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Cycling the Hot CNO: A Teaching Methodology

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Abstract. An interactive activity to teach the Hot Carbon, Nitrogen and Oxygen (HCNO) cycle is proposed. Justification for why the HCNO cycle is important is included via an example of X-ray bursts. The activity allows teaching and demonstration of half-life, nuclear isotopes, nuclear reactions, protons and α-particles, and catalytic processes. Whilst the process example is specific to astrophysics it may be used to teach more broadly about catalytic processes. This practical is designed for use with 10-20 participants, with the intention that the exercise will convey nuclear physics principles in a fun and interactive manner.

1. Introduction

The field of Nuclear Astrophysics offers many challenges, including measurements of the rates at which nuclear reactions occur in key astrophysical sites. This information helps to predict the structure of complex stellar environments, for example when a star explodes. Replicating these astrophysical environments in the lab is challenging. From the measurements and predictions we aim to explain the origin of nuclei and the mechanisms by which they are formed. Some of the key mechanisms are:

- The proton-proton chains, where hydrogen fuses to make helium.
- The triple-alpha process, where three α-particles (helium nuclei) fuse to make Carbon.
- Carbon, nitrogen, oxygen cycles (CNO), fusing hydrogen to helium through a catalytic fusion process.
- The rp-process, where rapid proton capture forms nuclei on the neutron-deficient side of the valley of stability.
- The s-process and r-process, where slow neutron capture and rapid neutron capture occur respectively, forming nuclei along the valley of stability and on the neutron rich side of the valley of stability.

The rate at which these processes occur is dependent on the environment. In the following section X-ray bursts are highlighted. They offer a particularly interesting example on which to base taught discussions on the Hot-CNO cycle due to their energetic nature.

1.1. X-Ray Bursts

X-Ray bursts consist of a neutron star (‡) and a companion. The neutron star accretes (or steals) matter from the companion. The mass of the companion affects the X-ray burst significantly with high mass X-ray bursts having a donor companion of mass greater than 10 times the mass of the sun and low mass X-ray bursts having a companion mass of less than approximately the mass of the sun Ref. [2].

Type 1 X-ray bursts are associated with a thermonuclear flash. Their light curves have a length of 10s of seconds to minutes and gives information on their make-up Ref. [3]. An accretion disk builds up around the neutron star as mass leaves the donor star. This matter falls onto the surface of the neutron star, causing increased pressure and temperature on the compact object Ref. [3]. These pressures become high enough such that nuclear energy is transferred almost entirely into heat, resulting in yet higher temperatures. This is thermonuclear runaway and occurs in X-ray bursts, in which the temperature often exceeds 1GK Ref. [3].

Heavier nuclei are created in notable quantities in the hydrogen/helium rich region mainly through α-capture reactions; such as the Hot-CNO (HCNO) cycle breakout, and the rp-process Ref. [3]. The triple α-process and α-induced breakout reactions initiate the thermonuclear runaway in X-ray bursts Ref. [4] and hence the rp-process. The rp-process forms heavier nuclei up to Tellurium 107 (^{107}Te) where photon induced α-decay, called photodisintegration, limits the process Ref. [5].

2. Classic CNO Cycle

To understand the breakout, or escape, from the CNO cycle, the CNO process and nomenclature should be explained. Fig. 1 shows two of the classical CNO cycles.

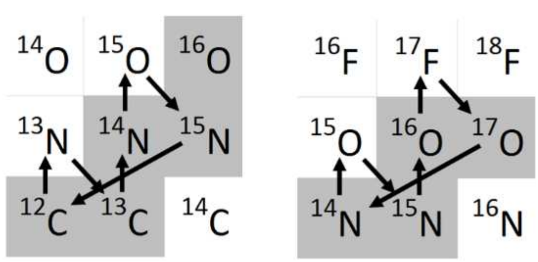

Figure 1: CNO cycle diagrams for “classical” CNO cycles. Isotopes in grey are stable.

‡ A neutron star is a dense star with a mass around 1.4 times that of the sun but a radius of around 10 to 15km Ref. [1]

All variations of the CNO cycle such as those in Fig. 1 fuse hydrogen into helium; this typically occurs at temperatures less than 0.1GK. If the environment is particularly energetic, such as that of an X-ray burst, the temperatures are higher and this allows additional reaction processes to occur over the normal CNO cycle.

3. HCNO Cycle and Breakout

Fig. 1 depicts the CNO cycle as at temperatures upto 0.1GK. Below 0.4GK the HCNO cycles are more predominant with minimal breakout. At temperatures around 0.5GK oxygen α-capture rates become significant and as illustrated in the textbook authored by Iliadis [1] there are three main breakout cycles, here we shall consider two, which are shown in Fig. 2. It can be seen that in this HCNO cycle, some of the α-decay points seen in the CNO cycle are bypassed through proton capture.

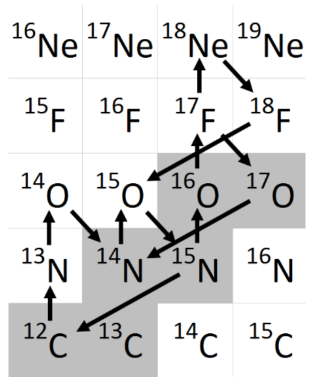

Figure 2: The HCNO cycle. Note that a breakout can occur via a reaction with an α-particle at ^{15}O or ^{18}Ne.

By understanding the rate of breakout in reactions such as $^{18}\text{Ne}+\alpha \rightarrow \text{p}+^{21}\text{Na}$, the rate at which nuclei are induced into the rp-process can be more accurately estimated. Understanding of these processes not only develops a basic knowledge of decay mechanisms but offers the opportunity to be able to explain potential formation mechanisms of heavier elements. An interactive and engaging concept has been developed by the authors. The following activity will enable participants to revise taught material in an unconventional engaging fashion and develop their knowledge beyond the standard syllabus. The participants can be from a wide variety of educational backgrounds including school level or undergraduate. Key topics to be covered can be seen in Sec. 4.2.

4. Activity

4.1. The Hot-CNO cycle in stellar explosions (particularly in novae and X-ray bursts).

The practical illustration Cycling the Hot-CNO is intended as an illustration of nuclear reactions in stellar explosions. This includes a practical experience of the concept of "half -life" for unstable nuclear isotopes. The illustration is designed for use with 10-20 participants at a time, although there is scope to use this demonstration with larger numbers or a class split into groups. (For example, we would suggest splitting a big class of more than 20 students into two groups, and either make two copies of the illustration or have one group do the part without the breakout followed by another group where the breakout is included). The activity is discussed as a secondary school or sixth form based activity, but there is also scope to use it for public engagement.

4.2. Topics of Relevance

- Nuclear isotopes (several isotopes of each element).
- Nuclear reactions (particularly proton absorption, but other reactions are involved)
- Protons and α-particles (absorbed and emitted).
- β decay (8 of the isotopes decay by beta decay).
- Half-life (the illustration is particularly designed to help understand the random nature of decay).
- Stars, particularly stellar explosions: novae and X-ray bursts. (However, part of this cycle is also the dominant form of hydrogen fusion for stars that are at least three times as massive as our sun. In this case, the process is slower and the longer half lives are therefore not a hindrance. In this case the catalytic process follows the cycle: ^{12}C, ^{13}N, ^{13}C, ^{14}N, ^{15}O, ^{15}N, and at last back to ^{12}C.)
- Catalytic processes in general. (Not only important in nuclear astrophysics, but also critical for chemical processes such as the catalytic processes used to clean up the exhaust gasses in cars.)

4.3. Procedure

Each participant in the exercise acts as a nucleus undergoing reactions that comprise the HCNO cycle. To begin, the participants must each choose one of the following isotopes: ^{12}C, ^{13}N, ^{13}C, ^{14}N, ^{15}O, ^{15}N, or ^{16}O to start from. The isotopes, as seen in Fig. 3, should be printed and laminated. These isotopes should be attached to the floor securely using adhesive tack, to avoid any trips or slips. The participants must each stand so they can touch their isotope with their foot. Several participants are allowed to "be the same isotope" at the same time. With varied decay times it would be expected that some isotopes may have more participants "waiting" than others; this will demonstrate that some isotopes in the cycle act as waiting points, in which large quantities of relatively long-lived isotopes build up.

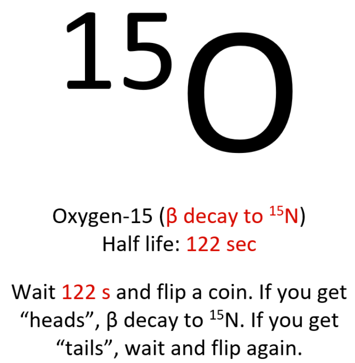

Figure 3: An example of an isotope card that should be printed and laminated.

Using a stopwatch and a coin, each participant must then move around the network of reactions and decays by following the instructions written on each of the isotope cards. For example, if you stand on ^{14}O (that is you are an ^{14}O nucleus): you must then wait 71s (the half-life of the isotope) before flipping a coin. If the coin shows heads up, you will beta decay to ^{14}N. If the coin shows tails, you have to wait for another half-life and try again. After 10 minutes of the participants moving around, the possibility of breakout can then be introduced after which some of the participants will gradually jump out of the cycle. Fig. 4 shows one of the breakout-point markers that can be introduced. The benefit of running the activity without breakout first is that it demonstrates the HCNO cycle prior to breakout conditions being met.

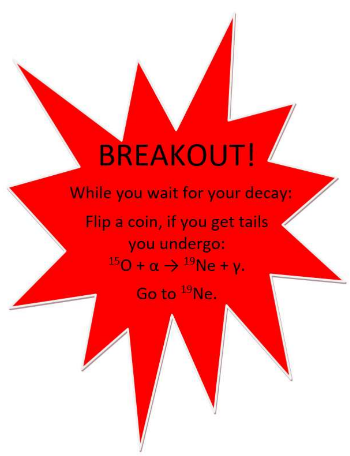

Figure 4: A breakout point marker, add these to ^{15}O and ^{18}Ne.

When participants reach these breakout-point markers they should follow the instructions given. If the beta decay half-life expires, they must flip the coin for the beta decay. Should they fail to beta decay, they may continue flipping for the breakout until a second beta decay half life passes. Not all participants should be expected to escape the cycle and some will continue to cycle around the HCNO cycle as shown in

Fig. 2. With a younger audience it may be more engaging to make this feature into the successful outcome of a game and offer some reward for achieving breakout (or the largest number of decays in X minutes).

4.4. Time and Equipment

The activity will typically require a 10 minute explanation (depending on the level of the audience) and 15 minutes for the practical part of the illustration. It is suggested that more time is dedicated to the practical part of the exercise if the networks with and without breakout are run with separate groups following each other. The space required for this exercise is dependent upon the number of participants but a space of around 4m by 4m is recommended as a minimum and the following equipment is required:

- Laminated A3 printout of the isotopes (see separate file). Cut out the two stars before laminating.
- Adhesive-tack or similar for fastening to the floor.
- One stop watch (or phone), one coin and an A5 chart printout per participant.

An example presentation, the tiles and handout are available online on the University of York, Physics Department, Binding Blocks website (§) in the Teaching Materials section.

4.5. Preparation

The laminated printouts are placed on the floor, if possible fixed to the floor with adhesive-tack or similar. In the first instance, the two breakout-point markers are not included. The printouts are placed in the order shown in Figures 2 or 5. The spacing should be 1-2 feet.

4.6. Activity Integration into the Classroom

The activity can be embedded into a longer class where the topics in Sec. 4.2 are all included. The class can start with a revision session of α-decay, α-capture and β-decay. The CNO cycle can then be explained and introduced.

After the introduction the interactive activity can begin with HCNO cycle, explaining to the students that higher temperatures are required compared to the CNO cycle. To help the students understand the processes through which they proceed an A5 printout of the nuclear chart region can be given to each participant, such as a smaller version of Fig. 5. As they travel around the cycle they can then mark their path on the handout, this will aid discussions later.

After the interactive component the class can be split into groups of four or five students each with a large printout of the tiles seen in Fig. 5.

§ https://www.york.ac.uk/physics/bindingblocks/

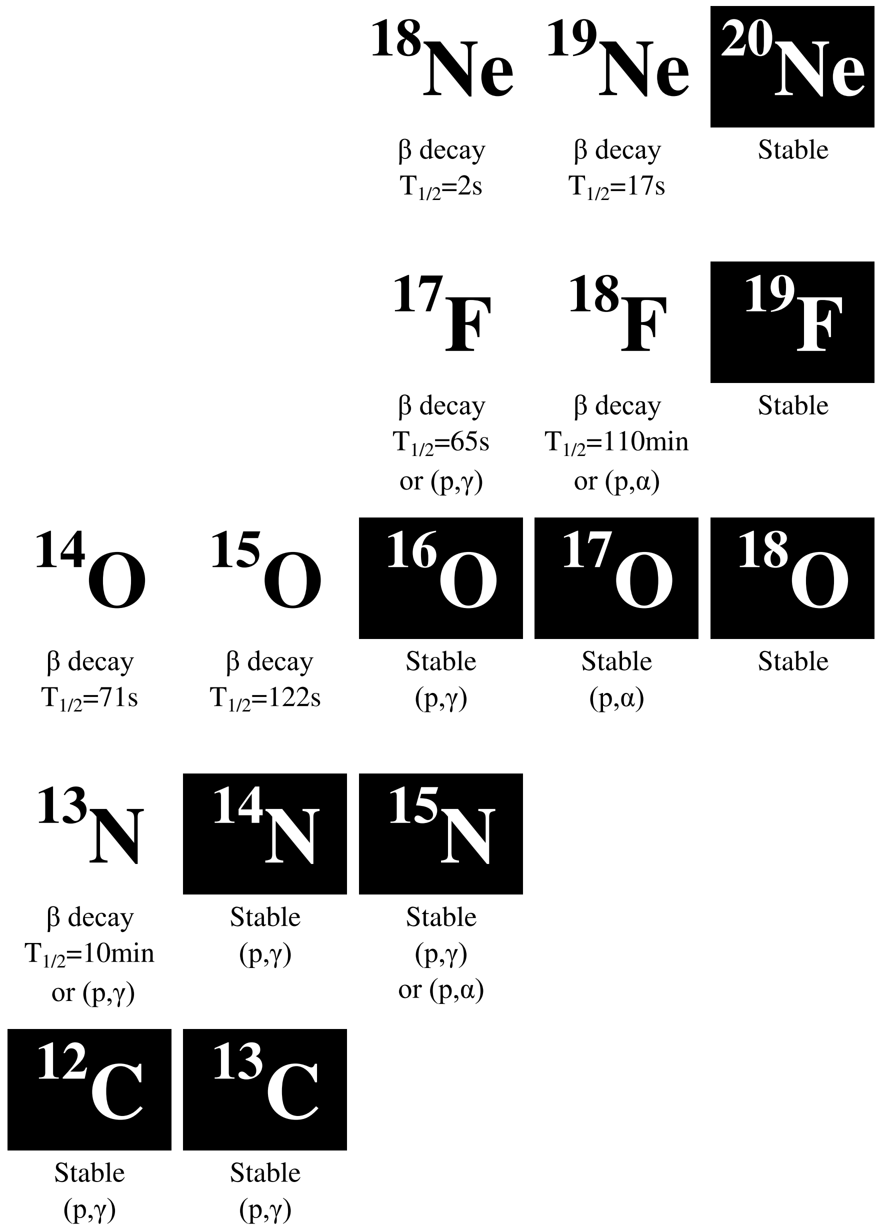

Figure 5: A group handout printed on A3 which is the same region of the nuclear chart as the interactive tiles. Below each tile the isotope's stability is denoted and if not stable, its half life. Also included is the path the HCNO cycle would follow when the isotope absorbs a proton.

In Fig. 5 shorter reaction nomenclature is used; where R+a=P+b is denoted by R(a,b)P. For example ^{14}N+p=^{15}O+γ would be represented by (p,γ) under the ^{14}N tile.

This reaction nomenclature should help students to identify the loops of the HCNO cycle whilst introducing them to more compact nomenclature.

The following is a list of suggested tasks and questions to get students engaged with the nuclear physics behind the cycle.

- Draw on the reaction arrows with each of the HCNO processes in a different colour.
- For each arrow what is the reaction type?
- In each loop what has been created/destroyed? (This is to get the students to arrive at the idea that the process is catalytic)
- How many HCNO processes/catalytic loops are there?
- Were there any differences between the reaction path you took during the activity and the paths of others? (To improve student engagement with guided talk through the different reaction paths)
- Why did you get stuck at ^{14}O and ^{15}O?
- With a high-level group: asking about the existence of ^{15}F and ^{16}F may be beneficial, including a discussion of its unbound nature and extremely short half-life.

Having discussed these questions the activity could then be run with breakout included and a discussion on the variation of conditions as well as the idea that breakout means the catalyst material is used up and that the process is no longer catalytic.

This activity can be preceeded by a Binding Blocks activity [6], an activity looking at properties of the nuclear chart as a whole and at more specific properties of the chart [7]. The two activities have been run alongside each other successfully at a high school level nuclear masterclass held recently at the University of York.

5. Conclusions

An example environment for the HCNO cycle is given and related to the formation of much heavier elements. An activity is presented which is designed to engage participants in an interactive way to further their knowledge of stellar nucleosynthesis. Instructions are presented to run the activity with requirements defined. It is hoped that this activity will enable further engagement in more advanced nuclear physics at a younger age.

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