Ренессанс в резонансном рассеянии
(новые задачи-новая техника)

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TTIK Method Applications

Number of Publications

YEAR


Number of Publications

0 0 0 0 1 1 1 4 8 10 11

YEAR
Resonance reaction

\[ \sigma \propto \frac{\Gamma_{in} \Gamma_{out}}{(E - E_0)^2 + \left(\frac{\Gamma_{tot}}{2}\right)^2} \]

The goal is to study properties (level structure) of compound nuclei rather than the properties of the residual species.

Cross section strongly depends on energy.
Resonance elastic scattering

Cross section in case of single isolated resonance
(spin zero particles)

\[ \frac{d\sigma(\theta)}{d\Omega} = \frac{(2L+1)^2}{4k^2} \frac{\Gamma_{el}^2}{(E-E_0)^2 + \frac{1}{4}\Gamma_{tot}^2} P_L(\cos \theta) \]

\( L=1 \)

Coulomb Scattering

\( L=2 \)
W.M. Wilson,
E.G. Bilpuch,
G.E. Mitchel

N.P. A 271
(1976)

Fig. 1. The $^{42}\text{Ca}(p, p)$ differential cross section at $160^\circ$ over the entire energy range. The solid line represents a multi-level fit to the data.
$^{42}\text{Ca}_{20} + p \rightarrow ^{43}\text{Sc}$
NEW
Radioactive beams (beams of exotic nuclei)
Main goals:
1. To obtain information on exotic nuclei
2. Nuclear astrophysics
3. $\alpha$ clusters in exotic nuclei
motivation (1) nuclear astrophysics
X-ray burst and novae

CNO: $T_9 < 0.2$  
Hot CNO: $0.2 < T_9 < 0.5$  
rp process: $T_9 > 0.5$
Resonances in exotic nuclei

Conventional nucleus

Proton rich exotic

Neutron rich exotic

Density of levels is low. Even simple considerations can work.

Density of levels is high. Practically it is not possible to use theoretical predictions.

\[ ^{8}\text{He} + p \rightarrow ^{9}\text{Li} \quad (T=5/2) \]
Inverse geometry and thick target technique

- High efficiency
- Good energy resolution
- 180 degree (c.m.) measurements are possible
- Excitation function is continuous
- Low excitation energies could be measured due to energy amplification in inverse kinematics

Scattering chamber

Methane gas

Detectors
just kinematics


classical (conventional)
\[
E_1 = \frac{E_0}{(M_2 - M_1)^2 + (M_2 + M_1)^2} \sim E_0 \sim E_{cm}
\]

\[
M_2 \gg M_1
\]

elastic (inversed)
\[
E_2 = 4E_0 \frac{M_1M_2}{(M_2 + M_1)^2} \sim 4E_0 \frac{M_1}{M_2} \sim 4E_{cm}
\]

\[
M_1 \gg M_2
\]

inelastic (inversed)
\[
E_2 = 4\{E_0 - Q \frac{(M_2 + M_1)}{2M_2}\} \frac{M_1M_2}{(M_2 + M_1)^2}
\]

\[
Q/E_0 \ll 1
\]

\[
\Theta_{cm} = 180^0
\]
$E_{\text{rec}} \approx 3 \text{ MeV}$ for a resonance, corresponding 1 MeV cm energy of the $^{16}\text{O}^{+}\alpha$ interaction (while in the conventional kinematics of $^{16}\text{O}^{+}\alpha$ interaction, the corresponding energy of $\alpha$ particles at $180^\circ$ will be only 300 keV.)

**Assumptions:**
1. The recoil energy loss in the target is much smaller than that of the heavy ions
2. The resonant scattering is the dominant process
Resonance states in $^{20}\text{Ne}$

$^{16}\text{O}+\text{He}$

$180^0$

Inelastic

$\text{Excitation energy of } ^{20}\text{Ne}, \text{(MeV)}$
- Primary beam $^{14}\text{N} @ 12 \text{ MeV/A} – \text{K500 Cyclotron}$
- Primary target LN$_2$ cooled gas target $\text{H}_2 \ p=3.0 \text{ atm}$
- Secondary beam $^{14}\text{O} @ 4.5 \text{ MeV/A}$

Purity: $>99\%$
Intensity: $\sim 10^6 \text{pps}$
**15O+p**

*D.W. Lee et. al*

*LBNL 2007*

<table>
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<th>Ecm [MeV]</th>
<th>Γ [keV]</th>
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<td>0.521</td>
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<tr>
<td>1-</td>
<td>0.721</td>
<td>91.1 ± 9.9</td>
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<tr>
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<td>0.947</td>
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<tr>
<td>3-</td>
<td>1.256</td>
<td>14.1 ± 1.7</td>
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</table>

*(l=0 2.1±0.5, l=2 1.4±0.3)*

*Phys. Rev. C 76, 024314 (2007)*
FIG. 1. An isobaric energy level diagram for the A=16, T=1 nuclear states
Table II. Comparison of $^{16}$F experimental results with the isobaric analog states in $^{16}$N and with theoretical calculations in the framework of the potential model.

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<th>$^{15}$N</th>
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<th>$^{16}$F</th>
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<th>$^{16}$F Theory</th>
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<tr>
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<td>3</td>
<td>0.87</td>
<td>0.721±17</td>
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</tbody>
</table>

$^a$ OXBASH calculation reported in Ref. [36].

$^b$ This work.
Problem of 7th nucleon

If our identifications are correct it is indeed remarkable that shell-model calculations whose parameters are optimized in the valley of stability should work so well so far from the valley. Since this nucleus is only produced in an exotic reaction, it is rather unlikely that even the $L$ transfers can be determined.

N.A.F.M. Poppelier et al., PL 157B, 120 (1985)

Calculations  Experiment
Excitation function for the $^{10}$C+p elastic scattering

FIG. 4. The lowest energy levels for $^{11}$Be and $^{11}$N.
The calculations are made for a light nucleus (A=11), starting with typical parameters:

\[ V_0 = -55 \text{ MeV}; \quad V(\text{ls}) = 6 \text{ MeV}; \quad R = r_0 A^{1/3}; \quad r_0 = r_0 (\text{ls}) = 1.2 \text{ fm}; \]
\[ a = a (\text{ls}) = 0.6 \text{ fm}, \text{ and keeping } a + R = \text{constant.} \]

Shell model neutron binding energies versus the ratio of the diffuseness parameter to the radius of the potential.
Single particle levels in $A=15$ and 17

$^{16}\text{O}+n$

$^{17}\text{O}$

$^{16}\text{O}+p$

$^{17}\text{F}$

$^{15}\text{C}+n$

$^{15}\text{C}$

$^{14}\text{C}+p$

$^{14}\text{C}+n$

$^{15}\text{F}$

$^{15}\text{F}$

Calculations*
Excitation functions for $^{14}$O+p elastic scattering

The solid lines are the final fits. The dotted curve in the upper panel shows the fit assuming a $1/2^+$ ground state and $3/2^+$ excited state. The dash-dotted curve shows the fit assuming a $1/2^+$ ground state and $5/2^+$ excited state. The second panel shows the separate contributions of s wave (dot-dashed line) and d wave (dotted line). The dashed line in the third panel shows the best fit which has a diffuseness parameter of 0.64 fm.
$^{18}$Ne+p, $\theta=180^0$ c.m.


F. de Oliveira Santos et al.: Study of $^{19}$Na at SPIRAL
Figure 3. Level Scheme of $^{18}$Ne. The dashed line arrow shows a transition to the excited state of $^{17}$F.

Figure 2. Measured cross sections for the $^{14}$O(α,p)$^{17}$F reaction. The asterisk mark is the new observation.
Excitation function for the $^{14}\text{O}(\alpha,2p)$ reaction

Counts

Excitation Energy in $^{18}\text{Ne}^*$ (MeV)

- 7.06
- 7.71
- 8.50
- 9.20
- 10.65
- 10.16
- 10.35
- 10.78
Bad News  
$^{12}\text{B}+\text{p} \rightarrow ^{13}\text{C}$ 
$\text{T}=3/2 \quad 1$  
$\text{T}=1/2 \quad 2$  
(isobaranalogs of $^{13}\text{O}$ and $^{13}\text{B}$)

Good News  
More than 10 decay channels are open for the $\text{T}=1/2$ states.

If everything OK, how to take into account the $\text{T}=1/2$ channel? By using classical R-matrix?

$$\sigma = (A_{\text{hard sphere}} + A_{\text{Resonance}})^2$$
A = 13 isobar diagram
Figure 6: Excitation functions for $^{12}$B+p elastic scattering measured at 165$^\circ$ and 150$^\circ$in (c.m.). The solid line represents the best R-matrix fit which includes six T=3/2 resonances and the absorption phase shift (see text). Arrows on the top figure indicate excitation energies of the high-lying resonances. The R-matrix fit was convoluted with the experimental resolution function.
Figure 7: The $T=3/2$, $A=13$ isobaric chain. Numbers shown in parentheses after the spins in the shell-model calculations are $\hbar\omega$. Only those $T=3/2$ states that were observed in the present work are shown for $^{13}\text{C}$. 
α-cluster structure in light $N \neq Z$ nuclei

Historically the α-particle (nucleus of helium atom) model of the atomic nucleus was the first leading model of nuclear structure.

Later the α clusters (correlated motion of two protons and two neutrons with zero spin) were introduced...

Figure 5. Geometric α-particle structures predicted by Brink [63]. Note that the arrangements reflect the number of possible bonds between α-particles predicted by Hafstad and Teller [5].

Martin Freer
α-cluster structure in light N=Z nuclei

The single particle limit for the resonance width, $\Gamma_w \sim \frac{\hbar^2}{\mu R^2}$, represents the maximum single particle reduced width (without antisymmetrization) for a particle (with reduced mass, $\mu$) in a nuclear potential with radius $R$. 

\begin{center}
\begin{tikzpicture}
\node (a) at (0,0) {\text{\textcolor{red}{16}O}};
\node (b) at (0,-1) {\text{\textcolor{red}{15}N+p}};
\node (c) at (0,-2) {\text{\textcolor{red}{12}C+\alpha}};
\node (d) at (0,-3) {12.2\ MeV};
\node (e) at (0,-4) {7.2\ MeV};
\node (f) at (0,-5) {0^+};
\node (g) at (0,-6) {2^+};
\node (h) at (0,-7) {4^+};
\node (i) at (0,-8) {5^+};
\node (j) at (0,-9) {6^+};
\node (k) at (0,-10) {7^-};
\end{tikzpicture}
\end{center}
The Wigner Limit, $\sim \hbar^2/\mu R^2$, is an estimation of the maximum reduced width a particle (with reduced mass $\mu$) can have (without antisymmetrisation) in a potential of radius $R$.

W. L. $\sim 1$ MeV for the $\alpha$ widths in the light nuclei

W. L. $\sim 4$ MeV for the nucleon widths in the light nuclei

Time of flight of 1 MeV n through a nucleus corresponds to $\sim 6$ MeV
The no core shell-model calculations for the nucleus $^{12}\text{C}$. The left hand part of the figure shows the experimental results. The calculations using the CD Bonn $N-N$ interaction with increasing numbers of oscillator orbits are shown on the right.
The number of nodes $N$ for the radial wave functions are calculated by the harmonic-oscillator relations as

$$2N + L = \sum (2n_i + l_i),$$

where $L$ is the angular momentum of the cluster, while $n_i$ and $l_i$ the corresponding shell model numbers for nucleons.
$^\text{10}\text{Be} (\alpha + ^6\text{He})$

$^\alpha + ^6\text{He}$ wave function in a potential well with forbidden states

Potential parameters:
$R = 2.58 \text{ fm}; \ a = 0.7 \text{ fm}; \ V_0 = -116.8 \text{ MeV}$
How to obtain from experiment data on the shell/cluster degree of freedom relationship

1. Single nucleon transfer reactions- relatively difficult, small cross section [$^{15}$N(d,n) Bohne et al., NP A196, 41 (1973)]

2. Nucleon decay of the $\alpha$-cluster states in $N=Z$ nuclei-very difficult

Are there $\alpha$-cluster states in $N\neq Z$ nuclei?

What is interplay between the shell model (nucleon) and $\alpha$-cluster structure?
Isobar diagram for $A=18$
Excitation functions for the $^{14}$C+$\alpha$ and $^{14}$O+$\alpha$ elastic scattering

$^{14}$C($\alpha$,\,$\alpha$) at 169°

$^{14}$O($\alpha$,\,$\alpha$) at 180°

NP A148 (1970) 480--491
The excitation functions of the $\alpha^{14}$C elastic scattering at various angles

Excitation function at 90° degrees in c.m. was taken from the literature18. Red curve is the best R-matrix fit, blue dashdotted curve is the best fit without very broad 0+ state at 3.7 MeV.
- Moment of inertia in $^{18}$O is increased with respect to $^{16}$O.

- Cluster states are more fragmented in $^{18}$O.

Resonances in the elastic $\alpha + ^{14}\text{C}$ channel.

Very broad $\Gamma \approx 3$-5 MeV $0^+$ state at 3.8+/-0.5 MeV above the $\alpha$ decay threshold was observed.
\( \alpha \) halo state in \(^{18}\text{O}\)

\( 0^+ \) at 3.8\(+/-0.5\) MeV (~10.0 MeV \(^{18}\text{O}\) excitation energy) with width of ~3-5 MeV is necessary to fit the \( \alpha + ^{14}\text{C} \) data. This width corresponds to a pure \( \alpha \) particle state.
α halo states

- **12C**: 10.3 MeV; \( \Gamma \approx 3 \) MeV
- **16O**: 11.2 - 14.5 MeV; \( \Gamma \approx 3-5 \) MeV
- **18O**: 10.0 MeV; \( \Gamma \approx 3-5 \) MeV
- **20Ne**: 8.7 MeV; \( \Gamma \approx 1 \) MeV
$^{14}\text{C}(\alpha,n)$}

J.K. Bair, J.L.C. Ford, C.M. Jones

PR 144 799 (1966)
Thank ya’ll
Plan of the talk

- **Introduction**

  *New renaissance of resonance reactions studies is feed by astrophysics as well as by the structure of exotic nuclei*

- **Technique**

  *Thick target inverse kinematics method*

- **Examples**
$^{14}\text{O} + \alpha$ identification spectrum
Fig. 3. Comparison of the largest s- and p-wave resonances observed in $^{42}\text{Ca}(p,p)$ with the levels (and their strengths) observed in the $^{42}\text{Ca}(d,p)$ reaction. The energy scales are matched by aligning the strong $\frac{1}{2}^-$ analogue and parent states. Despite the apparent correlation between the largest $\frac{1}{2}^-$ resonances and the $l = 1$ parent states, attempts to match the analogues and/or analogue fragments with the appropriate parent states proved futile (see discussion in text).
Three particle kinematics for the broad range of the ion incident energy.
Fig. 6. the Dalitz plot of the coincident protons from the reaction $^{14}\text{O}(^4\text{He},2p)^{16}\text{O}$. The energy of protons are given in lab system.
$^{12}\text{C}(T=0) + p(T=1/2) \rightarrow ^{13}\text{N}(T=3/2)$

$^{12}\text{C}(p,p)$ excitation functions

W.J. Thompson et al., P.R.L 45, 703 (1980)
proton decay modes of the $^{18}\text{Ne}$ states
Excitation function for the $^{12}$B+p elastic scattering at 165°.

The Rutherford scattering +$L=0$ resonance

The Rutherford scattering
2p decay of 8.45 MeV state in $^{18}$Ne

Reaction place identification through time of flight

\[ 14\text{O} \]

\[ \Delta T \]

\[ p_1 \]

\[ p_2 \]
$^{14}\text{O} + \alpha \rightarrow ^{18}\text{Ne}^*$

$^{17}\text{F} + p$

$p + ^{17}\text{F}^* \rightarrow p + ^{16}\text{O} + p$
Nucleosynthesis in Cosmos

- Big Bang
- Stellar evolution
- rp process
- s process
- r process

Stable
Observed Unstable

293 2,771 3,064

NNDC (BNL, 2000)
**Figure 4.5.** Single resonance R-matrix fits for the experimental data from the detector at 7.5°. The solid line shows the fit with the assumption of a single $\frac{1}{2}^+$ resonance. A $\frac{3}{2}^+$ assignment would lead the fit shown by the dashed line. A $\frac{1}{2}^-$ assignment would lead to the fit shown by dotted curve.
$R$-matrix fit. $^{14}\text{O}+\alpha$ excitation functions.
\[ ^{18}\text{O} \rightarrow ^{14}\text{C} + \alpha \rightarrow 2n, 8.0 \text{MeV} \]

\[ 14\text{C} + \alpha, 180^\circ \text{cm} \]

\[ \text{d}\sigma/\text{d}\Omega, \text{mb/sr} \]

\[ E_{\text{cm}}, \text{MeV} \]
$^{18}\text{O}$ Alpha cluster structure

$^{16}\text{O}$ Alpha cluster structure
Figure 4.1. Level scheme of the mirror nuclei $^{13}$B and $^{13}$O. The dashed lines in the $^{13}$O level scheme represent levels from Ref. [1]. The solid lines are the present results. On the right side of the figure, OXBASH calculations [18] with the WBT [67] interaction are presented.
Figure 4.2. The schematic experimental setup of TwinSol. The "lollipop" reduces contamination of the beam by intercepting ions that focus at a different location relative to the $^{12}$N beam.
### RESONANCE PARAMETERS FOR LEVELS IN $^{13}$O

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<td></td>
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<td>MeV</td>
<td>MeV</td>
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<tr>
<td>1</td>
<td>$1/2^+$</td>
<td>2.69±0.05</td>
<td>0.45±0.1</td>
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<tr>
<td>2</td>
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<td>0.08±0.03</td>
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<tr>
<td>3</td>
<td>$(3/2^-)^1$</td>
<td>(4.55)</td>
<td>(0.24)</td>
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<tr>
<td>4</td>
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<td>5</td>
<td>$(3/2^+)^1$</td>
<td>(5.70)</td>
<td>(2.00)</td>
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1° Distant resonances used in the R-matrix fit.
Energy Resolution for IKTT Method
$^{11}\text{C}(50 \text{ MeV}) + p$, zero degree

![Graph showing energy resolution for different targets. The x-axis represents energy in MeV, and the y-axis represents energy resolution in keV. Two lines are shown: one for a solid target, CH$_2$, and another for a gas target, CH$_4$. The line for the solid target shows a U-shaped curve, while the line for the gas target is decreasing.]
$l=0$ resonance in $^{37}$Cl

$E_{cm}$, MeV

$do/d\omega$, mb/sr

$0.2$ keV resolution

$10$ keV resolution

$l=0$ resonance in $^{15}$N

$E_{cm}$, MeV

$do/d\omega$, mb/sr

$0.2$ keV resolution

$10$ keV resolution
Lower Limit for observation is about 1keV

\[ \Gamma = 1\, \text{keV} \]

\[ LL = \sim 0.04 \times Z \, (\text{MeV}) \]
Are inelastic resonances dangerous?

$^{11}$C(36 MeV) + p

**Elastic $M>m$**

$$E_m = 4 \frac{mM}{(M+m)^2} \left( E_0 - \frac{E^*}{2} \frac{M+m}{m} \right).$$

**Inelastic $M>m$ ($\theta_{lab}=0$)**

$$E_m = E_0 \frac{4mM}{(M+m)^2} \cos^2 \theta_{lab}.$$

![Graph showing cross sections](graph.png)

Figure 2. Measured cross sections for the $^{14}$O($\alpha$,p)$^{17}$F reaction. The asterisk mark is the new peak.
Spectroscopy of $^{12}\text{N}$ in the $^{11}\text{C} \ (3/2^-) + p$ elastic scattering
(no simplifications)
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<td>3$^-$</td>
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$^{11}\text{C}(2.00) + p$ | 2.601 |

$^{11}\text{C} + p$ | 0.601 |
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<td>1.17</td>
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<tr>
<td>$r_o(\text{Coulomb})$</td>
<td>1.21</td>
<td>1.21</td>
<td>1.21</td>
</tr>
<tr>
<td>$a$</td>
<td>0.64</td>
<td>0.71</td>
<td>0.735</td>
</tr>
<tr>
<td>$a_{st}$</td>
<td>0.64</td>
<td>0.64</td>
<td>0.64</td>
</tr>
<tr>
<td><strong>Nucleon binding energy (MeV)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>3.270/0.105</td>
<td>1.218</td>
<td>-1.290</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>4.140/0.600</td>
<td>0.478</td>
<td>-2.795</td>
</tr>
</tbody>
</table>

$^a$For the $s$ state $V_o=-53.27$. 
Energy relationship for (p, n) reactions

\[
\begin{align*}
^{16}\text{C} \ (T=2) & \rightarrow ^{16}\text{N} \ (T=1) \\
^{17}\text{C} \ (T=5/2) & \rightarrow ^{17}\text{N} \ (T=3/2)
\end{align*}
\]

\[V_c \approx 2.7 \text{ MeV}\]

No T-allowed nucleon decay
Isobaric analogs of $^9\text{He}$ in $^9\text{Li}$.

$^8\text{He}$ \quad T=2 \\ $^9\text{Li}$ \quad T$\geq$5/2, T$\leq$3/2

$^9\text{Li}$ decay back to elastic channel is hindered due to the presence of the other channels.

There are only two isospin allowed decay channels for T=5/2 states

$$\Psi_{^9\text{Li}(T=5/2)} = \frac{1}{\sqrt{5}} \Psi_{^8\text{He}+p} + \frac{2}{\sqrt{5}} \Psi_{^9\text{Li}(T=2)+n}.$$
Figure 1: a) Decay pathways for the $T=3/2$ resonance in $^7$Li, and b) the successive kinematics stages of the studied reaction.
TWINSOL RNB, University of Notre Dame
a) Part of the $\gamma$-ray spectrum from the $90^0$ Ge detector. The solid curve was obtained with a CH$_2$ target, the dotted curve was taken with a carbon target.

b) The spectrum in the 0$^0$ Clover detector obtained by subtraction of the carbon contribution, the dotted curve was taken with a carbon target. The Compton background is approximated by a straight line as shown.

c) The final spectrum of the Doppler shifted 3.56 MeV $\gamma$-rays. The solid line shows the contribution from the known T=3/2, $J^{\pi}$ =3/2$^-$ state in $^7$Li. The dotted line includes the effect of T=1/2 resonances.
The solid curve shows a calculation of the $\gamma$-ray spectrum including the analog of the $^7\text{He}_{g.s.}$ and a $1/2^-$, $E_{ex} = 3.1$ MeV, $\Gamma = 6$ MeV excited state. The dotted line is the effect from the g.s. resonance plus a state at $E_{ex} = 0.6$ MeV having $\Gamma = 1$ MeV.

\[ p + ^{6}\text{He} \rightarrow ^{7}\text{Li} \rightarrow \text{n} \]

\[ ^{6}\text{Li}(3.56;0^{+};T=1) \]

\[ ^{6}\text{Li} \text{ gr. state} \]

\[ ^{6}\text{He}(3.56) \]

\[ ^{6}\text{Li}(0^{+}) \text{ decays only by } \gamma \text{ emission!} \]
Figure 2: a) Part of the $\gamma$-ray spectrum from the 90° Ge detector. The solid curve was obtained with a CH$_2$ target, the dotted curve was taken with a carbon target. b) The spectrum in the 0± Clover detector obtained by subtraction of the carbon contribution, the dotted curve was taken with a carbon target. The Compton background is approximated by a straight line as shown. c) The final spectrum of the Doppler shifted 3.56 MeV $\gamma$-rays. The solid line shows the contribution from the known $T=3/2$, $J^\pi=3/2^-$ state in $^7$Li. The dotted line includes the effect of $T=1/2$ resonances.
7Be discrimination

The graph shows the distribution of counts as a function of energy from a PMT, with different labels indicating energy peaks:

- $^{14}$O peak at $10^{-2}$
- $^{7}$Be peak at $10^{-4}$
- $^{14}$O+$7$Be peak at $10^{-6}$

The energy scale is labeled as 'Energy from PMT (Channels)'.
Two channels multi level expression was used to make the R-matrix fit. All notations are the same as in the article of A.M. Lane and R.G. Thomas (1958) \([U]\)-collision matrix, \(Lc\) –logarithmic derivative of the outgoing wave functions at the channel radius, \(E_\lambda\)-level position, and the \(\gamma_{\lambda l}\) is the reduced width amplitude.

\[
U_{cc}^{J\ell} = U_{cc}^{J\ell \text{ pot}} + \frac{\exp[2i(\omega _\ell + \delta_{J\ell})]2iP_\ell [R_{11}^{J\ell} - L_2^{J\ell} (R_{11}^{J\ell} R_{22}^{J\ell} - R_{12}^{J\ell 2})]}{(1 - R_{11}^{J\ell} L_1^{J\ell})(1 - R_{22}^{J\ell} L_2^{J\ell}) - L_1^{J\ell} R_{12}^{J\ell 2} L_2^{J\ell}}
\]

\[U_{cc}^{J\ell \text{ pot}} = \exp[2i(\omega _\ell + \delta_{J\ell})],\]

\[R_{mk}^{J\ell} = \sum_{\lambda} \frac{\gamma_{m\ell\lambda}^{J\ell} \gamma_{k\lambda}^{J\ell}}{E_{\lambda} - E},\]

\[\delta_{J\ell} = \lambda + i\mu\]