, 17-21 (2009))

$E_{\text{decay}} (2^+) = 630\pm40 \text{ keV}$

The first resonance state, inferred to be the $2^+$ state, was not clearly identified due to the possible near proximity of the first $2^+$ and $1^+$ states in $^{24}$O. Since the position of the first $2^+$ excited state is one of the indicators for magic nuclei, unambiguous identification of this state is essential to confirm that $^{24}$O is a double magic nucleus.
Comparison between the previous and present experiments

<table>
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<th>Previous (MSU)</th>
<th>Present (RIKEN)</th>
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<tbody>
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<td>Secondary Beam</td>
<td>$^{26}$F</td>
<td>$^{24}$O</td>
</tr>
<tr>
<td>Secondary Target</td>
<td>Be</td>
<td>Liquid hydrogen</td>
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<tr>
<td>Reaction</td>
<td>nucleon removal reaction</td>
<td>$(p,p')$ reaction</td>
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**Reaction**

$$^{26}\text{F} + \text{Be} \rightarrow ^{25}\text{O} + p \rightarrow ^{24}\text{O}^* + n \rightarrow ^{23}\text{O} + n$$

**DWBA calculation**

Program DWBA70, R. Schaeffer, J. Raynal, unpublished; Extended version DW81, J.R. Comfort, unpublished.

$$^{24}\text{O}(p,p')^{24}\text{O}^*, E_p = 67 \text{ MeV}$$

Projectile-nucleon effective interaction: M3Y

Optical potential: KD02

Shell model interaction: USDa

Experiment at RIKEN


$^{40}$Ar beam @ 95 MeV/u, ~50 pnA
Secondary beam identification (1)

**Diagram:**
- PPAC1 and PPAC2
- D2 and D1
- F1, F2, F3
- Plastic scintillator and SSD
- Production target
- Beam swinger
- Beam swinger at F0
- 40Ar beam @95MeV/u, ~ 50pnA

**Equations:**
- $v \sim \frac{1}{TOF}$
- $\Delta E \sim \frac{Z^2}{v^2}$

**Heat map:**
- TOF from F0 to F2 (nsec)
- Isotopes: Na, Ne, F, O, N
Secondary beam identification (2)

\[ \nu \sim \frac{1}{\text{TOF}} \quad \Delta E \sim \frac{Z^2}{\nu^2} \quad BQ = \frac{A}{Ze \gamma m_u} \frac{\nu}{c} \]

![Diagram of beam interaction and particle identification](image)

- **D1**: Production target
- **D2**: Beam swinger
- **PPAC1** and **PPAC2**: Plastic scintillator and SSD

\[^{40}\text{Ar beam \textcolor{orange}{\@95MeV/u, \sim 50pnA}}\]
Experimental Setup

- Neutron counter array
- Liquid hydrogen target system, NDCs, DALI, MDC
- Dipole magnet
- Veto counter
- Hodoscope
- FDC
- LH$_2$
- DALI NaI array
- NDC1
- NDC2
- Neutron counter array
- Dipole magnet
Nuclear charge identification

Diagram showing a neutron counter, veto counter, hodoscope, FDC, dipole magnet, MDC, LH₂, DALI NaI array, NDC1, and NDC2. A graph shows the relationship between TOF (arbitrary unit) and ΔE/Δx (arbitrary unit), with peaks at Z = 7, Z = 8, and Z = 9.
Isotopic identification of the oxygen isotopes
Neutron counter analysis (Light output)
Neutron counter analysis (Timing)

\[ \text{Missing mass} = \left[ (E_p - E_n + M_{Li})^2 - (P_p^2 + P_n^2 - 2P_pP_n \cos \theta) \right]^{1/2} - M_{Be} \]
Reconstruction of the decay energy using the invariant mass method

\[ E_{\text{decay}} = \sqrt{(E_f + E_n)^2 - (P_f + P_n)^2 - (M_f + M_n)} \]
Decay energy of $^{22}\text{O} + n$

$E_{\text{decay}} = 45 \pm 2 \text{ keV}$

$E_{\text{decay}} = 46 \pm 3 \text{ keV}$

RIKEN (Preliminary)


Decay energy of $^{23}$O + n

$E_{\text{decay}} = 610^{+72}_{-53}$ keV at $\Gamma = 5.6$ MeV

Yellow histogram: simulated resonant contribution.
Dashed line: nonresonant contribution (background described by Maxwellian distribution).
Solid line: sum of the yellow histogram and the background.

Present (RIKEN) | Previous (MSU)
$E_{\text{decay}} = 610^{+72}_{-53}$ keV | $E_{\text{decay}} = 630\pm40$ keV
The $2^+_1$ energies

The high $2^+_1$ excited energy of $^{24}$O shows the property of double magic nucleus.

New observed higher excited state in $^{24}$O
We have investigated the unbound excited state of $^{24}$O using the invariant mass method in the $^{23}$O+$n$ decay channel via the proton inelastic scattering of $^{24}$O in inverse kinematics. We have observed the first $2^+$ excited state of $^{24}$O at the decay energy $E_{\text{decay}} = 610\pm\frac{72}{53}$ keV (preliminary) above one neutron separation energy and confirmed the previous result of the state ($E_{\text{decay}}$(MSU)=630±40 keV). The corresponding excitation energy is $4.70\pm0.15$ MeV adopting $S_n(^{24}$O)=4.09±0.13 MeV (Taken from B.Jurado*).

Such a high excitation energy of the first $2^+$ state comparing with those in the neighboring even-even nuclei strongly indicates the property of double magic nuclei.

Thank you!
Extra slides
Energy dependent Breit-Wigner line-shape

\[ \sigma \sim \frac{\Gamma_1(E)\Gamma_l(E_R)}{(E - E_R + \Delta_l)^2 + \Gamma_l(E)^2/4} \]

\[ \Gamma_1(E) = \Gamma_l(E_R) P_l(E)/P_l(E_R) \]

\[ \Delta_l(E) = 2 \Gamma_l(E_R)(S_l(E) - S_l(E_R))/P_l(E_R) \]

R.G. Thomas,
Reviews of Modern Physics 30, part1, (1958)

\[ \Gamma(E_R) = 1 \text{ MeV} \]