Determining the ANCs for 13C→12C+n for Nuclear Astrophysical Studies

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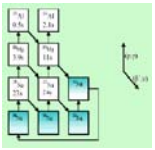
Background

The Big Picture

- The gamma ray signature from the decay of ^{22}Na (in nova explosions) has not been observed by gamma-ray telescopes
- One possible explanation is that its precursor, ^{22}Mg, may be depleted by radiative proton capture (^{22}Mg(p,γ) ^{23}Al)
- The experiment aims to determine the ANC → the astrophysical S-factor and, thus, an accurate estimate of how much ^{22}Na should be expected



In a Direct Radiative Capture Process

$$\sigma \propto |M|^2 \qquad M = \langle \Phi(^{23}Al)|\hat{O}|\Phi(^{22}Mg)\chi_{(r)}\rangle = \langle I^{^{23}Al}_{^{22}Mg+p}(r)|\hat{O}|\chi^{(+)}(kr)\rangle$$

In a Direct Transfer Reaction

$$\left(\frac{d\sigma}{d\Omega}\right) \propto |M'|^2$$

Where the Transition Amplitude is

$$M' = \langle \Phi(^{12}C)\Phi(^{23}Ne)\chi^{(-)}|V_{tr}|\Phi(^{13}C)\Phi(^{22}Ne)\chi^{(+)}\rangle$$

Integrating over the internal coordinates

$$M' = \langle I^{^{23}Ne}_{^{22}Ne}\chi_f^{(-)}|V_{tr}|I^{^{13}C}_{^{12}C}\chi_i^{(+)}\rangle$$

Furthermore, if the transfer is peripheral

$$I^A_{Bp} \approx C^A_{Bp}\frac{W(2\kappa r_{Bp})}{r_{Bp}} \qquad r_{0B}<R_X$$

Thus, for the overall reaction

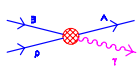
$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(C_{^{13}C\to n+^{12}C}\right)^2\left(C_{^{12}Ne+n\to^{23}Ne}\right)^2\frac{\left(d\sigma/d\Omega\right)_{DWBA}}{\left(b_{n+^{12}C}\right)^2\left(b_{n+^{22}Ne}\right)^2}$$

The $C_{^{13}C\to n+^{12}C}$ ANC can be easily determined in a separate neutron exchange reaction ^{13}C(^{12}C,^{13}C)^{12}C where the system vertices are identical before and after the reaction

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = \left(C_{^{13}C\to n+^{12}C}\right)^4\frac{\left(d\sigma/d\Omega\right)_{DWBA}}{\left(b_{n+^{12}C}\right)^4}$$

Using Mirror Systems

- Normally a ^{22}Mg beam would be used and the proton transfer rate would be measured directly
- Instead, we
  - Use a ^{22}Ne beam and measure the neutron transfer rate
  - This indirectly measures the original system's mirror system, and uses charge symmetry to back out the appropriate parameters to relate the two



Mirror System Relationship

$^{23}_{13}Al_{10} \rightarrow {}^{22}Mg + p$

vs.

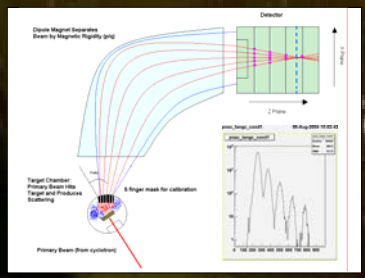
$^{23}_{10}Ne_{13} \rightarrow {}^{22}Ne + n$

Experimental Setup

The experiment

- K500 superconducting cyclotron produces ^{22}Ne beam at 264 MeV and bombards 100μg/cm^2 ^{13}C target
  - In order to determine the ^{13}C(^{12}C, ^{13}C)^{12}C ANCs, a ^{12}C beam is produced at 127MeV and bombards an identical target

•The scattered particles then enter the MDM (multipole-dipole-multipole) Spectrometer



The Detector

- The remaining particles enter the Oxford detector which consists of:
  - 4 resistive wires to measure the x position and angle of the incoming particles
  - An ionization chamber filled with isobutane to measure the ΔE (energy loss) in the chamber

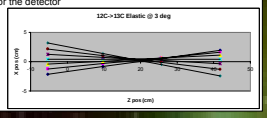
– A plastic scintillator at the back to measure the residual energy

Data Analysis

Data analysis step 1:

Calibration

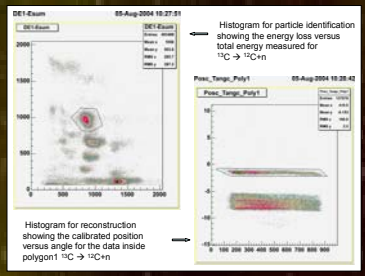
- A ^{197}Au target is first placed in the target chamber for calibrating the position of the wires in the detector
- A mask is placed at the exit of the target chamber so that the particles entering are confined to a 5x 0.1 deg slits 0.77deg apart
- The resulting experimental data can then be used in conjunction with a Raytracing code to determine a proper position calibration for the wires as well as determine the focal plane of the beam
- A similar setup is used with the elastic scattering on the real target to get an angular calibration for the detector



Data analysis step 2:

Getting Good Data

- The calibrations are used to produce histograms of the calibrated data
- Events from many reaction products are visible in the data and may overlap
- Within the code, conditions are set in order to select only the desired data
- Multiple histograms and graphs are used for purposes of particle identification and reconstruction

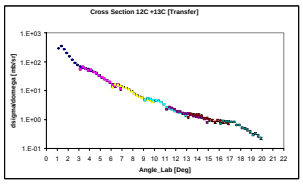


Histogram for particle identification showing the energy loss versus total energy measured for ^{13}C → ^{12}C+n

Histogram for reconstruction showing the calibrated position versus angle for the data inside polygon1 ^{13}C → ^{12}C+n

Determining the Experimental Cross section

- The raw data results in an angular distribution which is then normalized to give an absolute cross section

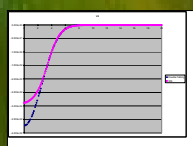


Theoretical Calculations

Calculating the Theoretical Cross Section

- Computer programs (JLM, Ptolemy…) are used to calculate:
  - the nucleon density for the incoming and outgoing channels
  - the double folded interaction potential
- The double-folded potential is then fit with a Woods-Saxon potential by varying the geometric parameters as well as the normalization constants**

**The results of elastic scattering are to be used to determine the optical model parameters



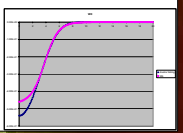
A program using the Hartree-Fock method is used to calculate the nucleon densities and a double-folded potential is calculated

$$U(r) = \iint \rho_1(r_1)\rho_2(r_2)v_{12}(r_1 - r_2)d\vec{r}_1 d\vec{r}_2$$

A Woods-Saxon potential is then fit to the double-folded potential (in the region of interest) allowing for the extraction of the optical model parameters

$$U(r) = -V_0 f(r, R_r, a_r) - iW_0 f(r, R_w, a_w)$$

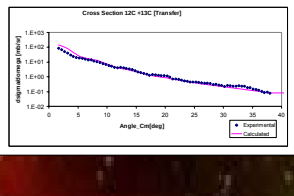
where $f(r) = \frac{1}{1+e^{\frac{r-R}{a}}}$



Conclusions

Putting it All Together

- With the Woods-Saxon optical model parameters, a theoretical cross section is then calculated and normalized by comparing it to the experimental results



ANCs

•The proportionality constant between the experimental and calculated cross sections is known as the Spectroscopic Factor

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = S_1 S_2\left(\frac{d\sigma}{d\Omega}\right)_{DWBA} \Rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{exp} = S^2\left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

•The Spectroscopic Factor is directly related to the system ANC

$$S = \frac{C^2}{b^2}$$

Where C system ANC
b single particle ANC

The preliminary result for the ^{13}C→^{12}C+n system ANC is: $C^2 \cong 2.1\text{fm}^{-1}$*

*Value found in literature=2.35±0.12 fm^{-1}

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