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Nuclear Astrophysics

The field of Nuclear Astrophysics is concerned with the application of nuclear physics to astrophysics. Nuclear processes are responsible for producing the elements in the Universe as well as generating the energy which allows stars to shine.

Our research is primarily focused on the determination of the rates of nuclear reactions in quiescent and explosive stellar environments.

Many experiments are performed with the local accelerator. Other measurements, particularly studies of reaction rates involving radioactive nuclear species, are performed elsewhere – for example radioactive beam experiments at Oak Ridge National Laboratory.

CNO Breakout

Proton-induced reactions which “break out” from the standard CNO cycle, typically involving proton-rich unstable nuclei.

- **$({}^3\text{He}, n)$ Reactions.** These reactions provide spectroscopic information on proton-rich nuclei. Measurements of ${}^{16}\text{O}({}^3\text{He}, n){}^{18}\text{Ne}$ are already underway; measurements on ${}^{20}\text{Ne}$, ${}^{24}\text{Mg}$, and ${}^{28}\text{Si}$ are planned for the future.
- **${}^{17}\text{F}$ Radioactive Beam Measurements.** ${}^{17}\text{F}$ beams with intensities of $\approx 10^6$ ions/sec on target are available at ORNL. These intensities are sufficient to measure proton-transfer reactions such as ${}^{14}\text{N}({}^{17}\text{F}, {}^{18}\text{Ne})$; if additional beam intensity becomes available it will be possible to measure ${}^{17}\text{F}(p, \gamma){}^{18}\text{Ne}$ directly.

Branching Ratio Measurements

In many cases nuclear reaction rates depend critically upon branching ratios, i.e. the probabilities of an excited nuclear level decaying into various allowed channels.

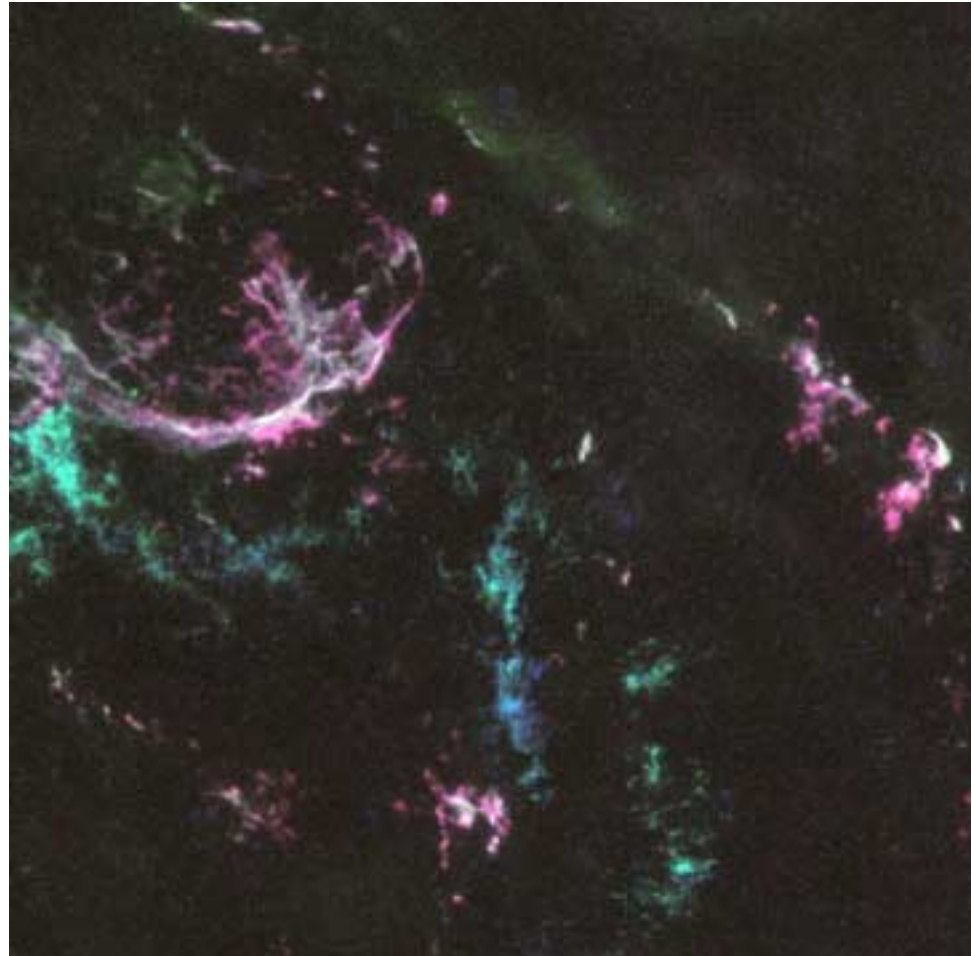
- Proton and γ decay of states populated by $({}^3\text{He}, n)$ reactions – useful for determining (p, γ) reaction rates.
- γ -ray branching ratio of the $E_x = 7.12$ MeV state of ${}^{16}\text{O}$ – important for calculating “cascade” contributions to the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction rate.
- ${}^{20}\text{Ne}({}^3\text{He}, \alpha){}^{19}\text{Ne} \rightarrow {}^{15}\text{O} + \alpha$ – the ${}^{15}\text{O}(\alpha, \gamma){}^{19}\text{Ne}$ reaction rate is essentially determined by α -decay probability of the $E_x = 4.033$ MeV level of ${}^{19}\text{Ne}$.

Supernova Remnant N132D

Hubble Space Telescope image of the 3,000-year-old supernova remnant N132D in the Large Magellanic Cloud. The precursor star to this remnant is estimated to have been 25 times more massive than our Sun. Supernova events of this type produced many of the heavier elements in our solar system, including carbon, oxygen, and iron. The material is ejected into the interstellar medium by the explosion, and then incorporated into future generations of stars. The gas and dust which formed our solar system was enriched in life-sustaining elements via this mechanism.

This "true color" picture was made by superposing images taken on 9-10 August 1994 in three of the strongest optical emission lines: singly ionized sulfur (red), doubly ionized oxygen (green), and singly ionized oxygen (blue).

Photo credit: Jon A. Morse (STScI) and NASA



Application to Medical Physics

Most cancer treatment is based on gamma rays which have a low Linear Energy Transfer (LET). Neutrons produce higher LET through the (n,p) and (n, α) reactions. The high LET radiation is more damaging to the tumor compared to the surrounding healthy tissue than low LET radiation. The high LET radiation is also more localized to the tumor area.

Boron Neutron Capture Therapy

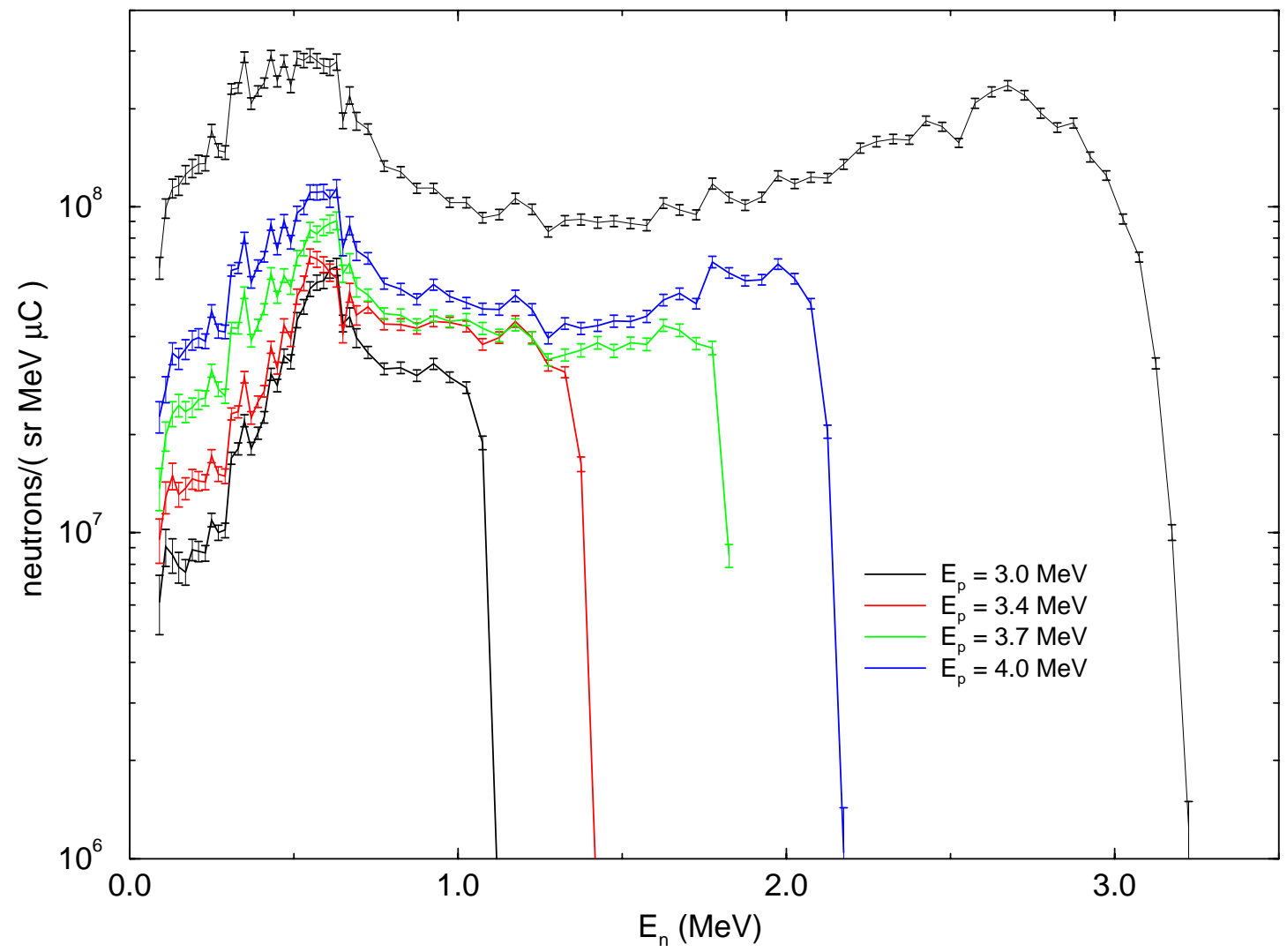
Some isotopes, such as ^{10}B , have a positive Q-value and a large low energy cross section for (n, α). A low energy neutron of 0.1 MeV can produce a ~ 2.5 MeV alpha particle. These low energy neutrons produce little damage to normal tissue. If the boron can be introduced into the tumor selectively the dose is highly concentrated.

Test of Be(p,n) as Neutron Source

- Beryllium can take large beam currents due to its high melting point of 1278° C.
- Low gamma yield. (A factor of 8-10 lower than ${}^7\text{Li}(p,n)$.)
- Need neutron production cross section for $E_p \leq 4$ MeV.
- O.U. Facility ideal with few background neutron.
- We have completed measurements for $3.0 \leq E_p \leq 5.0$ MeV.

Be(p,n) Thick Target Source

$\theta = 0$

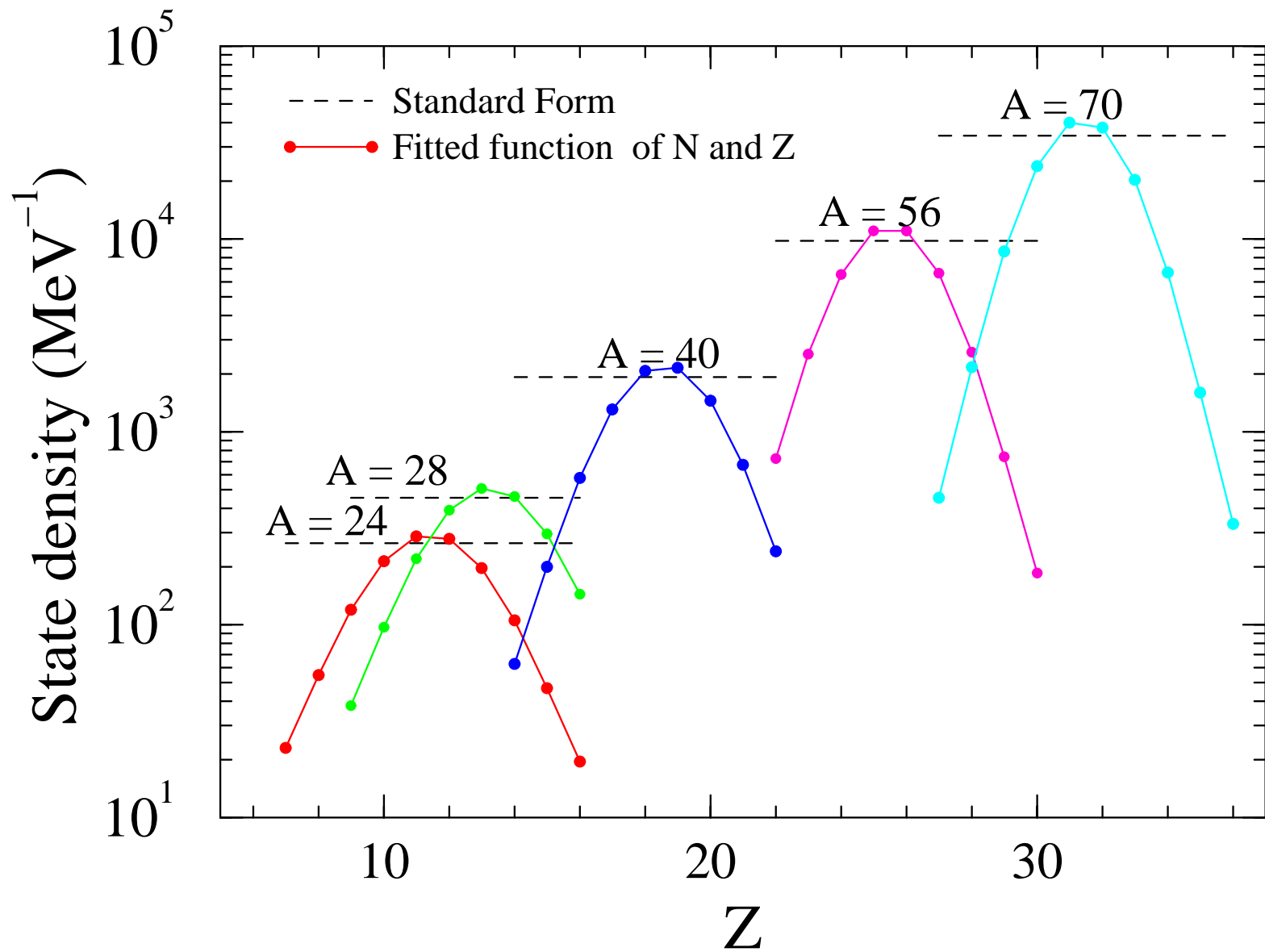


Nuclear Level Densities

- Level density is the number of excited levels of a nucleus as a function of energy
- Level Densities are needed for statistical model calculations of yields in nuclear reactions.
- They are particularly important in nuclear astrophysics and in shielding and transport calculations.

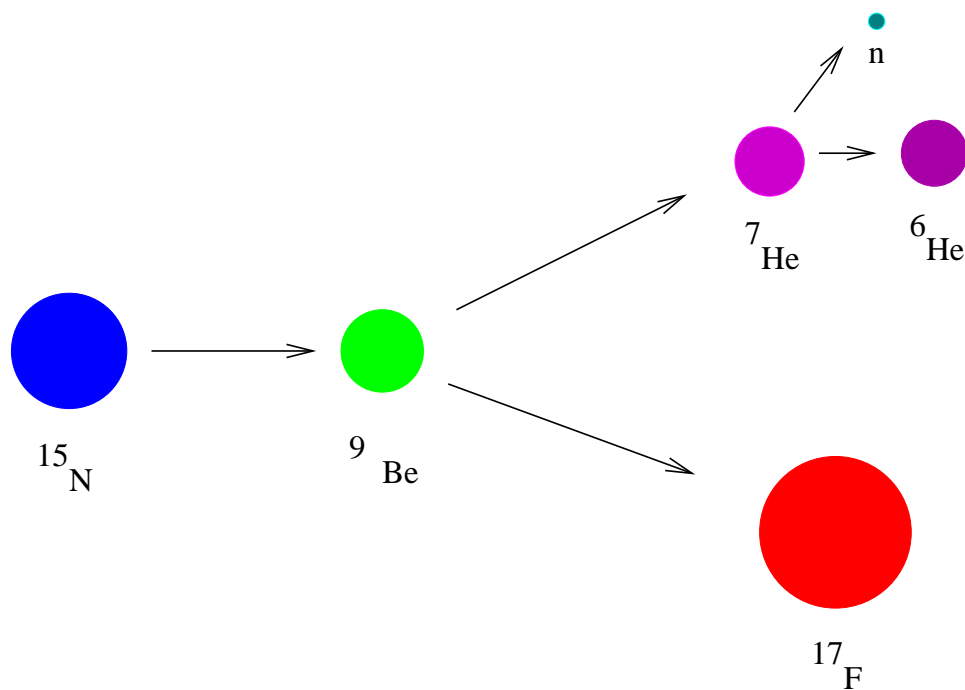
Methods of Studying Nuclear Level Densities

- **Spectroscopy** - measure excitation energies of all level in a given energy region- *only possible at low energy*
- **Evaporation Spectra** - measurement of the shape of the spectrum of emitted particles - *can be used even if levels overlap (level width > spacing*
- **Ericson Fluctuations** - Find variation in close section in fine energy steps - *can relate this to level densities*
- **Facilities at O.U. are well suited for studies based on all of the above methods**
- **Theory** - work on theory of level densities is also done at O.U. - currently we are trying to include collective effects in level density calculations.



Study of Exotic Nuclei by Binary Reactions

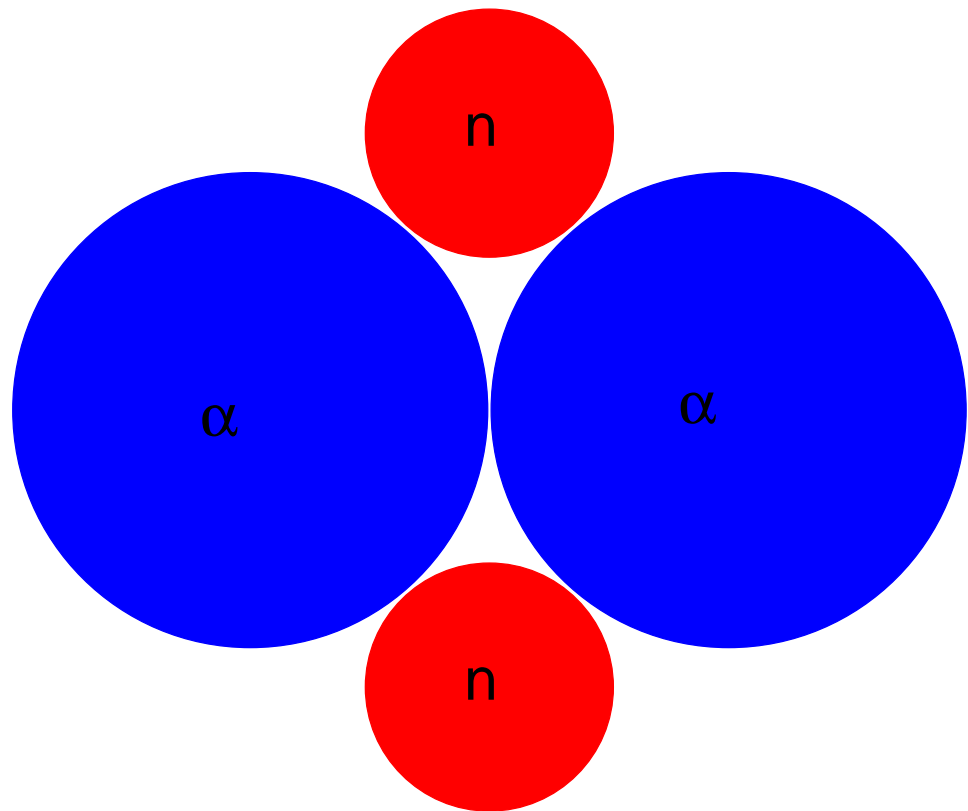
Binary reactions are when only two nuclei are involved of the reaction in both in the beginning and for the time when they are near each other. The binary reactions allow the study of very short lived states by study of a long lived companion with only the ground state stable against particle decay as shown in figure to the right .



Binary Reaction

Molecular States in the Beryllium Isotopes

The beryllium isotopes have been of great interest due to the structure of the states which have recently been observed. Rotational bands with an energy dependence of $E = k(J(J + 1))$. The moment of inertia found for these states implies a separation of 2-3 fermi between alpha for a structure where the beryllium isotopes are some number of neutrons coupled to two alpha particles.



Molecular Rotational Bands of Beryllium Isotopes

