Nuclear Astrophysics
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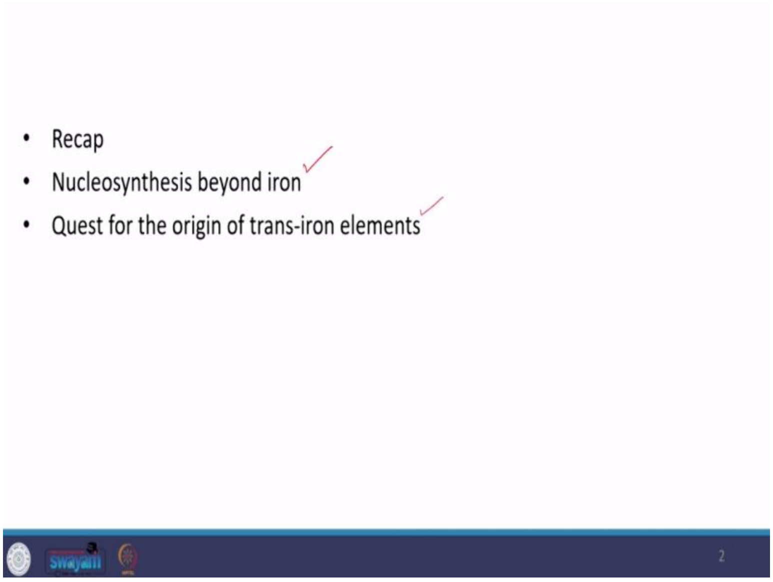
Lecture – 29
Nucleosynthesis Beyond Iron

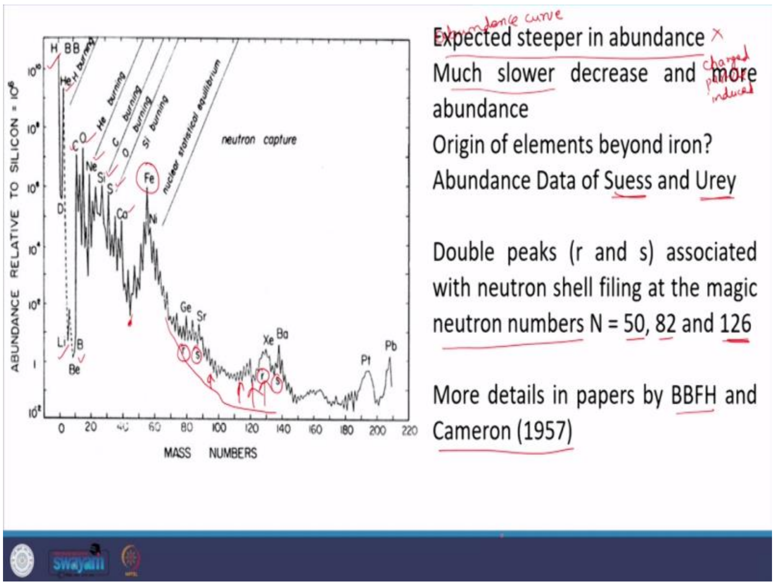
Welcome to today’s lecture on synthesis of elements beyond iron. As a recap, let me quickly summarize what we discussed in the previous lectures. After PP Chain, CNO Cycles, we have seen the importance of triple alpha process in the creation of carbon 12, where we have seen the role played by Hoyle state and there is a state in carbon 12 in order to match with the observed abundance as Hoyle suggested.

Fortunately, the difference between alpha threshold and the Hoyle state is less and the temperature available in that environment is sufficient to provide value E_0, i.e., centroid of the Gamow peak, to cause the resonance. The state is available to faster the resonance, so that the rate of carbon formation is in such a way that the ratio of carbon to oxygen is 0.6.

And in the last lecture we have seen that it has to operate in a moderate rate so that it is consistent with the ratio of carbon to oxygen. Then, after carbon creation and survival, we have seen the different burning stages in the advanced stage and how carbon burning takes place. After carbon burning, as expected, it was not oxygen burning, but it was neon burning. Then comes oxygen burning and then silicon burning, which leads to the formation of elements around iron peak. How are elements synthesized beyond this? That is topic of today’s lecture. What are the physics processes, the salient features of synthesis of elements beyond iron?



- Recap
- Nucleosynthesis beyond iron
- Quest for the origin of trans-iron elements



Abundance curve

Expected steeper in abundance ×

Much slower decrease and more abundance

charged particle induced

Origin of elements beyond iron?

Abundance Data of Suess and Urey

Double peaks (r and s) associated with neutron shell filing at the magic neutron numbers N = 50, 82 and 126

More details in papers by BBFH and Cameron (1957)

Let us see the most important diagram in this course, abundance curve. We are going to analyze this abundance curve from a different perspective, i.e., the quest for trans-iron elements and the synthesis of elements beyond iron. See the expected steepness in the abundance. Overall, the trend is bit steeper. Of course, there is an exception regarding the formation of iron element. Suddenly, there is a rise in the abundance around the iron peak. If it continues, then the curve after iron is expected to be steeper than shown in the curve.

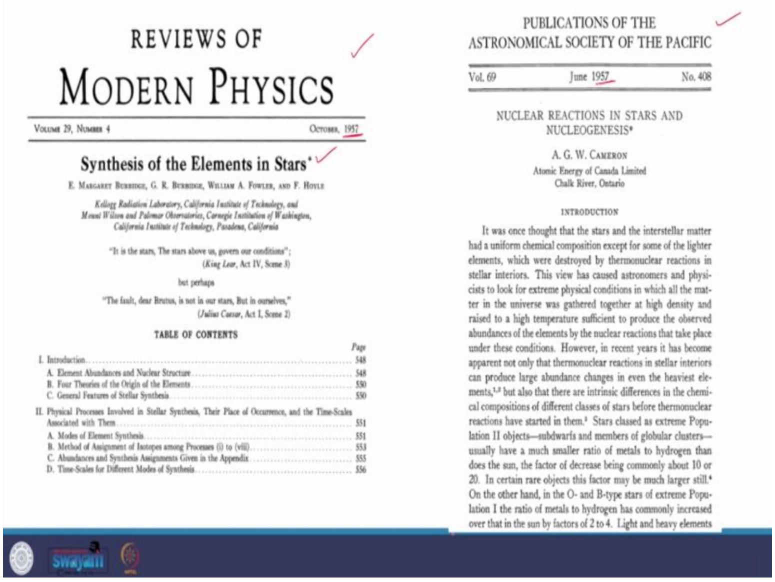
But it is above that line. People thought if it is the charged particle induced reactions or photodisintegration reactions which are happening till the formation of elements around iron peak, then why cannot they continue after this? Of course, Coulomb barrier consideration is always there, but it was also there even up to iron peak.

So, expected steeper in the abundance curve is not observed based on charged particle induced reactions. Instead, the observation was much slower decrease and more abundance. Even the abundance data after the iron peak is more than expected if it was because of the charged particle induced reactions. So, these two observations against the trend were expected by the people based on the charged particle induced reaction. So, what is the origin of elements beyond iron?

Suess and Urey they have made a breakthrough. Data collected and complied by them help us understand the origin of elements beyond iron.

You can see r and s designated at Ge, St, Xe, Ba peaks. They are double peaks. If you see the number of neutrons corresponding to these peaks, they were found to be associated with 50 or 82 or 126. By the time, shell model was existing and corresponding to the neutron shell filing at the magic neutron number 50, 82 and 126, the observed abundance curve is showing some peaks.

So, these details were discussed in detail by Burbidge, Burbidge, Fowler and Hoyle. Independently, Cameron also explained the abundance curve, not only for the synthesis of elements below the iron, but also the synthesis of elements beyond the iron.



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

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"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

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PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 69 June 1957 No. 408

NUCLEAR REACTIONS IN STARS AND
NUCLEOGENESIS*

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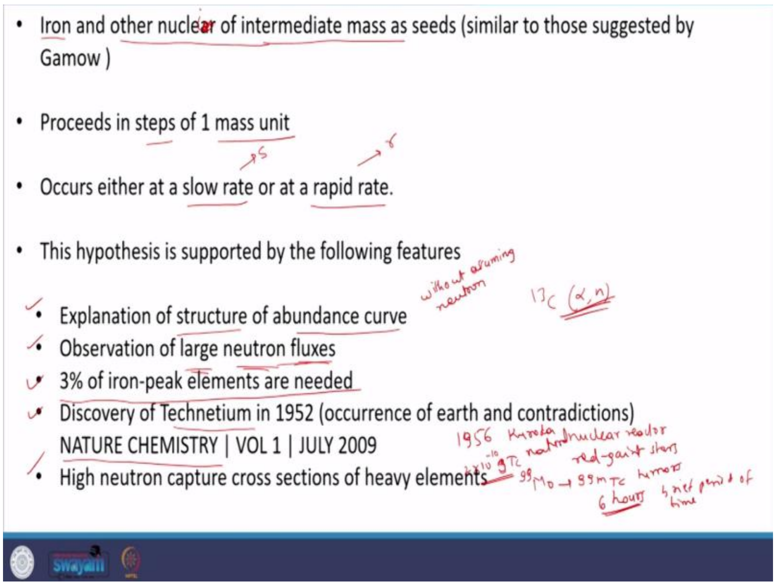
INTRODUCTION

It was once thought that the stars and the interstellar matter had a uniform chemical composition except for some of the lighter elements, which were destroyed by thermonuclear reactions in stellar interiors. This view has caused astronomers and physicists to look for extreme physical conditions in which all the matter in the universe was gathered together at high density and raised to a high temperature sufficient to produce the observed abundances of the elements by the nuclear reactions that take place under these conditions. However, in recent years it has become apparent not only that thermonuclear reactions in stellar interiors can produce large abundance changes in even the heaviest elements,[1,2] but also that there are intrinsic differences in the chemical compositions of different classes of stars before thermonuclear reactions have started in them.[3] Stars classed as extreme Population II objects—subdwarfs and members of globular clusters—usually have a much smaller ratio of metals to hydrogen than does the sun, the factor of decrease being commonly about 10 or 20. In certain rare objects this factor may be much larger still.[4] On the other hand, in the O- and B-type stars of extreme Population I the ratio of metals to hydrogen has commonly increased over that in the sun by factors of 2 to 4. Light and heavy elements

These are the papers which I think I have shown you in one of the previous lectures. Synthesis of elements in stars in 1957, and in same year, same topic was covered by Cameron. Both published independently and in the same year. These two papers help us have an idea about the synthesis of elements and how elements are cooked within the stars. Readers are strongly recommended to go through these papers.

Even now, researchers are considering these as classic papers in the field of nuclear astrophysics.



- Iron and other nuclear of intermediate mass as seeds (similar to those suggested by Gamow)
- Proceeds in steps of 1 mass unit
- Occurs either at a slow rate or at a rapid rate. → s → r
- This hypothesis is supported by the following features
  - Explanation of structure of abundance curve without assuming neutron
  - Observation of large neutron fluxes $^{13}C(\alpha,n)$
  - 3% of iron-peak elements are needed
  - Discovery of Technetium in 1952 (occurrence of earth and contradictions)
    NATURE CHEMISTRY | VOL 1 | JULY 2009
    1956 Kuroda natural nuclear reactor
    red-giant stars
  - High neutron capture cross sections of heavy elements
    2×10^{-10} g Tc
    $^{99}Mo \to {}^{99m}Tc$ tumors
    6 hours short period of time

Continuing our discussion on the origin of elements beyond iron, we can always expect that iron and other nuclei of intermediate mass act as a seed. This was also the suggestion given by Gamow. They are happening within the stars. Neutrons are playing important role in the synthesis of elements; we can say that the reactions proceed in steps of one mass unit at a time and either they will occur at a slow rate or at a rapid rate. Slower process is called as s process and faster is called as r process, whose details we will discuss very soon.

Either they occur at a slower rate or a rapid rate, they are supported by the following interesting features. I am going to discuss five important features of abundance curve highlighting the elements beyond the iron peak. The first feature supports the hypothesis of neutron induced reactions, i.e., the explanation of structure of abundance curve cannot be done without assuming the neutrons. If you ignore the charged particles' induced reactions, there is no other particle induced reaction which can explain the structure of the abundance curve other than neutron. So, this is the one of the important features which supports our hypothesis.

Second feature is that people have occasionally observed large neutron fluxes from the star and other places in the universe. I have discussed few reactions in the previous lecture like $^{13}C(\alpha,n)$ and role of nitrogen in how neutrons are produced. So, when people observed large neutron fluxes experimentally, then they thought neutron fluxes can come out from within the stars. Also, neutrons are formed within the stars in a big number. So, when neutrons are available, there is automatically a possibility that these neutrons will induce the reactions.

Calculations have shown that only 3% of iron peak elements are sufficient to act as the seed and they are available. This is another feature.

One of the fascinating discoveries, which made people confident that it is the neutron induced reaction because of which elements are synthesized beyond the iron peak, is discovery of technetium in 1952. There are some contradictions when people say that Technetium cannot be found on earth now but produced artificially only. There are a few contradictions, and the readers are strongly suggested to go through the paper of nature chemistry published in 2009.

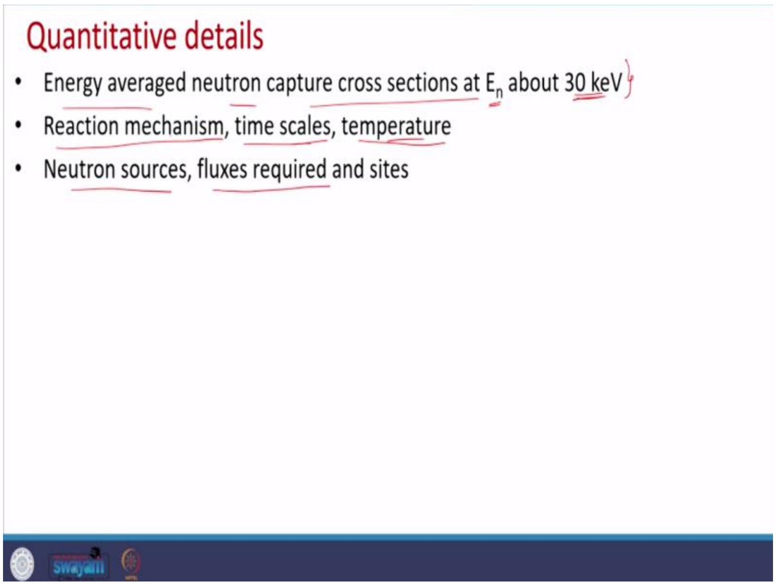
It was generally believed that any Technetium that might have been present when the earth was first formed, has long since decade radioactively. We know this because even the longest-lived isotope of the element Technetium has a half life that is too short in comparison with the age of the earth. But, in 1956, Japanese radio chemist Paul Kuroda predicted that natural nuclear reactor might have existed deep within the earth once. I am talking about nuclear reactor beneath the earth that would have existed. Five years later, he reported that a sample of African Pitchblende contained about 2×10^{-10} of Technetium. You will read in many textbooks that it is not possible to observe Technetium on earth. Some of data, which I am presenting, are in contradiction with what has been written in the textbooks. Let us see some more information about this Technetium. In 1962, a team of French Scientists have confirmed the prediction of Kuroda, that a natural nuclear reactor used to exist beneath the earth by investigating the rock samples in the republic of Gabon in the Africa. The analysis has shown that there were trace amount of Technetium present in these minerals too. So, it is still contradicting the common textbook statement that Technetium does not occur naturally on earth. If you turn to the sky, it was detected in some so-called red giants stars as long ago as in 1952. So, you can see the synthesis of Technetium in red giant stars.

Despite its exotic heritage, the Technetium is now widely used in medicine as a diagnostic tool. Radioactive ^{99}Mo is allowed to decay to form ^{99m}Tc, an excited metastable nuclear state which drops to the ground state with the loss of a gamma ray. This gamma ray can be measured in radio diagnostic procedures for the detection of tumors, among other things. The usefulness of this Technetium lies in a number of specific properties that it has. The decay of the excited form has half life about 6 hours and this 6 hours is very attractive property for the medical purposes because it is long enough to be injected into a patient but still sufficiently short for its emission to intensity to be measurable at low concentrations. Moreover, the short half life means that patient need only be exposed to radiation for a brief period of time. So, this is all about the Technetium whose discovery has confirmed the hypothesis of neutron induced reactions causing the formation of elements beyond the iron.

When neutrons emitted because of the reactions happening before the iron peak synthesis somehow thermalize, the heavy elements that we are expecting beyond iron peak have very high neutron capture cross sections. So, the ability of the elements to capture the neutrons confirm the hypothesis that by capturing the neutrons new elements can be formed.

These five features of abundance curve supports our understanding of neutron induced reactions which is the reason for the formation of elements beyond the iron peak.

Now we need some numbers regarding this neutron induced reaction to establish quantitatively. When I say quantitatively, it means that we have to know the behavior of cross section of these neutron induced reactions and what is the order of neutron induced reactions cross section.

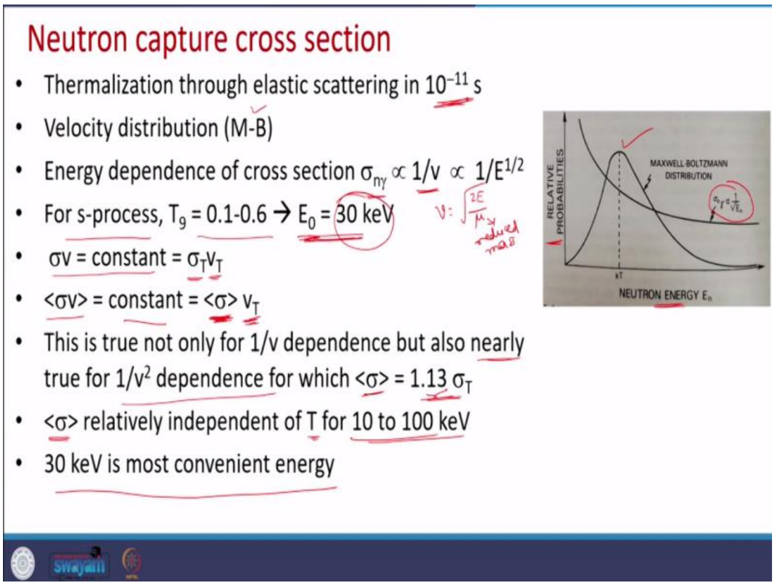


Quantitative details

- Energy averaged neutron capture cross sections at E_n about 30 keV
- Reaction mechanism, time scales, temperature
- Neutron sources, fluxes required and sites

Energy averaged neutron capture cross sections at the energy about 30 keV. What is so special about this 30 keV? I will discuss very soon. So, we need the information on capture cross sections when the neutron energy is about 30 keV and we also need to know the mechanism of the neutron induced reactions and what is the time scale over which this neutron induced reactions are happening. And at what temperature these reactions are happening. We need numbers corresponding to all these features. And we need to know what the sources of neutrons are. When we do measurement of the cross sections, we get information about all these things.

What are the neutron fluxes required for the reactions to happen? We need to measure the cross section of neutron induced reactions to know this number also. What are the possible sites astrophysical sites for this neutron induced reaction. So, we need to have numbers corresponding to all these parameters.



Neutron capture cross section

- Thermalization through elastic scattering in 10^{-11} s
- Velocity distribution (M-B)
- Energy dependence of cross section $\sigma_{n\gamma} \propto 1/v \propto 1/E^{1/2}$
- For s-process, $T_9 = 0.1\text{-}0.6 \rightarrow E_0 = 30$ keV
- σv = constant = $\sigma_T v_T$
- $\langle\sigma v\rangle$ = constant = $\langle\sigma\rangle\, v_T$
- This is true not only for 1/v dependence but also nearly true for $1/v^2$ dependence for which $\langle\sigma\rangle = 1.13\, \sigma_T$
- $\langle\sigma\rangle$ relatively independent of T for 10 to 100 keV
- 30 keV is most convenient energy

$v: \sqrt{\frac{2E}{\mu}}$ reduced mass

Let us the neutron capture cross section: the relative probability and the neutron energy, how the cross section varies with the energy. It plays very important role in understanding relation between the cross section of neutron induced reaction and the energy of the neutrons. In the star's shell. neutrons are formed with different energies due to different types of nuclear reactions. They are poly energetic.

These poly energetic neutrons undergo elastic scattering with nearby nuclei. Because of this elastic scattering with expected scattering time scale of about 10^{-11} seconds, they get thermalized. Once neutrons are thermalized, the velocity distribution follows the Maxwell–Boltzmann, as shown here.

The energy dependence of cross section is 1 / v dependence. Can't it be $1/v^2$? Yes, sometimes it could be. Then what about this discussion? Will it change? We will see.

Velocity of neutron is $\sqrt{\frac{2E}{M}}$ and sometimes we use μ (Reduced mass) in place of M. As I said, the reactions can occur with a slower rate or rapid rate. If it occurs with the lower rate, then we call it as s process, whose features we will discuss more in due course.

For s-process the estimated temperatures are in the range of 0.1 to 0.6 gigakelvin and E_0 is around 30 keV. Where has this 30 keV come from? I will explain now. When σ is proportional to 1 / v, we can always consider the product of σ and v as a constant.

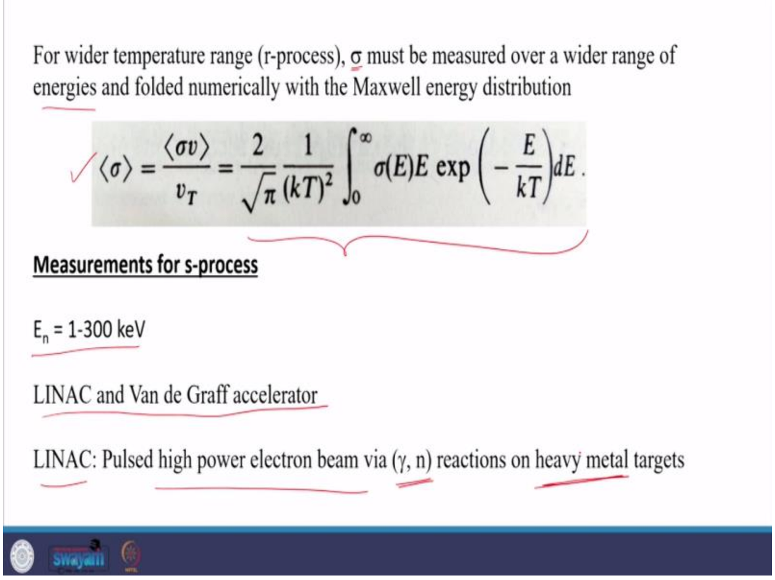
Because they are thermalized, we can always say the constant value is also equal to the product of the cross section corresponding to thermal neutron and velocity corresponding to thermal neutron.

Now we are in the position to write reaction rate per particle pair, the average kind of thing. The average value of σv is also constant, but now I am writing the cross section as the averaged value and velocity of the thermal neutron outside this average. Are we allowed to write down this?

This is true not only for 1 / v dependence, but also nearly true for 1 / v^2 dependence also. Because, if you do the simple calculation, the average cross section <σ> is about 1.13 σ_T. So, there is a small increment when compared to the 1 / v dependence. For 1 / v^2 dependence it is just 0.13. So, it is okay in majority of the cases to consider both for 1 / v and 1 / v^2 dependence.

We can always say that energy averaged capture cross section can be considered and it has been observed that the energy averaged capture cross section is relatively independent of temperature for the energy range from 10 to 100 keV. So, you can take any value within 10 to 100 keV. That is how people have taken E_0 as 30 keV.

There is a reason to select 30 keV as some standard E_0 value. 30 keV is the most convenient energy for understanding the neutron induced reactions and if we are able to measure the reaction cross sections at this energy, then we can get better understanding of the synthesis of elements within the stars beyond iron peak.



For wider temperature range (r-process), σ must be measured over a wider range of energies and folded numerically with the Maxwell energy distribution

$$\langle \sigma \rangle = \frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{1}{(kT)^2} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{kT}\right) dE .$$

Measurements for s-process

E_n = 1-300 keV

LINAC and Van de Graff accelerator

LINAC: Pulsed high power electron beam via (γ, n) reactions on heavy metal targets

For wider temperature region, higher than 0.1 to 0.6, we cannot take σ at certain energy like 30 keV, but it needs to be measured over a wider range of energies. Then we have to fold numerically with the Maxwell–Boltzmann distribution and once we fold the measurement of capture cross sections over wide range of energies and Maxwell energy distribution, the capture cross section average value looks like follows:

$$\langle\sigma\rangle = \frac{<\sigma v>}{v_T} = \frac{2}{\sqrt{\pi}}\frac{1}{(kT)^2}\int_0^\infty \sigma(E)E\ exp\left(-\frac{E}{kT}\right)dE.$$

It is folding between energy dependence of neutron capture cross sections and the Maxwell–Boltzmann distribution that gives rise to this kind of formula for the cross section.

Now, how can one measure s process, which is happening with a slow rate? In order to measure the s process, one has to go for energy of the neutron to say 300 keV. The most widely used facilities are LINAC, i.e., linear accelerator or Van de Graff accelerator. We cannot directly get neutron beam from any accelerator because they are not charged particles. So, we use pulsed high power electron beam and a target so that we can get (γ,n) reactions. Normally, we get this kind of reaction when we use target based on heavy metals.

When electron beam is used on the heavy metals, the reactions will give neutrons and these neutrons have to be thermalized so that one can initiate the neutron reactions relevant for the nuclear astrophysics. More details about s process and r process will be discussed in the next lecture. Thank you very much for the attention.