New Results with TECSA: Study of the d\(^{(26}\text{Al},p)^{27}\text{Al}\) reaction

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Motivation for TECSA Detector

- TECSA pools existing resources from TAMU (USA), Univ. of Edinburgh (UK), and INFN-LNS (Italy).
- **Goal**: Build detector suitable for transfer reaction measurements with rare isotope beams.
- The silicon detector array should cover a large solid angle to maximize efficiency while providing needed granularity.
- We use TECSA to develop methods applicable to nuclear astrophysics, nuclear structure and stockpile stewardship such as ANC, TH Method and other surrogate techniques.

Davinson et al. NIM A 454, 350 (2000)
Xu et al. PRL 73, 2027 (1994)
Galactic images with Comptel and Integral

- Satellites detect 1.8 MeV gamma ray from $^{26}$Al$^g$ $\beta$-decay.
- Lifetime of $^{26}$Al$^g$ is $7.2 \times 10^5$ yrs.
- Gives evidence of ongoing Nucleosynthesis in stars in the galaxy.
- Want to understand production and destruction of nuclei like $^{26}$Al in stars – maybe $^{26}$Al$^m$ ($0^+$) is important?
Satellites detect less 1.8 MeV $\gamma$-rays than expected.

In astrophysical environment ($0.1 \, \text{GK} < T < 0.4 \, \text{GK} \rightarrow 100 \, \text{keV} < E_{\text{CM}} < 600 \, \text{keV}$) $^{26}\text{Al}$ can also be destroyed by $^{26}\text{Al}(p,\gamma)$.

Try to investigate levels of interest for $^{26}\text{Al}^m(p,\gamma)$ and $^{26}\text{Al}^g(p,\gamma)$ by studying IAS states in $^{27}\text{Al}$ with $^{26}\text{Al}(d,p)$ reaction.
$^{27}\text{Si} - ^{27}\text{Al}$ - IAS Levels

Possible IAS levels

- $6336.3 \pm 0.3$ (2.1, 0.5)$^+$
- $6332.4 \pm 0.3$
- $5.5^-$
- $8287$
- $8478 \pm 0.3$

$^{27}\text{Al}$ experiment

$^{27}\text{Al}$ shell model

A.E. Champagne, et al., NPA 512 (1990) 317-332

Layout of TAMU – Cyclotron Institute

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

MARS

MARS RECOIL SPECTROMETER 1992

Q\alpha SPECTROMETER 2012

TAPE TRANSPORT & PRECISION DECAY FACILITY 1999

NIMROD 1999

MDM SPECTROMETER 1993,2000

ECR ION SOURCE

RADIATION EFFECTS FACILITY 1994, 2000, 2005

BEAM ANALYSIS SYSTEM 1994

K150 (88\°) CYCLOTRON

CB-ECR SOURCE

ELECTRON C bánƯơnIOM GUIDE

HEAVY ION GUIDE

LLNL LINE 2011

4/12/2012

DREB 2012 - Pisa - Roeder
• $^{26}$Mg primary beam from K500 at 16 MeV/u.
• Produce $^{26}$Al beam with $^{26}$Mg(p,n) reaction.
• Refocus Beam in detector chamber on CD$_2$ target.
Tune MARS to select 2 different reaction mechanisms.

Expect “Transfer” solution to have more $0^+$ isomer than the “Fusion-Evaporation (FE)” solution. How do we check?
β-decay measurement of isomer ratio

Setup:
V.E. Iacob et al., PRC 82, 035502 (2010)

- Exit Window + Scintillator
- Tape
- 4π Proportional Counter

- $^{26}\text{Al}^{m} T_{1/2} = 6.35 \text{ s}$
- Determine ratio with $\#\beta$-decays / $\#^{26}\text{Al}$ total
- “Transfer” solution – 66% $0^+$, 34% $5^+$
- “Fusion-Evaporation (FE)” solution – 36% $0^+$, 64% $5^+$
Overview of d($^{26}$Al,p)$^{27}$Al setup

- TECSA – 16-ring annular array at back angles.
- 451 $\mu$g/cm$^2$ CD$_2$ target.
- Energy degraded to 5 MeV/u and 3 MeV/u with 152 $\mu$m $^9$Be foil.
- Scintillator+PMT at back of chamber for timing measurements.
- Beam stop to reduce $\beta$-background from beam.
Details of the TECSA setup

- MSL type-YY1 Si detectors, single-sided, 16 strips each
- 8 detectors form a 16-ring annular array with 128 strips
- Movable (Z-axis) and rotatable target holder.
- Measured at 21 cm and 12 cm distance, Covered $\theta_{cm}$ 5°-25°.
- PSD for focusing the beam.

Focusing and Energy Degradation

Final Energies after $^9$Be foil

- **D12 = 421 A ("Transfer")** – 131.4 ± 8% MeV
- **D12 = 402 A ("Fusion-Evaporation")** – 77 ± 9 % MeV

Target diameter = 15.8 mm
• Timing difference between TECSA and scintillator allows separation of coincidence data from random background.

• Primary beam from cyclotron is coming in RF pulses from cyclotron every 76 ns (13.1 MHz).
• Similar states are populated in the 2 cases
  – 131 MeV data had 66% $^{26}\text{Al}^m$, 34% $^{26}\text{Al}^g$
  – 77 MeV data had 36% $^{26}\text{Al}^m$, 64% $^{26}\text{Al}^g$

• Can the structure of the states be distinguished?
**Structure of $^{27}$Al**

- $^{27}$Al density of states is high, often there are at least 2 single-particle structure choices within $\sim 300$ keV.
- Investigate differences with cross sections and DWBA, (L-values).

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Spin</th>
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<tbody>
<tr>
<td>? 8.7</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>7.07</td>
<td>1/2$^+$ or 7.17, 9/2$^+$</td>
</tr>
<tr>
<td>6.81</td>
<td>1/2$^+$ or 6.5, 7/2$^+$</td>
</tr>
<tr>
<td>5.50</td>
<td>11/2$^+$ or ?</td>
</tr>
<tr>
<td>4.510</td>
<td>11/2$^+$ or 4.811, 5/2$^+$</td>
</tr>
<tr>
<td>3.004</td>
<td>9/2$^+$ or 2.982, 3/2$^+$</td>
</tr>
<tr>
<td>0.843</td>
<td>1/2$^+$</td>
</tr>
<tr>
<td>0</td>
<td>5/2$^+$</td>
</tr>
</tbody>
</table>

*N.B. - Unpopulated states not shown…*

Compare with $^{26}$Mg(d,n) from J. Uzureau et al., NPA 250 (1975) 163
J. Uzureau et al., noted that for $^{26}$Mg(d,n) reaction that $L=0$ and $L=2$ angular distributions are distinguishable at forward angles.

Simple DWBA calculations carried out with program TWOFNR using scaled global potentials (Perey&Perey and CH89).

M. Igarashi et al., Surrey Univ. version
Angular Distributions

- Data points are corrected for the measured isomer/g.s. ratio.
- 0.843 MeV state is confirmed as $L=0, \frac{1}{2}^+, {^{26}}\text{Al}^m + p$
- 3.0 MeV state found to be the $L=0, \frac{9}{2}^+, {^{26}}\text{Al}^g + p$
- Can tell difference in structure with the calculations.
Summary of Preliminary Results

- \(d(^{26}\text{Al}^m, p)^{27}\text{Al}\) populated:
  - 0.843, 1/2\(^+\) (\(L=0\))
  - 6.7, 1/2\(^+\) (\(L=0\))
  - ? 8.6 MeV state (candidate IAS state)

- \(d(^{26}\text{Al}^g, p)^{27}\text{Al}\) populated:
  - 3.0 MeV, 9/2\(^+\) (\(L=0\))
  - 4.5 MeV, 11/2\(^+\) (\(L=0\))
  - 5.6 MeV, 11/2\(^+\) (\(L=0\))

- Saw mainly \(L=0\) states. \(L=2\) states have maximums outside of angular range measured.

- Further work needed to verify structure of 8.6 MeV state.
Future Plans

• Continue analysis of current data
  – Identify states of astrophysical relevance (8.6 MeV state ?).
  – Improve DWBA calculations.

• Planning future measurements of relevance to nuclear astrophysics.
  – $d(^{26}\text{Al},p)^{27}\text{Al}$ – (more statistics needed)
  – Trojan Horse Method – $^{18}\text{F}+p \rightarrow ^{18}\text{Ne}+n$
  – $d(^{30}\text{P},^{31}\text{P})n$
Thank you
Energy Calibration

- Calibrated with $^{228}$Th, $^{241}$Am, and $^{148}$Gd α-sources.
- Resolution: 40 keV (strip), 50 keV (ring).
• Observed protons from $^{15}\text{C}$ g.s. [$1/2^+$] and first excited state [$5/2^+$].
• Resolution was $\approx 100$ keV FWHM.
Results $d(^{14}\text{C},p)^{15}\text{C}$

- Angular distributions cover $4^\circ < \theta_{\text{cm}} < 34^\circ$
- DWBA calculations with TWOFNR, global potentials.
- Calculations reproduce general features of angular distributions.
- ANC calculated for part of thesis work of M. McCleskey.

Nuclear reactions

- Projectile + target -> reaction product(s) + residual residue(s)
  - Scattering: 1+2 -> 1+2
  - Two-body reactions: 1+2 -> 3+4
  - Multi-fragmentation: 1+2 -> 3+4+5+ ...
- Kinematic conditions: incident energy, scattering (react) angle
  - Normal kinematics: $M_p < M_t$. Inverse kinematics: $M_p > M_t$
  - $E_{lab} \rightarrow E_{cm} = (M_t/M_p+M_t)E_{lab}$ (non-relativistic)
- Measure cross section: $\sigma = n_r$ detected/incident $p$ per area/n target nuclei
- Angular distributions: $d\sigma/d\Omega = f(\theta)$ (info on space character of interaction)
- Excitation functions: $\sigma = f(E_{inc})$ (info on time character of interaction)
- Momentum distributions