Nuclear Astrophysics

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Lecture - 40

Time of Flight Method and Indirect Methods

Welcome students to last lecture of this course. I hope all of you have enjoyed the various aspects of nuclear astrophysics. On several occasions, I have provided an introductory kind of information in this field of nuclear astrophysics. In this lecture, I am going to discuss one experimental technique for measurement of neutron energies, because it is the neutron which is playing important role in the synthesis of elements beyond the iron.

Let me give you an overview of the course, which I have tried to give in the very first lecture. Then I will discuss some of the important experimental methods, which we call as indirect methods. So, the contents of today's lecture are as follows.

In the last lecture, what we have discussed? The kinematics of nuclear reaction. In today's lecture we will see one of the important applications of kinematics of nuclear reaction content, which I have covered in the previous class. So, in the kinematics of nuclear reactions we have seen, what is the relation between angles of the emissions of reaction products between laboratory frame of reference and centre of mass frame of reference?

Why centre of mass frame is useful in nuclear reactions? From theoretical point of view, the motion of centre of mass does not carry any meaning. So, we have considered a frame of reference where the centre of mass is at rest. So, both projectile and target were moving and they are approaching with each other with some velocities. So, this was the situation imagined in centre of mass frame of reference.

Whereas, in lab frame target is in general at rest and projectile is moving. In the stars where actual nuclear reactions are taking place, both projectile and target, they are moving with respect to each other. They are randomly moving inside the stars. That kind of situation we cannot create within the laboratory. So, it is very important to relate various quantities in a nuclear reaction, when we consider the frame of reference as a laboratory frame and as a centre of mass frame.

We also have seen, if the incident particle is having energy above threshold value. In case of endothermic reaction, the reaction products energies, they will be of two sets and after a certain value, it will be only one. So, those kinds of things we are going to use in today's lecture. So, last two lectures mainly covered the kinematics of nuclear reaction, where I have discussed the relation, mathematical relations between various quantities pertaining to nuclear reaction.

First in laboratory form of reference and then in CM frame of reference. So, this was the content of previous two lectures. So, in today's lecture, I will discuss a method called as time of flight method. Then, I will list out a few important methods which we call as indirect methods in nuclear astrophysics. What is their importance? What are their advantages and disadvantages?

I will try to show you some of the important facilities around the world, including one of the important facilities coming up within India. So, these are the contents of today's lecture, which will be the last lecture of the course nuclear astrophysics. Let us start with time-of-flight method.

So, what is the background of this time-of-flight method? When we want to perform any nuclear reaction relevant for astrophysics. It is important to know the energy distribution of the incident particles. What about if the incident particle is neutron? If incident radiation is gamma ray, because gamma ray interacts with matter via photoelectric Compton and pair production, and in all these cases the outcome is common, that is electron.

And the electron energy is nothing but the incident gamma energy and this electron is depositing the energy depending on the detector medium. So, it is not very difficult, it is quite easy to measure the energy of the gamma ray by calibrating the detector. If we want to detect the gamma rays, if we want to know the energies of the gamma rays. What about neutrons? In laboratory I have said not many neutron sources are available.

One has to perform the nuclear reactions to produce the neutrons also. How to measure the energies of the neutrons? As I said, there is one source Californium 252 source which emits a neutron of energies up to say 15 MeV. And there is a source Am-Be source, where alpha particle from americium reacts with beryllium to give neutrons.

This also produces energy of the neutrons from 10 to 15 range and one can use a plutonium beryllium source. So, these are few sources which we use in the laboratory to test the performance of the detector for neutrons. To understand this synthesis of elements beyond iron; one has to go for s process or r process. Various features of this s and r process I have discussed in the previous lectures.

So, it is a neutron which is inducing the nuclear reactions for the synthesis of elements beyond iron. What is the approximate energy range of these neutrons? It is a few kV to few MeV. How to know these energies of the neutrons? Because if you want to perform the nuclear reaction, it is important to know the energies of the neutrons. And whatever sources I have discussed now, americium beryllium, plutonium beryllium, californium 252.

These are the sources which one can use in the laboratory for testing the performance of the detector for neutrons. But these neutrons are not mono energetic, they are poly energetic. But nevertheless, you need to find out the energies of those neutrons, not very easy task. Because unlike gamma which gives rise to electrons within the detector, it could be in scintillator, it could be in gas, it could be in semiconductor.

So, either you have electron hole pairs or electron positive ions. In the case of scintillator, it is electron, which is produced in these three processes of photoelectric Compton and pair production. But whereas in case of neutrons, they are interacting via scattering and absorption and in the scattering also elastic scattering and inelastic scattering.

So, they are leading to the recoil nuclei within the detector medium. So, it is a recoil nuclei, which is depositing the energy in second step; in the first step neutral energy is given to the nucleus. Now, if it undergoes absorption not in scattering, then the absorption of neutron leads to the production of many types like it could be neutrons again, it could be charged particles, it could be gamma rays and these gamma rays again gives electrons.

So, it is purely in direct measurement. So, keeping this in mind, it is not very easy to find out the energies of the neutrons. And the lack of mono energetic neutron sources in the laboratory is also a major challenge for measuring the response of the detector for neutrons. So, the calibration is a quite challenging task, if you do not have mono energetic neutrons. So, how to measure the energetic of the neutrons?

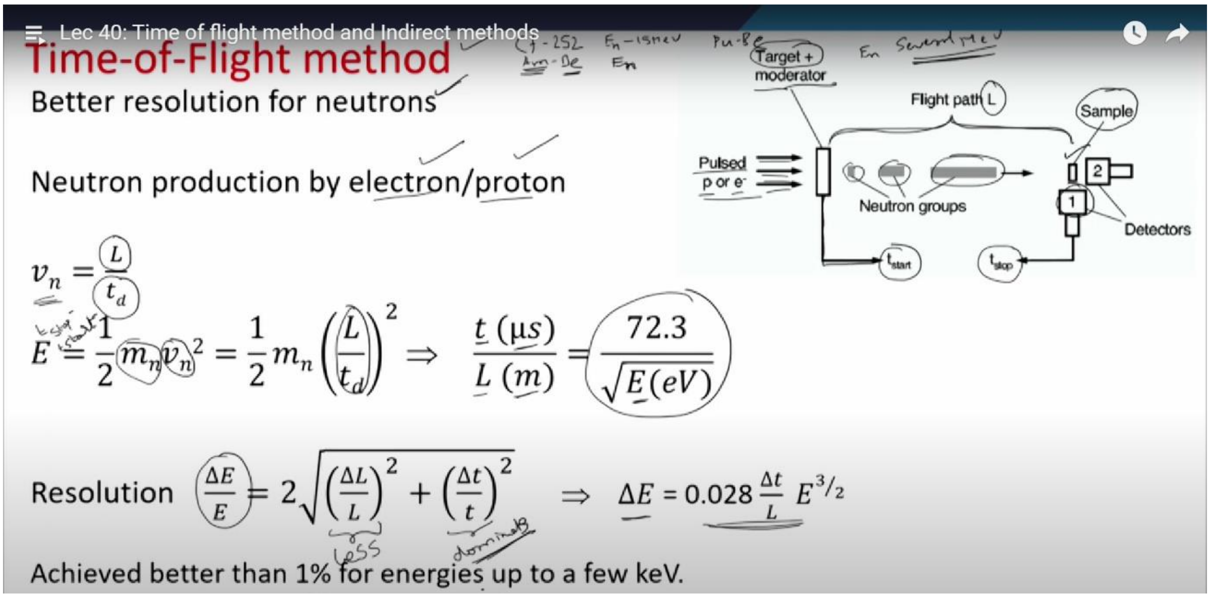
That is the purpose of this discussion, where I am going to discuss a method called as time-of-flight method. What is the essence of this time of flight? The energy of the particle, in this case neutron can be measured by the distance travelled by the particle. So, what does it mean? You need to have a location where neutrons are produced by the nuclear reaction and you need to have another location where neutrons have to be collected.

At one-point neutrons are produced, at another point neutrons are collected. The distance travelled by the neutron from the production point to the collection point can be measured that is length. The time taken by this neutron in travelling this distance can be easily calculated.

Because mass is known, so by applying simple formula of energy of a particle half m v square; mass of the particle is known, velocity can be found out by distance travelled and divided by the time taken by the neutron to reach from the production point to the collection point. Let us see what are the important features of this time-of-flight method? This method has proved to be much superior to most of the other techniques, when it comes to the better resolution for neutral energies.

So, that is the beauty of this time-of-flight method. And already have discussed how neutrons can be produced using the accelerator. Either you allow electron beam or you allow proton beam to fall on some target material, which produces neutrons. So, this production of neutrons by using accelerator facility, which gives electron beam or proton beam, already I have discussed in one of the previous lectures.

The first point is to have electron or proton beam to react with some material, which can give rise to neutrons. So, let us see this diagram, so it could be pulsed proton or pulsed electron beam. This arrow mark shows the pulsed proton or electron beam. So, this target is basically reacting with a proton or electron and giving rise to the neutrons. And the energy of these neutrons ranges up to several MeV.



Time-of-Flight method

Better resolution for neutrons

Neutron production by electron/proton

$$v_n = \frac{L}{t_d}$$

$$E = \frac{1}{2} m_n v_n^2 = \frac{1}{2} m_n \left(\frac{L}{t_d}\right)^2 \Rightarrow \frac{t\,(\mu s)}{L\,(m)} = \frac{72.3}{\sqrt{E(eV)}}$$

Resolution $$\frac{\Delta E}{E} = 2\sqrt{\underbrace{\left(\frac{\Delta L}{L}\right)^2}_{\text{less}} + \underbrace{\left(\frac{\Delta t}{t}\right)^2}_{\text{dominates}}} \Rightarrow \Delta E = 0.028\,\frac{\Delta t}{L}\,E^{3/2}$$

Achieved better than 1% for energies up to a few keV.

Now, the reaction of our interest is not up to several MeV, so you need to moderate it. So, that is why I am using moderator around this target. So, neutrons depending on the energies we can have bands and depending on the energy they can move fast or slow with respect to each other. Now, I am placing one sample by reacting with which neutron is undergoing reaction of our interest. That is reaction relevant for nuclear astrophysics.

So, this flight length, the distance travelled by the neutron is fixed. The place at which neutrons are produced using some electronic setup measure that starting time, neutrons will take some time to reach the sample. So, you measure that stopping time. The difference in this starting and stopping time gives us an idea about the energy of the neutron by taking the help of mass of the neutron and the flight path.

And here the detectors are used to measure the products from the nuclear reaction happened at the sample, because of the neutron irradiation. So, the velocity of the neutron is nothing but the flight length divided by time difference, nothing but t stop - t start. And the energy can be calculated by half m v square. Already mass of the neutron is known and velocity the neutron is calculated from L by td, where td is the time difference.

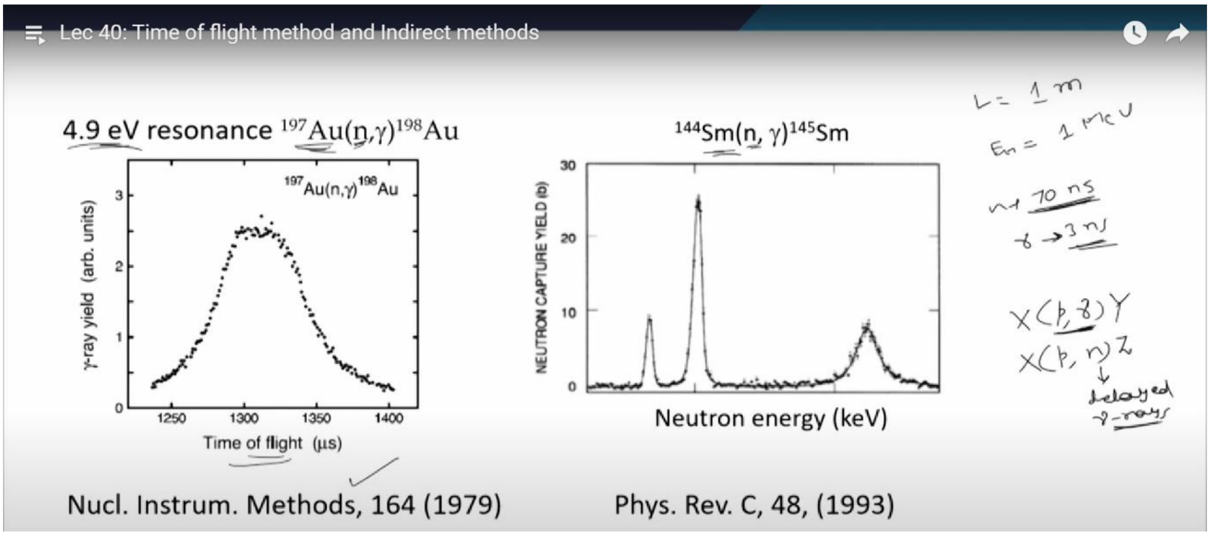
So, L by t d is nothing but the velocity of the neutron. And from this one can write down the ratio of time, of course in microseconds and length in meters as 72.3 by square root of E. So, once you know the t, once you know the L, one can find out energy in electron volts using this formula. So, because energy formula is known the fractional resolution in energy, it depends on fractional change in length and fractional change in time.

Which one will dominate on the energy resolution? Usually this is less, and usually it is a delta by t which dominates. Now, interestingly, whether we need to go for large separation, I mean whether we have to allow neutron to travel for long distance or short. If it is very long, then the time taken is very long, so delta by t is very less, so you will have better energy resolution. So, normally we prefer the flight length to be large.

However, we cannot go for long separation between the production of the neutron and the collection of the neutron places, because the number of neutrons falling on the sample where the nuclear reaction of our interest is taking place will come down. So, the acceptance angle will come down if L is more. So, one has to go for some kind of trade off. The distance between production point and collection point, if it is very large, the plus point is that time will be large.

So, delta by t will be less, so delta by E will be better. So, for better resolution it is very good, but the number of particles falling on the target material will come down, so the count rate will be affected. So, one has to consider the length in such a way that the uncertainty in the energy also should be less, at the same time count rate also should be reasonable. And delta E the resolution can be given in terms of delta t and L using this formula.

And, researchers could achieve better than 1% resolution, for energies up to a few KeV, using this time-of-flight method.



4.9 eV resonance ^{197}Au(n,γ)^{198}Au

^{144}Sm(n, γ)^{145}Sm

Nucl. Instrum. Methods, 164 (1979)

Phys. Rev. C, 48, (1993)

$L = 1$ m

$E_n = 1$ MeV

$n \to 70$ ns

$\gamma \to 3$ ns

$X(p,\gamma)Y$

$X(p,n)Z$

$\downarrow$

delayed

γ-rays

Let me show you some examples. When neutrons produced by irradiation of protons or electrons with some target material. When they react with a gold 197; the resonance at 4.9 electron volt has been studied and the count rate versus time of flight if you see, it gives a beautiful Gaussian kind of peak. For more details you can go through this paper. And another reaction neutron yield versus neutron energy if you see, neutron reacting with the samarium.

They give this kind of output with the help of time-of-flight method. Normally, with 1 meter L and for energies of the neutron say 1 MeV. The time associated with the neutrons is about 70 nanosecond and if you see for the gamma, it is about the 3 nanoseconds. So, you can see the difference in the timings corresponding to neutrons and gammas, because gamma travels with velocity of light much faster and neutrons travel slowly when compared to the velocity of gamma. Now, I am introducing another advantage of this time-of-flight method and that is how one can discriminate the gamma rays induced by neutrons in the detector from the gamma rays emitted during the nuclear reaction. Sometimes we want p gamma reaction to happen. Now, I am talking about totally different scenario. If I consider a reaction, where proton is falling on some target nucleus and it is giving a product nucleus Y and we are studying ready to capture reaction.

But this proton can also produce neutrons by reacting with X, and producing another product nucleus Z. So, these neutrons can induce background and can pollute the data that we are looking for. So, it is important to discriminate the gamma rays produced in p gamma reaction from the gamma rays produced by the neutron, which we are calling as delayed gamma rays. How it is possible?

To get rid of the background induced by p, n reaction when we use the p gamma reaction. Keep the detectors quite far and gammas will reach the detector first. In this particular case I have given you three nanoseconds and neutrons will take about 70 nanoseconds. So, these huge differences between the arrival times of neutrons and gamma rays can be used to discriminate prompt gamma rays from the neutron induced delay gamma rays.

So, what are the two advantages of time-of-flight method? One can measure the neutron energies and second one can separate the gamma rays which are emitted in the nuclear reaction, that means prompt gamma rays from the neutron induced gamma rays. So, these two are the advantages of time-of-flight method. So, let me touch one more aspect of the time effect method.

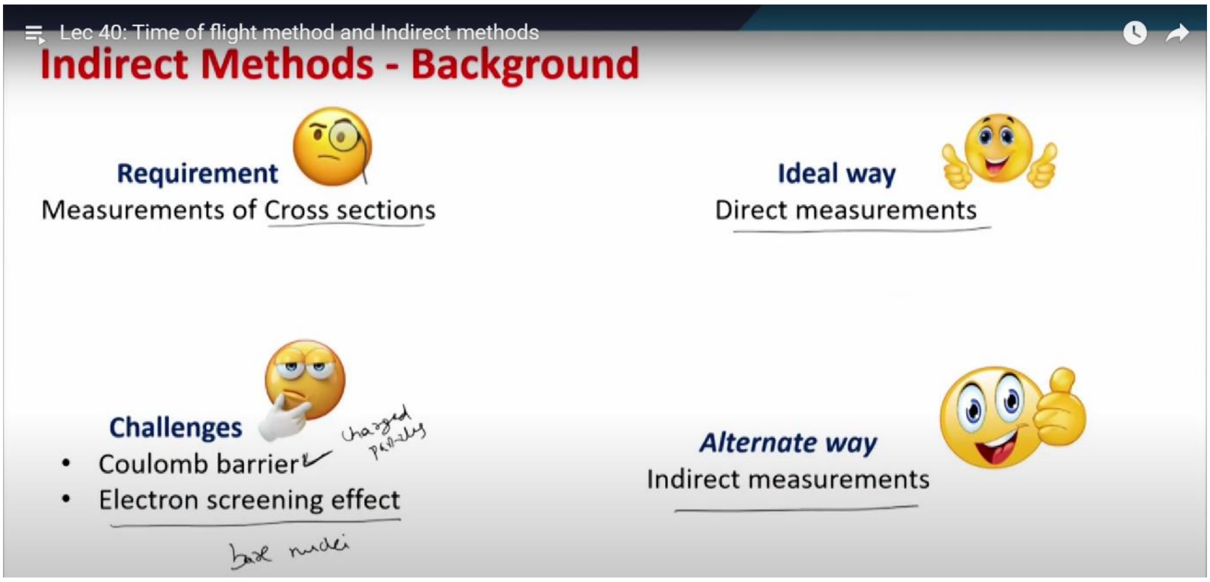
When we go for charged particle time of flight measurements, if I want to measure the energy of the charged particles, one can go for the charged particle-based time of flight as well. Now, I am not discussing the neutrons anymore, I have jumped into charged particle, time of flight measurement. Then, how do you measure the starting time and ending time? Let us use two detectors.

Number one delta E, a detector to detect the charged particle, but whose thickness is very-very less, very thin detector. So that, whenever the particle deposits some energy in this delta E detector, take it as a start signal. And then, compare to delta E you take another detector which is thicker, which we call as the E detector; you place at a distance away from the delta E detector. And from this E detector you take the stop signal.

So, now this difference in the start and stopping time will give you information about the energies of the charged particles. Now, this is very much suitable for the light particles that too medium energy. So, I am confining here the technique of charged particle time-of-flight measurements to two different types; one is light particles, at the same time they have to have energy not low or high but medium.

So, this charged particle time of flight is very much suitable for medium energy light particles. Why not heavy particles and low energy light particles? The problem is the scattering which can happen, if the low energy light particles are considered. Because of this, number of particles reaching the E detector will come down, so low energy light particles, it is not suitable. Heavy particles, even in very thin, it will be absorbed.

So, where is the question of reaching the second detector? So, their time-of-flight technique is not useful for the heavy particles also. So, as I said, this is important for prompt gamma emitted in reaction from neutron induced gamma rays.



Indirect Methods - Background

Requirement
Measurements of Cross sections

Ideal way
Direct measurements

Challenges
- Coulomb barrier
- Electron screening effect

charged particles
bare nuclei

Alternate way
Indirect measurements

Now, indirect methods; let me give you some background of these indirect measurements. So, after discussing time-of-flight method, I am taking up a different topic. It is the Hans Bethe's proposal, that fusion of nuclei could be the source of heavy energy produced from the stars, mainly sun.

People really became serious to carry out several measurements. They have done lot of theoretical work also. And they have seen what kind of reactions and what is the reaction mechanism, which produces the energy. Then they realize that within the stars whatever nuclear reactions are responsible for the energy production. They are also responsible for the synthesis of elements, which I have discussed earlier in the initial part of the course.

Now, to understand the energy production within the stars and also the stellar evolution and also the synthesis. The most important parameter which one has to measure is cross section of the nuclear reaction and how to measure them? Of course, one can go for the direct measurements. The direct measurements means the reaction of interest should match with the energy range at which we are carrying out the experiment.

I have discussed what is the problem in this. Number one; Coulomb barrier. Of course, when we consider charged particles and another thing is that electron screening effect which I have discussed. What I have discussed in the electronic screening effect? Inside the stars when fusion between two nuclei happens, there were no electrons around them.

Inside the stars they are bare nuclei. But in the laboratory when we allow the projectile beam to react with the target. The target material does not contain the bare nuclei, electrons are surrounding the nuclei of our interest. So, the presence of electrons around the nucleus is affecting the cross-section value. So, this is called as electron screening effect. So, what are the alternatives?

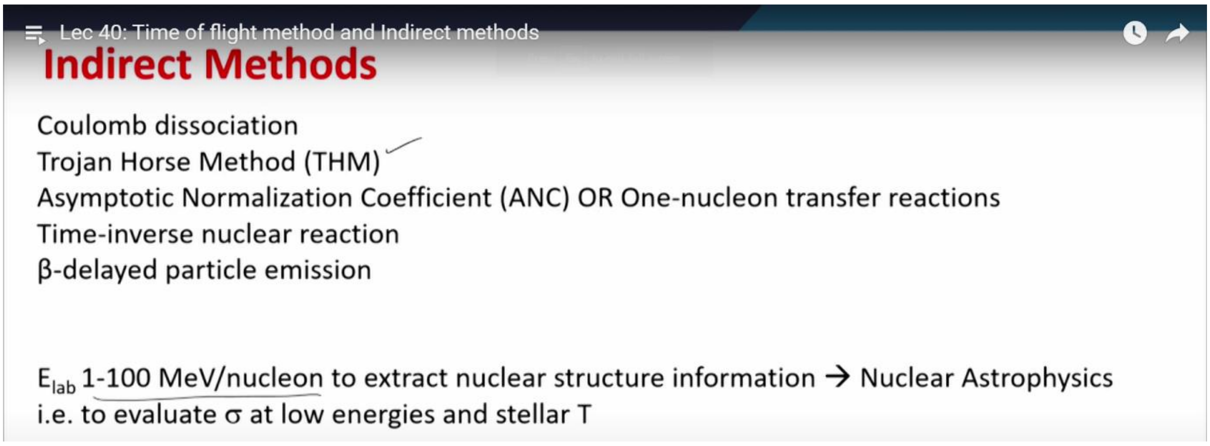
Another problem in these direct measurements is many times when we do not get the energy of our interest like within the Gamow window. We have to carry out the measurement at higher energies, then extrapolate the S values. But extrapolation always introduces high level of uncertainty, unless a lot of solid theoretical work is done. So, the alternate way is go for the indirect measurements. So, in these indirect measurements, what we do is?

We will do the nuclear reaction at high energy above the Coulomb barrier which we always can do it. From that we will extract the information within the Gamow region. So, that is how we carry out the indirect methods, many times radioactive ion beams are also used. Because, the nuclear reactions in the stars many times the nuclei involved are radioactive in nature and the radioactive nuclei target is very difficult to make unless it has very long half-life.

So, use the projectile containing the radioactive nuclei and take the stable target nucleus and carry out the nuclear reaction.

So, the direct measurements we know that coulomb barrier and electron screening effect poses problem. So, one has to go for the indirect methods and what are the challenges in indirect method? Usually, they are not capable to fix the reaction rate, which is important parameter for understanding the abundance of the elements without the direct measurement. So, this is one of the challenging thing in indirect methods.

And another important challenge is detector background in direct methods. What are the three main sources of background? I have discussed earlier, one is cosmic rays. To avoid this one has to go for the underground and then natural radioactivity and then target beam induced background. In natural radioactivity one can come across Potassium 40, which emits 1.4 MeV gamma.



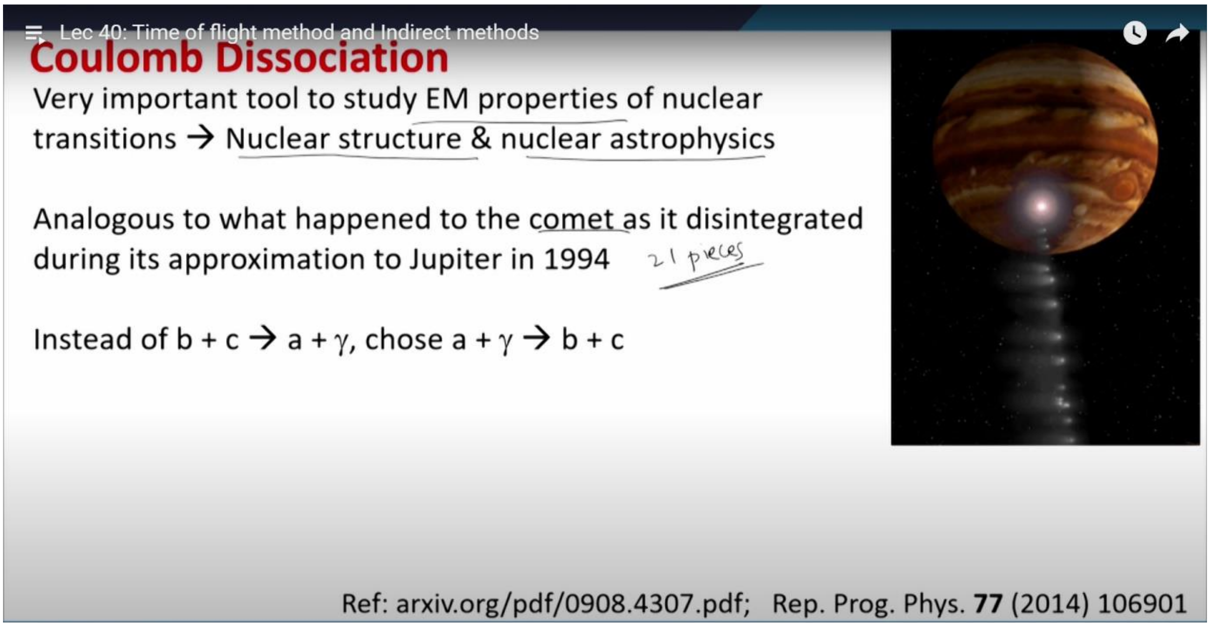
Indirect Methods

Coulomb dissociation
Trojan Horse Method (THM)
Asymptotic Normalization Coefficient (ANC) OR One-nucleon transfer reactions
Time-inverse nuclear reaction
β-delayed particle emission

E_{lab} 1-100 MeV/nucleon to extract nuclear structure information → Nuclear Astrophysics
i.e. to evaluate σ at low energies and stellar T

So, in that indirect methods, these are some of the methods like coulomb dissociation, Trojan Horse method, asymptotic normalization coefficient method, time inverse nuclear reaction, beta-delayed particle emission. So, these are some of the indirect methods which one can perform and this is the energy range of the projectiles, which are normally used in the indirect methods.

So, let me discuss one method, that is coulomb dissociation method. Which is basically useful to understand the electromagnetic properties of the nuclear transitions This is very important from the perspective nuclear structure. So, it is also useful for the nuclear astrophysics, because every nucleus is part of the star. So, basically it is analogous to, what happened to the comet?



Coulomb Dissociation

Very important tool to study EM properties of nuclear transitions → Nuclear structure & nuclear astrophysics

Analogous to what happened to the comet as it disintegrated during its approximation to Jupiter in 1994 21 pieces

Instead of b + c → a + γ, chose a + γ → b + c

Ref: arxiv.org/pdf/0908.4307.pdf; Rep. Prog. Phys. **77** (2014) 106901

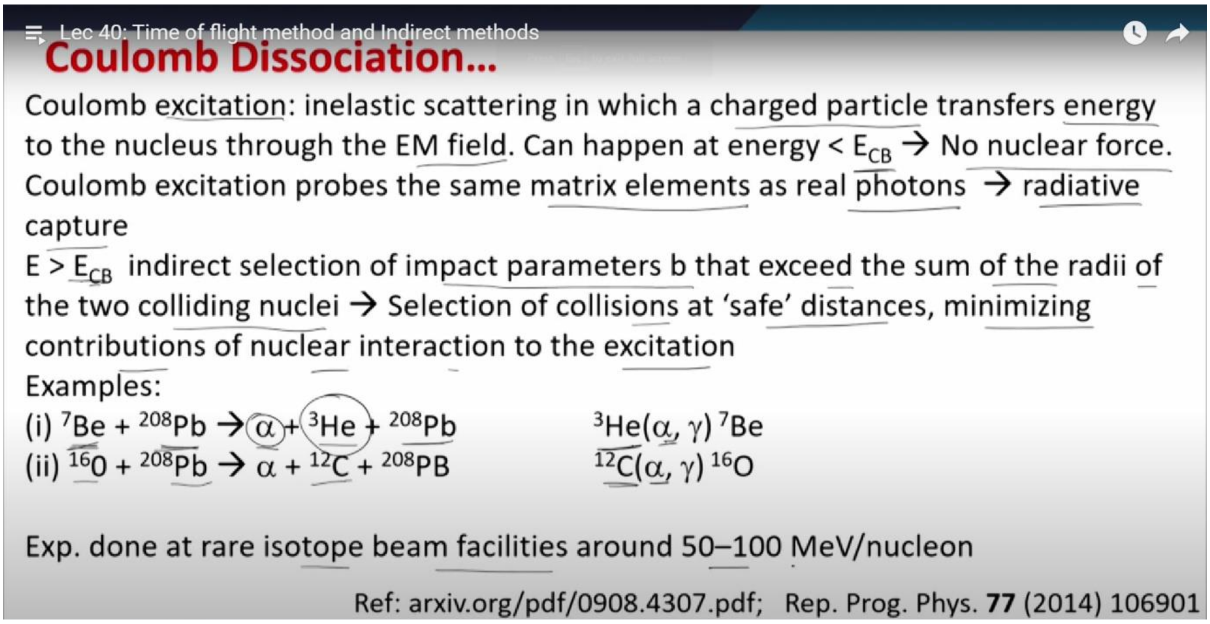
One interesting example I am giving, so you can see this photograph where this comet which is in bright colour and this is the Jupiter in 1994. Presumably when it came close to Jupiter it was single entity and it break up into about 21 pieces and it revolved around 2.2 days. After sometime these pieces of comet they try to affect the planet also. So, this is one of the classic examples for the coulomb dissociation.

Under the gravitational field of the Jupiter the comet has disintegrated. In the same way, when projectile comes to the coulomb field of the nucleus, it will undergo disintegration.

For example, if I want to study this ready to capture reaction and it is not possible to study. Then, what I will do is? I will choose this a + gamma, which gives raise me b + c, then go for the reverse method. So, in the coulomb dissociation method, first excitation happens which is basically analogous to like inelastic scattering. When, a charged particle transfers energy to the nucleus through the electromagnetic field.

Of course, it can happen even less than the coulomb energy also. The advantage in this excitation is no nuclear force is involved only coulombic field is involved. And this coulomb excitation probes the same matrix elements which is mathematical entities as the real photons. So, basically this coulomb disassociation is very ideal method for the radiative capture reaction. One can go for the above coulomb barrier energy.

This indirect selection of impact parameter b, exceeds the sum of the radius of the two colliding nuclei. Which allows us to select the collisions at safe distances. So that, we can minimize the contributions of the nuclear interaction to the excitation. For example, if I want to study the alpha + helium 3, what one can do is? Go for beryllium 7 projectile react with lead 208, then you will get alpha and helium 3 and lead 208.



Coulomb Dissociation…

Coulomb excitation: inelastic scattering in which a charged particle transfers energy to the nucleus through the EM field. Can happen at energy < E_{CB} → No nuclear force. Coulomb excitation probes the same matrix elements as real photons → radiative capture

E > E_{CB} indirect selection of impact parameters b that exceed the sum of the radii of the two colliding nuclei → Selection of collisions at 'safe' distances, minimizing contributions of nuclear interaction to the excitation

Examples:

(i) $^{7}Be + ^{208}Pb \rightarrow \alpha + ^{3}He + ^{208}Pb$ $\quad$ $^{3}He(\alpha, \gamma)\,^{7}Be$

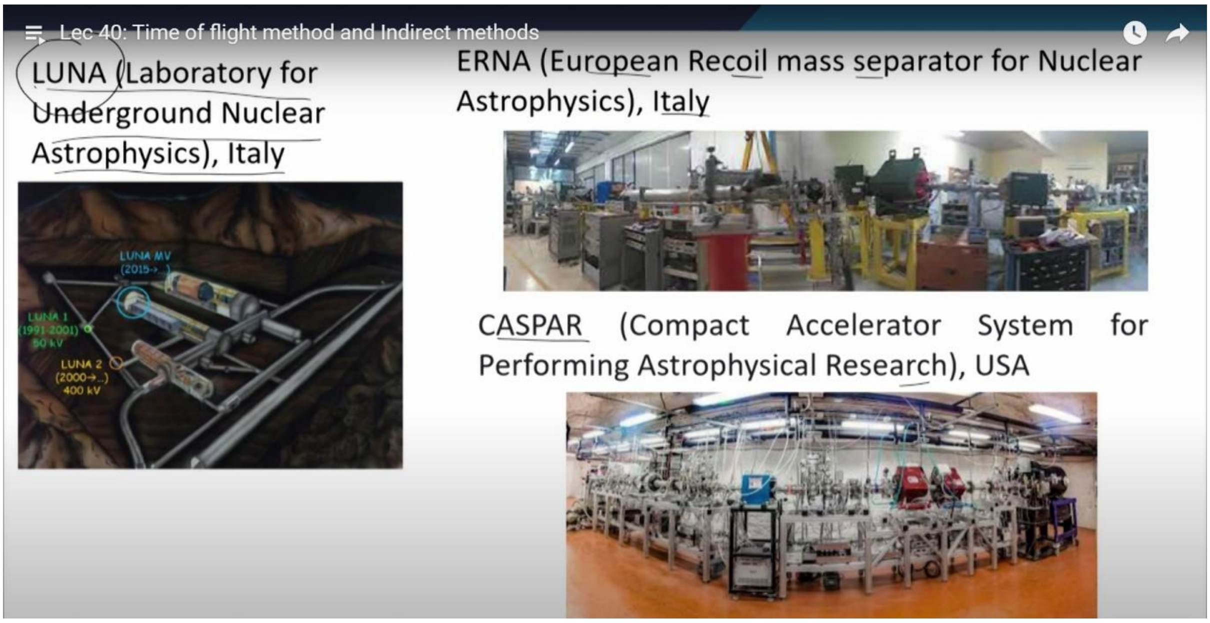
(ii) $^{16}O + ^{208}Pb \rightarrow \alpha + ^{12}C + ^{208}PB$ $\quad$ $^{12}C(\alpha, \gamma)\,^{16}O$

Exp. done at rare isotope beam facilities around 50–100 MeV/nucleon

Ref: arxiv.org/pdf/0908.4307.pdf; Rep. Prog. Phys. **77** (2014) 106901

So, this alpha and helium 3 can be detected using coincidence method and one can extract the information about the alpha + helium 3. Second example, if I want to go for alpha + carbon 12, then I can go for Oxygen 16 in coulomb decision method and lead 208 and where alpha and 12 C are produced, the detection of alpha and carbon 12 can be useful to extract the information of alpha + 12 using reciprocity theorem.

So, normally these kinds of experiments are done at rare isotope beam facilities around this kind of energy. And a lot of facilities are available in the world, so let me show you some of the laboratories.

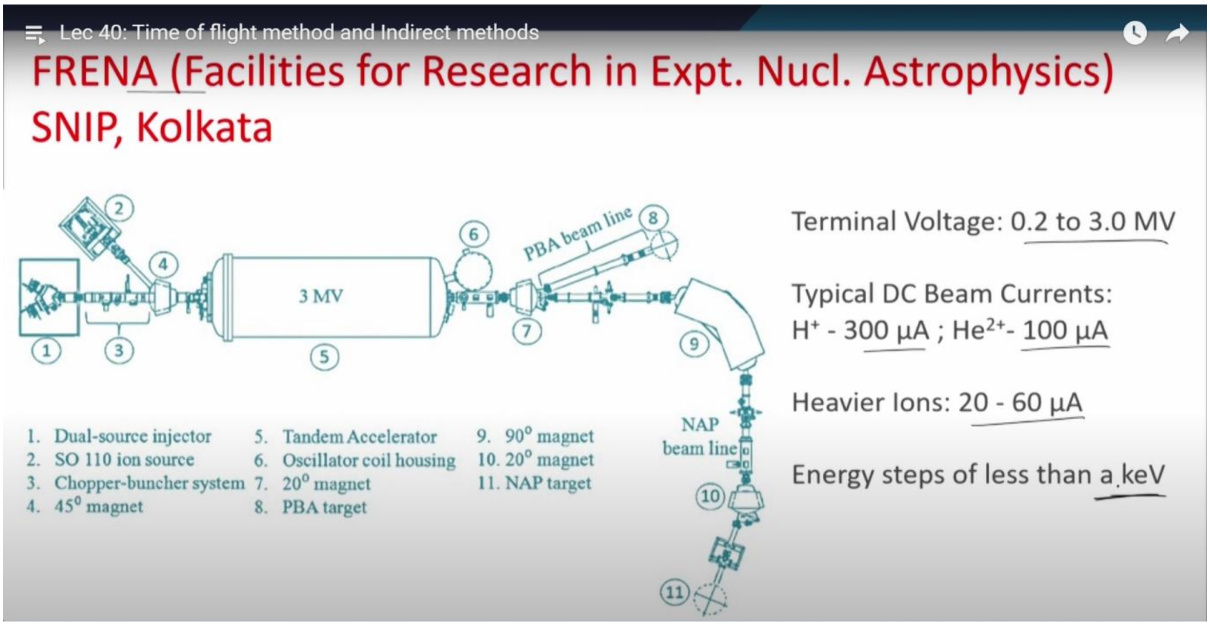


LUNA (Laboratory for Underground Nuclear Astrophysics), Italy

ERNA (European Recoil mass separator for Nuclear Astrophysics), Italy

CASPAR (Compact Accelerator System for Performing Astrophysical Research), USA

This is the laboratory for underground nuclear astrophysics, Italy and there is a European recoil mass spectrometer for nuclear astrophysics, Italy. And another facility is CASPAR, compact accelerator system for performing astrophysical research and this LUNA is basically underground facility which helps us to get rid of the natural radioactivity and also the cosmic rays contribution.



FRENA (Facilities for Research in Expt. Nucl. Astrophysics) SNIP, Kolkata

1. Dual-source injector
2. SO 110 ion source
3. Chopper-buncher system
4. 45° magnet
5. Tandem Accelerator
6. Oscillator coil housing
7. 20° magnet
8. PBA target
9. 90° magnet
10. 20° magnet
11. NAP target

Terminal Voltage: 0.2 to 3.0 MV

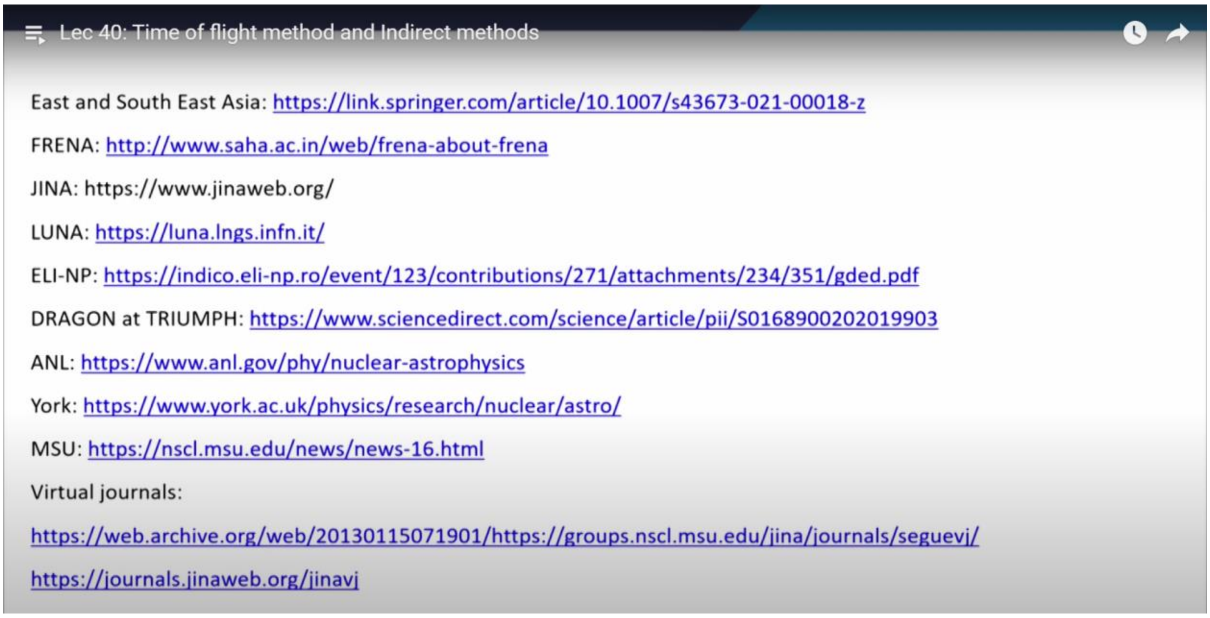
Typical DC Beam Currents:
H^+ - 300 μA ; He^{2+}- 100 μA

Heavier Ions: 20 - 60 μA

Energy steps of less than a keV

And in India a new facility is ready to have the experimental studies, FRENA in Saha Institute of Nuclear Physics, where the terminal voltage is up to 3 mega volts and typical beam currents for protons is about up to 300 microamperes and for alpha it is 100 microamperes and for heavier ions one can go for 60 micro amperes. And one can go for the less than one kilo electron volt steps.

And, in this slide I try to provide various facilities. So, thank you very much, I hope all of you have enjoyed these nuclear astrophysics course. I am looking forward to interact with you through assignments and tutorials as well. Thank you very much for your attention.



East and South East Asia: https://link.springer.com/article/10.1007/s43673-021-00018-z

FRENA: http://www.saha.ac.in/web/frena-about-frena

JINA: https://www.jinaweb.org/

LUNA: https://luna.lngs.infn.it/

ELI-NP: https://indico.eli-np.ro/event/123/contributions/271/attachments/234/351/gded.pdf

DRAGON at TRIUMPH: https://www.sciencedirect.com/science/article/pii/S0168900202019903

ANL: https://www.anl.gov/phy/nuclear-astrophysics

York: https://www.york.ac.uk/physics/research/nuclear/astro/

MSU: https://nscl.msu.edu/news/news-16.html

Virtual journals:

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