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ASTROPHYSICAL STUDIES WITH RADIOACTIVE BEAMS

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The use of radioactive beams has impacted astrophysical studies in primordial nucleosynthesis, stellar nucleosynthesis through several different burning scenarios, and nucleocosmochronology. Recent work, or studies to be performed in the near future, in each of these areas is presented.

1. Introduction

The recent development of radioactive beam facilities has had an enormous impact on experimental nuclear astrophysics. Such facilities have opened up the possibility of measuring cross sections of many nuclear reactions which previously could only be estimated from incomplete experimental information or from theoretical considerations. These cross sections, of course, are used to calculate the thermonuclear reaction rates used in astrophysical network calculations. The entire field of study of reactions with radioactive beams has only existed for about a decade, but interest and effort therein has intensified greatly since the first discussions of the research capabilities of radioactive beams began to be discussed. Since the first workshop[1] on reactions with radioactive beams, there have been numerous additional workshops, two international conferences[2], a recent review article[3], a facility proposal[4], which also serves as an excellent review of the field of nuclear physics with radioactive beams, and a rapidly growing list of completed experiments. In this presentation I will describe several types of studies which have been performed, which only a few years ago would have been impossible. My emphasis will be on the information which can be obtained from such studies, rather than on the facilities used therein. However, in a few cases I will also give brief facility descriptions.

One type of study I will describe impacts specific models of primordial nucleosynthesis. Some of those models perform their nucleosynthesis via a pathway through the nuclides slightly to the neutron-rich side of stability. Specifically, ^{8}Li, a short-lived nuclide, is pivotal to the predictions of such models. Thus reactions which either create or destroy ^{8}Li, as well as those which synthesize heavier nuclides from ^{8}Li, are important to such models. I will describe several of the reaction studies which have been performed recently, or which are currently in progress, which involve ^{8}Li.

The original motivation[1] for radioactive beams was for studies of reactions which affect hot stellar burning, e.g., the "hot CNO cycle," the "rp-process," and the "r-process." One of the key reactions in the Hot CNO cycle has now

been studied three times, using two different techniques. The three studies all gave the same answer, lending support to both techniques. While nuclear reactions are of importance to both the rp-process and the r-process, some of the nuclides which are crucial to their operation are sufficiently far from stability that their most basic properties, such as mass and lifetime, are important to the basic features of the processes. Thus the studies relevant to those processes which have been performed so far have not involved reaction studies on the radioactive nuclides, but measurements of masses and decay properties.

An important peripheral aspect of the r-process, which affects cosmology, has also evolved from the development of radioactive beam facilities. A recently developed facility has made possible the study of "bound-state β-decay," a process which is impossible to study experimentally without radioactive beams. This process is important to understanding the evolution in stellar environments of some of the r-process nuclides which serve as chronometers for estimating the age of the universe. A recent experiment of this type will be described, and its potential for the future outlined.

2. Primordial Nucleosynthesis

The abundances of the light nuclides, ^{2}H, ^{3}He, ^{4}He, and ^{7}Li, have long been advertised as providing strong confirmation of the standard model of primordial nucleosynthesis[5]. Although serious questions have been raised recently[6] about the agreement between the standard model prediction and the observed abundance for ^{4}He, the standard model none the less does produce remarkable qualitative agreement with the observed abundances of the light elements over ten orders of magnitude. In the past few years another group of models of primordial nucleosynthesis, the inhomogeneous models[7] has also received a great deal of attention. In these models the universe at the time of primordial nucleosynthesis is not assumed to be uniform, as is done in the standard model, but is allowed to have inhomogeneities, possibly (but not necessarily) as a result of the quark-hadron phase transition. Low density regions quickly become dominated by neutrons, while high density regions are proton dominated. Thus the reactions by which nucleosynthesis occurs in the two regions can be quite different, with those in the low density regions tracing out the nuclides slightly to the neutron-rich side of stability. The synthesis which occurs in the low density regions has the potential of producing relatively large abundances of nuclides heavier than ^{7}Li, in contrast to that of the standard model.

In particular, these models may be able to produce[8] abundances of ^{9}Be and ^{11}B which are several orders of magnitude larger than those predicted in the standard model. This realization has resulted in a major effort[9] by astronomers to measure the abundances of those nuclides in metal poor stars. While their efforts have been heroic (observation of ^{11}B is done with the Hubble Space Telescope), and have resulted in an increase in sensitivity to those nuclides of

more than an order of magnitude from earlier results, they have apparently not yet reached the plateau[10] which would signal the observation of the primordial abundances. However, more work is being done in an effort to push the abundance limits on those two nuclides down even further. The level at which their primordial abundance exists will ultimately determine the extent to which inhomogeneity existed in the early universe; it such were observed at any level above that predicted by the standard model it would rule out that model.

In any event, it is clearly important to refine the predictions of all the models of primordial nucleosynthesis as well as possible. The reaction network for nuclides around ^{8}Li is shown in Fig. 1. The reaction which dominates the production of ^{11}B has been found to be ^{8}Li(α,n)^{11}B over much of the parameter

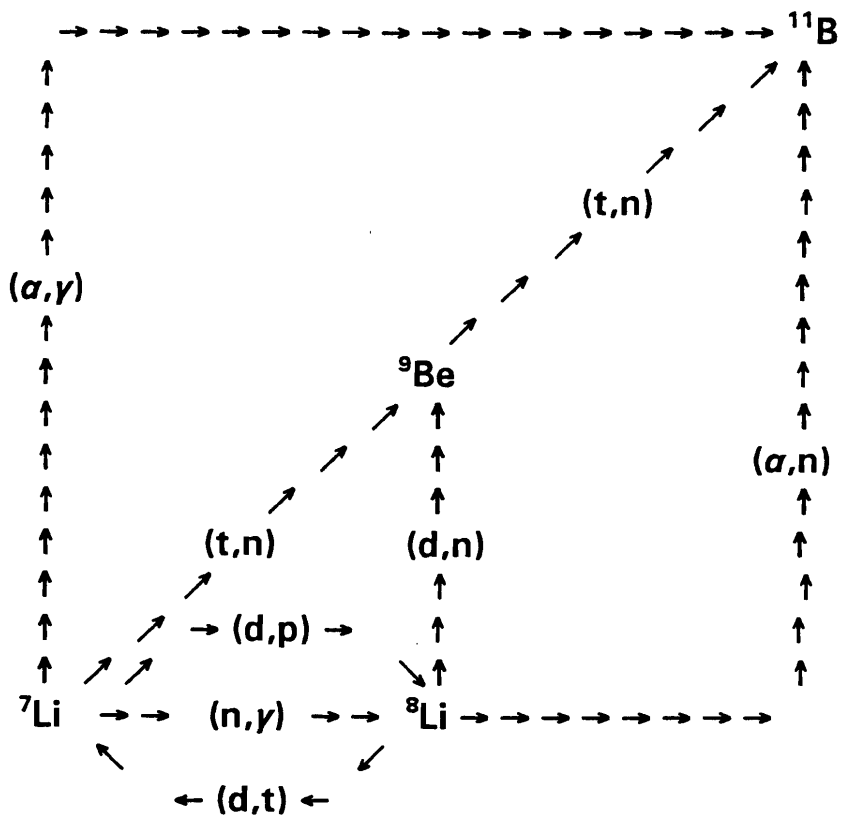

Figure 1. Reaction network in primordial nucleosynthesis for nuclides from ^{7}Li to ^{11}B.

space of the inhomogeneous models. Furthermore, ^{11}B appears to act as a funnel for synthesis of all heavier nuclides in those models, so this reaction also regulates the predicted abundances of all heavy nuclides. Thus this reaction is crucial to predictions of the inhomogeneous models. Unfortunately, direct study of this reaction is hampered by the 840 ms halflife[11] of ^{8}Li, necessitating use

of a ^{8}Li radioactive beam. A study[12] of the inverse reaction gave an estimate of the cross section to the ^{11}B ground state, but several excited states in ^{11}B could also be populated in ^{8}Li(α,n)^{11}B, so could contribute to the ultimate yield of ^{11}B.

To perform a direct measurement of this reaction, the RIKEN ring cyclotron was used to produce an 80A MeV ^{14}N beam, which impinged on a thick Be target. The resulting projectile fragments were analyzed and energy degraded by the RIKEN projectile fragment separator[13] to produce a ^{8}Li beam of from 10 to 20 MeV. Each ^{8}Li ion passed through a time-of-flight system which tagged it and measured its energy, then into the multi-sampling ionization chamber[14], a heavy ion detector which determined its trajectory and dE/dx value. The ^{4}He used in the detector served as both detector and target gas. The energy degradation of the ions as they passed through the detector allowed the simultaneous measurement of a large portion of the excitation function for this reaction.

The low energy ^{8}Li(α,n) reaction to all ^{11}B final states is shown in Fig. 2. It was found[15] to produce a cross section about five times as large as that[12] to just the ^{11}B ground state over the energy region which we were able to study. Unfortunately, the inability of the detector to discriminate between elastic scattering and reaction events at low energies, those below 1.5 MeV in the center of mass, prevented measurement of the cross section all the way down to the energies at which primordial nucleosynthesis occurs, slightly less than 1 MeV. Since the inverse reaction study[12] shows that the low energy cross section is resonance dominated, and that resonance could have quite different decay properties to the ^{11}B final states than would be produced by the reaction processes at higher energy, the actual enhancement due to the excited states remains to be determined. Several studies[16] have attempted to measure the enhancement expected from the dominant resonance, but questions associated with each of those prevent the determination of the actual number at present.

Another reaction of potential importance to predictions of inhomogeneous models of primordial nucleosynthesis is the ^{8}Li(d,n)^{9}Be reaction. It could both destroy ^{8}Li and synthesize ^{9}Be. The cross section to the ^{9}Be(g.s.) could be inferred from a study[17] of the inverse reaction. Thus, since all excited states of ^{9}Be decay by particle emission, that would determine this reaction's capability to synthesize ^{9}Be. However, if some of the ^{9}Be excited states were excited strongly in ^{8}Li(d,n), that reaction could destroy ^{8}Li very efficiently. Thus ^{8}Li(d,n)^{9}Be(g.s.) and ^{8}Li(d,n)^{9}Be(ex. sts.) must both be measured. Unfortunately, they require rather different experimental approaches.

The first stage[18] of the experiment, measurement of the ^{8}Li(d,n)^{9}Be(g.s.) cross section, was done using the Notre Dame-Michigan-OSU RB facility[19] to bombard a CD_2 foil with a ^{8}Li beam. This facility uses a superconducting solenoidal magnet to select and focus the ions of interest, ^{8}Li in this case, onto a secondary (CD_2) target. The resulting ^{9}Be(g.s.) ions were detected with solid state detector telescopes. Four or five point differential cross sections were measured at four c.m. energies from 1.6 to 2.8 MeV, thus yielding the excita-

tion function. The ^{8}Li beam energy was varied in two ways, one via use of absorber foils and one using different accelerator and superconducting solenoid parameters, to select the different energies. Although the data are presently being analyzed, that analysis has produced some of the angular distributions, one of which is shown in Figure 3.

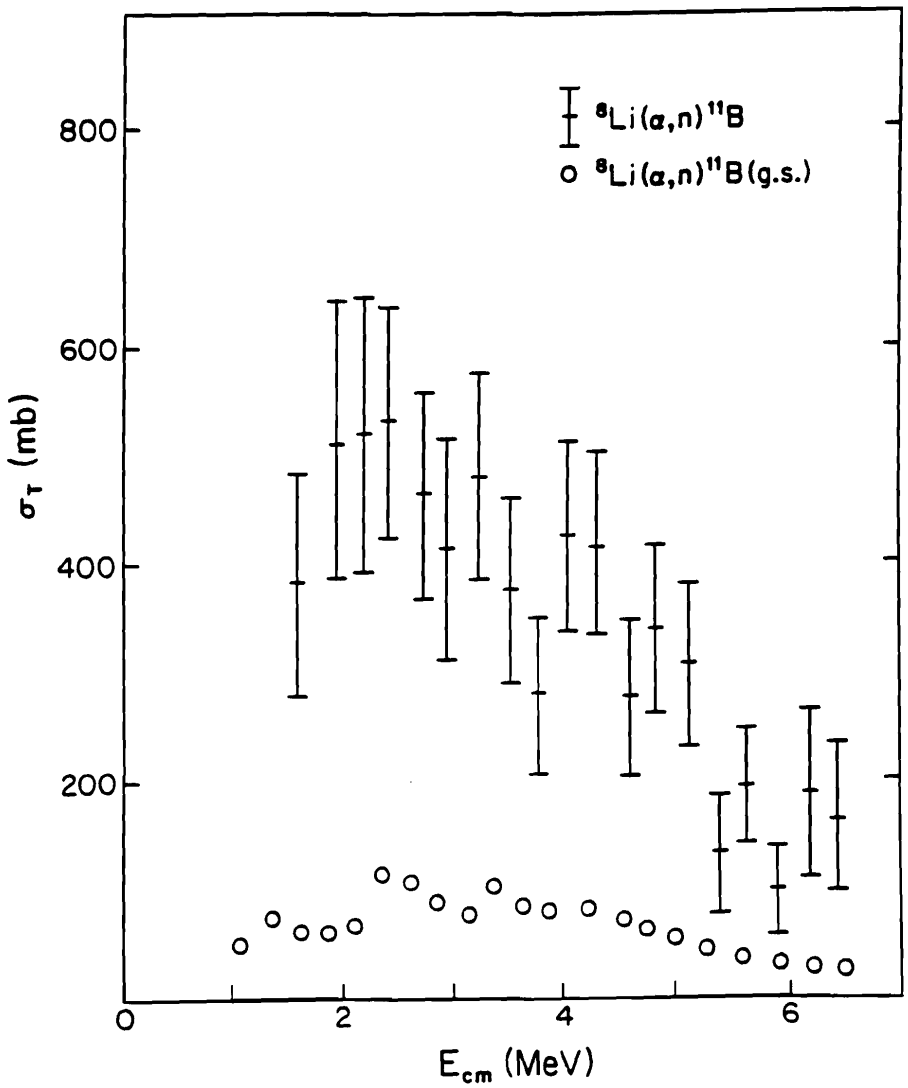

Figure 2. Cross section excitation function for ^{8}Li(α,n)^{11}B(all states) (crosses) and ^{8}Li(α,n)^{11}B(g.s.) (circles). A fairly constant factor of five is seen to exist between the two sets of data.

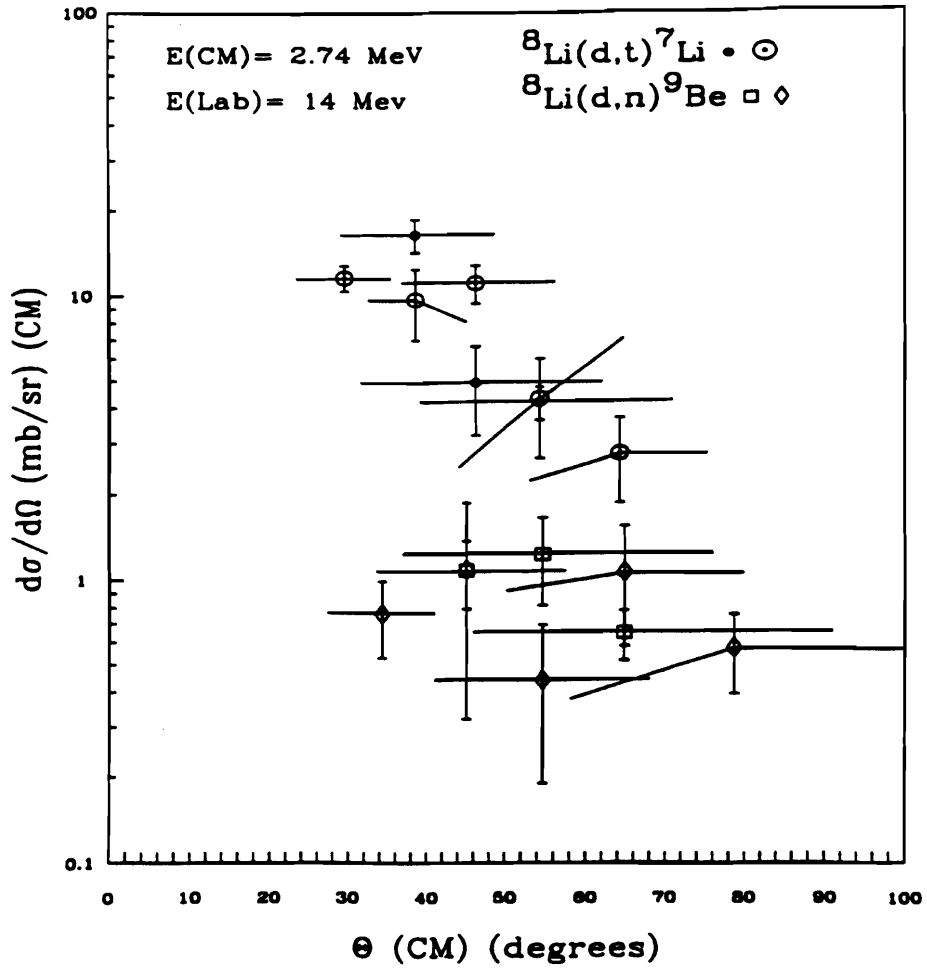

Figure 3. Differential cross sections for ^{8}Li(d,n)^{9}Be(g.s.) and ^{8}Li(d,t)^{7}Li at a center of mass deuteron energy of 2.74 MeV. The latter cross section is seen to be roughly an order of magnitude larger than the former.

We hope to study also ^{8}Li(d,n)^{9}Be(ex. sts.) using the Notre Dame-Michigan-OSU radioactive beam facility[19]. Since all ^{9}Be excited states decay with very short lifetimes into a neutron and two α-particles, the ^{8}Li(d,n)^{9}Be(ex. sts.) study cannot be done by detecting the recoiling ^{9}Be ions. Thus we plan to use two-dimensional position sensitive solid state detectors to observe[20] the two α-particles resulting from the breakup of ^{8}Be in coincidence. A preliminary run has shown both that this technique works very well, and that the cross section appears to be large. The actual running of this experiment, however, awaits analysis of the preliminary data.

As a serendipitous discovery resulting from the ^{8}Li(d,n)^{9}Be(g.s.) study, it was found[18] that the ^{8}Li(d,t)^{7}Li reaction has a large cross section, thus making it a potential ^{8}Li poison in the inhomogeneous models. Thus we also have measured that cross section at Notre Dame. The ^{8}Li beam was produced as for the ^{8}Li(d,n) studies discussed above (the experiments were run concurrently). The data obtained show that this reaction is indeed strong, and must be included in descriptions of primordial nucleosynthesis. The data are presently being analyzed; one of the angular distributions is also shown in Figure 3.

As is well known, a late time processing effect, homogenization[21], in which the high- and low-density regions which may exist during part of the period of primordial nucleosynthesis become mixed, has not been taken into account in any of the codes which produce abundance predictions in the inhomogeneous models. Thus the predicted abundances of the light nuclides are quite uncertain, as homogenization could have an enormous effect on them. For this reason it may be important to test the predictions of the inhomogeneous models with heavier nuclides, as they would be less susceptible to homogenization. In this context, we have begun a program[22] to study some of the nuclides which might be expected[23] to lie along the pathway of nucleosynthesis anticipated in the inhomogeneous models. These studies will involve short-lived nuclides such as ^{15}C and ^{17}N, nuclides which may be crucial to synthesis of Na, Mg, Al, and Si, potential important test cases for the inhomogeneous models.

3. The Hot CNO Cycle

The CNO cycle is well known to describe the C-catalyzed H-burning processes in which four protons are converted into an alpha particle, and energy is emitted. It is this process which dominates the nucleosynthesis and energy generation in the H-burning phase of stars somewhat more massive than our sun. This cycle is characterized by the fact that, at the temperatures characteristic of the cores of stars during their H-burning phase, several tens of millions K, the characteristic times for reactions are always much longer than the lifetimes for the attendant β-decays; the β-decays thus always have time to occur before the next nuclear reaction occurs.

However there can exist H-burning situations, not in the cores of stars but, e.g., in situations in which a collapsed star such as a white dwarf accretes matter from a companion star, in which H-burning can occur at a much higher temperature, in excess of a hundred million K, than that characteristic of the cores of even very massive stars. In such situations, the nuclear reactions occur so rapidly that the β-decays may not have time to occur; this is the Hot CNO cycle[24]. The network for the cycle is shown in Figure 4. There it can be seen that an interesting branch point occurs at ^{13}N; it can either capture a proton and become ^{14}O, or it can β-decay to ^{13}C, where it will soon capture another proton to become ^{14}N. Thus, understanding this part of the Hot CNO cycle, in particu-

lar, the speed at which the cycle proceeds, requires knowing the reaction rate, hence cross section, for the $^{13}N(p,\gamma)^{14}O$ reaction.

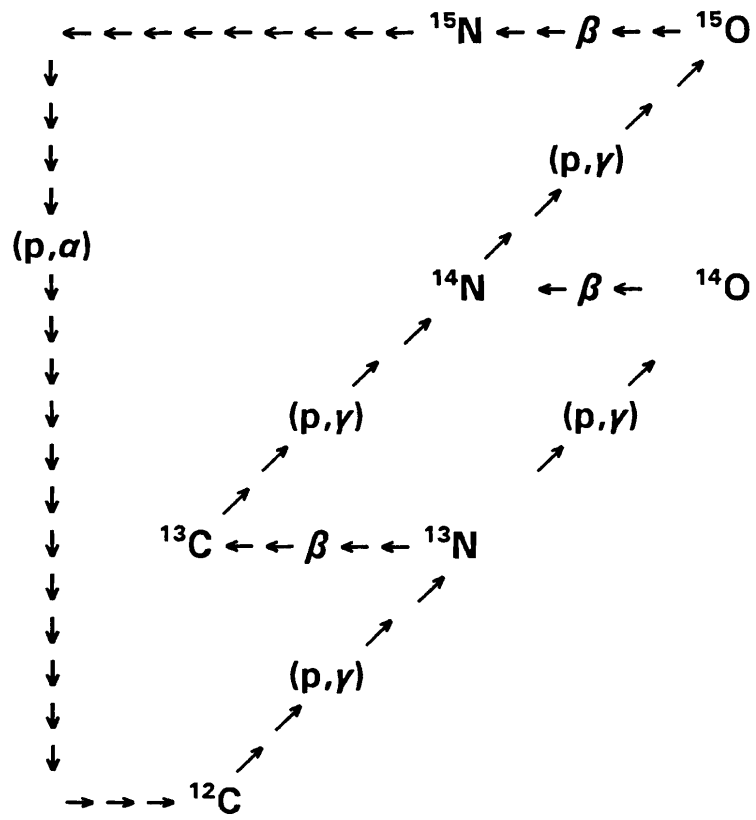

Figure 3. Network for the normal CNO cycle (densely spaced arrows) and additional pathway in the Hot CNO cycle (sparsely spaced arrows). The reactions or decays which occur along each path are as indicated.

This reaction rate is known to be dominated, at the temperature region of interest to the Hot CNO cycle, by a resonance associated with the 5.17 MeV level in ^{14}O; measurement of the parameters (partial widths) associated with this resonance is thus tantamount to measurement of the reaction rate. The crucial parameter is the partial width for decay of this resonance by γ-ray emission, Γ_γ. This parameter was measured recently by DeCrock et al.[25] by observing the γ-rays emitted from the interaction of a ^{13}N beam with an H target. This required a radioactive beam facility built in Belgium to do that experiment. It consists of an injector cyclotron, which produced a 30 MeV proton beam which bombards a ^{13}C target, where it produces ^{13}N via the $^{13}C(p,n)$ reaction. The ^{13}N is extracted from the ^{13}C target and sent to the ion source for a heavy ion accelerator, where the ^{13}N is accelerated to the energies of interest, several MeV per amu. This secondary beam is then directed to an H target, where γ-rays from the reaction of interest are observed. This experiment produced a value

for Γ_γ of 3.8 ± 1.2 eV.

However, Γ_γ was also measured by another technique[26], an indirect one involving "coulomb breakup." For such a measurement a beam of the final state nucleus, in this case ^{14}O, is produced. It bombards a heavy nucleus, e.g., Au or Pb, where it is coulomb excited to the states which serve as the compound nuclear states for the capture reaction on the target nucleus, ^{13}N in this case. The actual coulomb breakup is detected by coincidence detection of the break-up products, proton + ^{13}N in this case. This technique promises to provide much information in the future, as it will allow measurement via this inverse reaction approach of cross sections which would otherwise be impossible with present technology.

This approach was used to determine Γ_γ by two groups in the past two years. The first was Motobayashi et al.[27], who obtained a value for Γ_γ of 3.1 ± 0.6 eV, and the second was Kiener et al.[28], who obtained a value of 2.4 ± 0.9 eV. The fact that all three results agree is reassuring, but also provides a nice confirmation of the coulomb breakup approach to such measurements.

4. Studies of the rp-Process.

The rp-process[24] is really an extension of the basic features of the Hot CNO cycle to heavier nuclides, i.e., it requires a high temperature and an appreciable H abundance. Since this process occurs at a sufficiently high temperature that proton induced reactions proceed rapidly, and the process is thought only to last for a short time, it is thought that the path of the rp-process will pass through the nuclides which exist very near to the proton-drip line, or line of nuclei at which the limit to proton stability occurs. Since the proton capture reactions which drive the rp-process will proceed very rapidly at the high temperatures which characterize it, they are less important than the properties, e.g., lifetime and decay mode, of the nuclides which are involved. Thus measurements of such properties are what are needed, at least initially, to understand this process.

A section of the route of the rp-process is shown in Figure 5. There it can be seen that there are several places in the path of the rp-process which require β-decays, ^{62}Ge, ^{63}Ge, ^{65}As, ^{67}Se, ^{70}Kr, etc., for this process to proceed, simply because the nucleus which would be formed by another proton capture decays essentially instantaneously by proton emission. This rp-process path is as well known as it is because of recent work[29] done at Michigan State University, in which high energy heavy ions incident on target fragmented into many isotopes of each element, and the most proton rich nuclides with large enough halflives for them to be transmitted through the apparatus were then observed. Nuclei observed for the first time in this experiment are ^{61}Ga, $^{62,63}Ge$, ^{65}As, ^{69}Br, and ^{75}Sr.

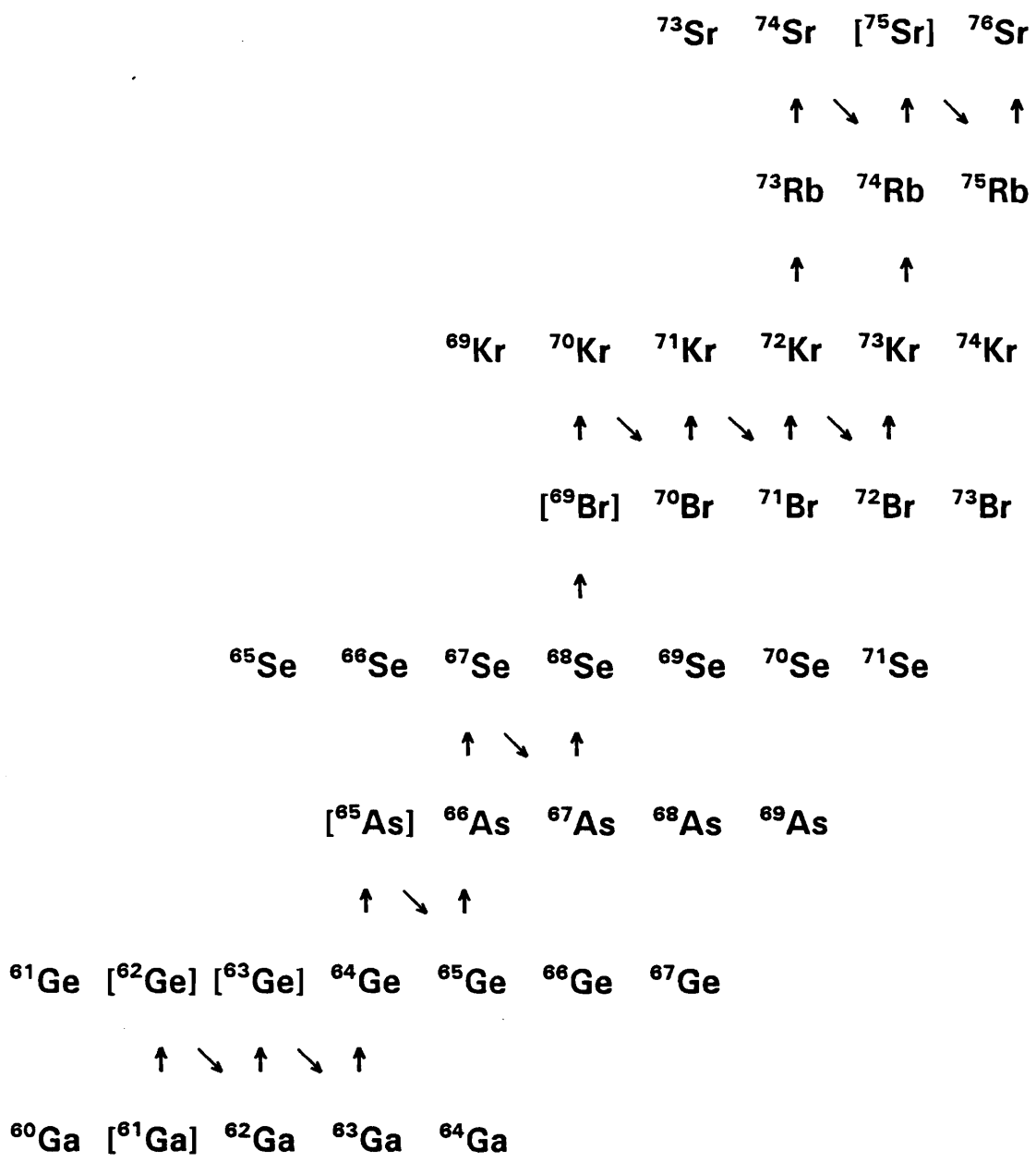

Figure 5. Proton rich nuclides existing over part of the path of the rp-process, indicated by the arrows. The nuclides recently discovered[29] by the MSU group are indicated in brackets. The upward arrows indicate proton radiative captures, while the diagonally downward lines indicate β^+-decays.

It should also be noted that a long-lived nucleus can stop the rp-process, since, if it is required to β-decay before the next proton radiative capture can occur, that decay may take longer than the tens of seconds the rp-process is thought to last. Such a case may be represented by ^{72}Kr. Because ^{73}Rb was not

observed in the MSU experiment (although other experiments claim to have seen it), it may be necessary for ^{72}Kr to β-decay to ^{72}Br before another proton can be captured to make ^{73}Kr and then ^{74}Rb. But ^{72}Kr has a halflife of 17 seconds, roughly the time the rp-process is thought to operate. This long a halflife would certainly inhibit synthesis of heavier nuclides in the rp-process.

5. The r-Process

At the other side of the nuclear valley of stability from the rp-process nuclides lie the neutron-rich nuclides. These are thought to be formed by neutron capture processes, either the s(low)-process[30] or the r(apid)-process[31]. Because neutron captures are not inhibited by the coulomb barrier, the temperature of the environment in which those captures occur has little effect on the thermonuclear reaction rates. But the temperature does affect the neutron density via its effect on the neutron producing reactions. The s-process is thought to occur during the helium burning phase of stellar evolution, at a temperature of about 150×10^6 K. Because it proceeds slowly (due to the low neutron density), it involves mostly stable or very long-lived nuclides. Since the subject of this paper is short-lived nuclides, this process will not be discussed further.

By contrast, the r-process is thought to occur at neutron densities 10 to 15 orders of magnitude higher than those thought to prevail during the s-process. Although the site of the r-process is not yet well established, there seems to be some agreement that only the conditions which prevail just after a supernova has exploded could produce the neutron densities necessary[32] to drive the r-process. The neutron captures which characterize it[31] are thought to occur rapidly until a "waiting point" nuclide is reached. Such points occur at neutron shell closures. Then a β-decay must occur before the next neutron capture reaction can occur. Since the abundances tend to build up at the nuclei with the largest halflives, the r-process abundances will favor the long-lived nuclei at the waiting points during the time, probably seconds, during which it occurs.

However, those progenitor nuclides are not the ones which will be observed, since they are many neutrons beyond the most neutron rich stable nuclei. They will, however, β-decay (possibly with concommitant neutron emission) to the neutron rich edge of the stable nuclides, thereby providing the r-process abundances. Examples of progenitors are thought to be ^{80}Zr (with a shell closure at 40 neutrons), which ultimately decays to ^{80}Kr, and ^{132}Sn (with a shell closure at 82 neutrons), which ultimately decays to ^{132}Xe.

However, the nuclides which have a shell closure at 126 neutrons are also of interest, as would also be subsequent shell closures as yet not unequivocally identified. Study of these, however, will present a challenge to experimentalists. Present designs for radioactive beam facilities[33] appear capable of producing beams of proton-rich nuclides out to the edge of stability to proton decay,

but the neutron-rich edge is considerably further from the valley of stability than is the proton edge. Thus considerable ingenuity will be required to produce all of the waiting point nuclides which might be involved in the r-process which produced the most massive nuclides.

6. Bound State β-Decay

One of the interesting curiosities to arise from nuclear physics is that of bound state β-decay[34], a process in which the electron emitted in the decay process does not go into the continuum, but rather goes into a bound orbital of the residual atom. Since this requires less energy than decay to the continuum (by the binding energy of the atomic orbital), nuclei for which the energetics do not allow them to undergo normal β-decay might be able to undergo bound state β-decay. And, since the lifetime for β-decay goes as the inverse of a high power of the energy of the emitted electron, bound state β-decay might, in cases where β-decay is possible but the lifetime is long, occur on much shorter time scales than would normal decay. Clearly the Pauli Principal inhibits bound state β-decay, though, completely preventing it for capture of the emitted electron into an inner shell of a neutral atom. However, if the atom is fully stripped, this decay process can readily occur. Although it has only been possible to study this process theoretically, a recently developed heavy ion storage ring at GSI Darmstadt can store fully stripped ions for long periods of time, making possible such experimental studies. Indeed, a preliminary study (although not one of bound state β-decay), in which the decay of ^{18}F (halflife = 110 minutes) was observed in an ^{18}F beam stored in the ring, has been performed[35].

This becomes of particular interest, however, in the context of nucleocosmochronology, the determination of the age of the universe using long lived radionuclides. A case in point is the Re-Os chronometer. General r- and s-process considerations[36] tell us how much Re relative to Os would have been expected to have been produced in the galaxy. Their decays, however, will have modified their relative abundances to the values we can now observe; the difference in abundance ratio thus tells us how long the nuclides have had to decay, and hence can give information about the age of the galaxy. This in turn gives a lower limit on the age of the universe. (The time required for galaxy formation has to be added on to determine the age of the universe.)

One problem with use of this chronometer, however, is that ^{187}Re can undergo bound state β-decay, which has been estimated[34] to result in a change in its terrestrial halflife of many orders of magnitude. Since some fraction of the ^{187}Re will exist for some its life in the hottest regions of stars, and those atoms will be highly ionized, this decay process is possible for those nuclides, and will have a large effect on the "halflife" one uses in the determinations of the age of the galaxy. Thus this effect must be taken into account, and the effect of

bound state β-decay must be determined.

It is anticipated[37] that experiments such as this one will be able to be performed in the near future with the GSI storage ring. That facility has the capability to store several beams at the same time, so one could store the ^{187}Re beam, then watch the buildup of the ^{187}Os decay product with time. This, together with an estimate of the fraction of the time ^{187}Re spends in a highly ionized state (near the cores of stars), would provide the required determination of the effect of bound state β-decay on the halflife of ^{187}Re, and hence provide a considerable improvement in accuracy in use of the Re-Os chronometer.

7. Conclusions

The field of research with radioactive beams has certainly come of age in the past few years, and its promise to astrophysics is now being realized. A number of interesting reaction studies have been completed, and many more will be forthcoming in the near future. These studies apply to primordial nucleosynthesis, stellar nucleosynthesis at extreme conditions, stellar processes involving synthesis of nuclides far from stability, and nucleocosmochronology.

8. Acknowledgement

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