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POSSIBILITY OF A CROSSED-BEAM EXPERIMENT INVOLVING SLOW-NEUTRON CAPTURE BY UNSTABLE NUCLEI — "RAPID-PROCESS-TRON"

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The possibility of a crossed beam facility of slow neutrons ⊗ unstable nuclei is examined in connection with the Japanese Hadron Project. With a pulsed proton beam of 50 Hz repetition with a 100 μA average beam current, one obtains a spallation neutron source of 2.4×10^8 thermal neutrons/cm^3/spill over a 60 cm length with a 3 msec average duration time by using a D_2O moderator. By confining radioactive nuclei of 10^9 ions in a beam circulation ring of 0.3 MHz revolution frequency, so that they pass through the neutron source, one obtains a collision luminosity of 3.9×10^{24}/cm^2/sec. A new research domain aimed at studying rapid processes in nuclear genetics at laboratory will be created.

1. INTRODUCTION

Nuclear syntheses in steller evolution undergo nuclear reactions involving unstable nuclei and, thus, are difficult to study at laboratories. Although new attempts to study (p,γ), (α, n) reactions, *etc.*, on unstable nuclei by using radioactive nuclear beams in inverse kinematics are in progress [1], studies of neutron capture reactions by unstable nuclei at the energy regions of astrophysical interest seem to be one step further away from reach, if not impossible, because such studies require two unstable particles (neutrons and unstable nuclei) to collide with each other.

In the present paper we examine the possibility of such an ideal experimental facility, in which a radioactive nuclear beam would cross thermal neutrons to induce neutron-capture reactions to a detectable amount. Although we are motivated by recognizing the extremely important role of neutron-capture reactions by unstable nuclei [2], the cross sections and their energy dependences are still totally unknown. The present study was triggered by surveying the possibilities of creating new ambitious experimental facilities based on the proposed Japanese Hadron Project, which will comprise KAON, MESON, NEUTRON and EXOTIC NUCLEI arenas for interdisciplinary science research based on a high-intensity 1-GeV proton linac and a compressor/stretcher ring [3]. A unique future possibility for the marriage of a neutron beam and a radioactive nuclear beam (RNB) arises here. The 1-GeV proton beam can produce thermal neutrons on one hand, and various accelerated radioactive beams on the other hand. How to merge these two sources and how to attain a high collision rate are discussed in the following sections.

2. NEUTRON SOURCE

For the present purpose we require the spallation neutrons to stay in a colliding region at high density for as long a time as possible. This requirement is different from the usual ones for pulsed neutron sources for condensed-matter studies, in which a short neutron spill is important for time-of-flight spectrometry. In the present case we employ a D_2O moderator which surrounds the production target. We have calculated the neutron density and its time distribution using the HETC-KFA-2 and MORSE codes developed at KFA [4] and ORNL [5], respectively.

The configuration of the production target and the moderator is shown in

Fig.1. The target is made of lead metal with a size of 16 cm diameter and 55 cm length. It is surrounded by a D_2O moderator which extends over a spherical volume of 100 cm radius. The result of a calculation is shown in Fig.2, where the time dependence of the thermal neutron density near the production target is presented. The curve consists of a short-lived component and a long-lived component with mean decay times of 0.96 and 3.7 msec, respectively. The density at t=0, $N_{n/n}(0)$, is $5.4\times10^{-6}/\text{cm}^3$ per produced fast neutron. The time distribution is approximated by

$$N_{n/n}(t) = N_{n/n}(0) \cdot g(t), \tag{1}$$

where

$$g(t) = a_1 \exp(-t/\tau_1) + a_2 \exp(-t/\tau_2). \tag{2}$$

Here, $a_1 = 0.74$, $a_2 = 0.26$, $\tau_1 = 0.96$ msec. and $\tau_2 = 3.7$ msec.

The time distribution plays an important role in increasing the collision rate, which is proportional to the decay time, as long as the circulating radioactive beam survives for a sufficiently long time. The time distribution is prolonged by using a D_2O moderator.

The number of fast neutrons per proton of 1 GeV energy, when hitting a large target of the present size, is about 20. Thus,

$$N_{n/\text{prtn}}(0) = 1.1 \times 10^{-4} \text{ /proton}. \tag{3}$$

Let us assume that we can use a pulsed beam of 50 Hz ($= f_{\text{pls}}$) repetition with 1.2×10^{13} protons/pulse (an average proton current of 100 μA); we then have

$$N_{n/\text{pulse}}(0) = 1.3 \times 10^9/\text{pulse}. \tag{4}$$

The spatial distribution of thermal neutrons, $N_{n/n}(x,t)$, also depends on time; they spread outwards as time passes. Simulated distributions at t = 0.25, 0.75, 1.5, 3.0, 5.6 and 8.8 msec are presented in Fig.3. Since the neutrons are distributed over a very large region, and we have no further way to confine them, we must make use of the entire high-density zone to collide them with a radioactive nuclear beam, as shown also in Fig.1. The total number of neutrons that collide with the RNB is given by

$$N_{tot}(t) = \int N_{n/n}(x,t)\mathrm{d}x, \tag{5}$$

which is time dependent. We can define the "effective length" by

$$d_{\mathrm{eff}}(t) = \frac{N_{tot}(t)}{N_{n/n}(0)}. \tag{6}$$

The effective length defined above is around 60 cm at $t = 0$, but decreases with time, but more slowly than does $g(t)$, as is shown in Fig.4. Its time distribution can be expressed by

$$d_{\mathrm{eff}}(t) = d_{\mathrm{eff}}(0) \cdot G(t). \tag{7}$$

The time integration of eq.(6) can be set to $d_{\mathrm{eff}}(0) \cdot \tau_{\mathrm{eff}}$, where τ_{eff} is called the effective neutron survival time. The numerical value of τ_{eff} is 3 msec. This picture is justified as long as the intensity of RNB remains constant.

3. CIRCULATING RADIOACTIVE NUCLEAR BEAM

Since RNB has no scattering effect through the neutron cloud, it can still be used for further collisions. We can thus use a circulating RNB to enhance the collision rate, since the neutrons stay for some msec, as shown in Fig.4. The enhancement factor on the luminosity by beam circulation is given by

$$\alpha = \sum_{n=1}^{\infty} G(n \cdot \Delta T) \simeq f \cdot \tau_{\mathrm{eff}}, \tag{8}$$

where f $(= 1/\Delta T)$ is the revolution frequency of the circulating beam and τ_{eff} is the effective neutron survival time (as defined above). Here, the lifetime of the circulating beam is assumed to be longer than the neutron surviving time. For f = 0.3 MHz the enhancement factor (α) amounts to 1000 or so.

The yield of unstable nuclei from spallation reactions depends on the species as well as the bombarding energy. An ion source using a thick target can typically provide unstable nuclei of the order of 10^9/sec or so. These ions are extracted from the ion source and accelerated by a front-end accelerator, such as an RFQ linac, to an energy of 1 MeV/u, and then injected into a ring.

Three different injection schemes are compared in the following. First, using a conventional method, *i.e.*, by the combination of multi-turn injection with RF stacking, the number of stored ions is estimated to be about 9×10^6, which is two orders of magnitude less than that required. Secondly, the charge-exchange injection of partially stripped ions using a gas stripper would provide only 10^4 ions in the ring, since the lifetime of the stored beam is so short due to collisions with the gas stripper.

We propose a third method which uses resonance ionization of the RNB at the injection section. A laser is used to remove one electron from the injected ion, but should not interfere the with stored ions. If the vacuum of the ring is in the 10^{-10} torr region, the beam lifetime due to electron stripping is estimated to be around

3×10^5 circulations. Although there is still a lot of work necessary to develop this scheme, this injection would enable us to store 10^9 ions in the ring.

4. LUMINOSITY

The luminosity of the present colliding section is given by

$$L = \alpha \cdot d_{\mathrm{eff}}(0) \cdot N_{\mathrm{RNB}} \cdot N_{\mathrm{n/pls}}(0) \cdot f_{\mathrm{pls}}. \tag{9}$$

The event rate is

$$R = \sigma \cdot L. \tag{10}$$

Using the values $\alpha = 1000, d_{\mathrm{eff}} = 60$ cm, $N_{\mathrm{RNB}} = 10^9$, $N_{\mathrm{n/pls}}(0) = 1.3 \times 10^9/\mathrm{cm}^3$, we obtain $L = 3.9 \times 10^{24}/\mathrm{cm}^2/\mathrm{sec}$.

The typical neutron capture cross section at a c.m. neutron energy of 30 keV is around 40 μb [6]. In such a case, the event rate to be expected from this luminosity is 1.2×10^{-5}/sec. Thus, events are rare; this number, however, is not astronomically too small. One can observe the neutron capture of unstable nuclei provided that such rare events are well isolated from the background.

5. IDENTIFICATION OF REACTION PRODUCTS

We now consider the detection of the rare product discussed in the previous section. Neutron capture causes the emission of capture gamma rays and mass increase in the capture product.

The detection of capture gamma rays is obviously difficult due to the existence of a huge gamma-ray background in the collision region. The capture product, itself, produced in the ring is a unique object to be detected.

As described before, the RNB is assumed to be stored in a beam-circulation ring with an energy of 1 MeV/amu. To obtain additional further details concerning neutron capture, we assume that 10^9 ions of $^{19}\mathrm{Ne}^{5+}$ are circulating in the ring. Due to electron cooling the RNB has a momentum resolution of 1×10^{-4}. In the center of mass frame the neutron kinetic energy (K_n) is given by

$$K_n = \frac{1}{2} M_n v_A^2 \left(\frac{M_A}{M_n + M_A}\right)^2, \tag{11}$$

where M_n and M_A are the atomic masses of the neutron and an unstable nucleus, respectively; v_A is the velocity of the unstable nucleus in the laboratory frame. Since M_A is normally much larger than M_n, which implies that the last factor is nearly unity, K_n is close to the energy per nucleon of the RNB. This result shows that in order to reproduce neutron capture phenomena at stellar temperatures of 10^8 to 10^{10} K, we need 10 keV to 1 MeV/u for the RNB.

When neutron capture takes place changes occcur in the velocity and charge state of the capture product. Upon neutron capture the velocity of the capture product suddenly changes by $M_A/(M_A + M_n)$ from the velocity of the RNB. In the case of $^{19}\mathrm{Ne}^{5+}$ this factor is 0.95. The momentum of the product, however, stays constant, and, thus, the product keeps the same orbit in the ring as long as the charge state remains unchanged.

A question concerning charge exchange of the product thus arises. Baur *et al.* [7] investigated the ionization probability of a target atom which is elastically scattered by a thermal neutron. The probability for the ionization of a K-shell electron of a carbon atom is predicted to be around 4×10^{-2}. It is interesting to note that there is no data at all concerning this process. For neutron capture at the present energy the ionization probability is reduced to 1×10^{-2}. The ionization probability for higher-shell electrons would be much higher than that for the K-shell, which has not yet been calculated. There is an additional contribution from the internal conversion process. Since a neutron capture accompanies emission of capture gamma rays, which are often followed by low-energy cascade gamma transitions, the internal conversion process of low-energy transitions is not negligible. The internal conversion produces a hole in an inner-shell orbit, which leads to the removal of an electron (or electrons) via the Auger process. This probability strongly depends on the specific structure of each nuclide.

Altogether, these two processes contribute to a change in the charge state of the neutron capture product. For the case of ^{80}Br it has been reported that the mean value for charge variation is $+0.5e$ [8]. It seems quite natural to assume from the above discussions that a non-negligible fraction of the products change their charge state. The detection of the fraction with charge exchange, i.e., $^{20}\mathrm{Ne}^{6+,7+\cdots}$, would be done in such a way that the charge state of the products would be analysed by a downstream dipole magnet.

The detection of another fraction without any charge exchange, i.e., $^{20}\mathrm{Ne}^{5+}$, will be achieved using a Wien filter in the ring. The velocity change mentioned above is reasonably large so as to give sufficient separation by the Wien filter. The Wien filter should not interfere the injection or accumulation of the beam; another filter is thus also placed in the ring in order to cancel the velocity dispersion totally.

There will be another way to detect the capture product of the same charge without having to use a Wien filter. After keeping the product in the ring for a sufficient time, electron cooling exerts a force on the product, so that its velocity becomes the same as that of the beam itself. In this case the magnetic rigidity of the product changes by a factor $(M_A + M_n)/M_A$, allowing us to separate the product at a highly dispersive section in the ring. The advantage of the charge-separation and the Wien filter methods, however, is that the time-differential signal for the products will also bear accurate background information, since the neutron target exists in a pulse structure.

6. CONCLUDING REMARKS

High-energy proton beams may provide a new tool for experiments of nuclear syntheses. The spallation reactions by a 1-GeV proton beam using a thick target generate two kinds of unstable beams, *i.e.*, neutrons and unstable nuclei. In this report we have proposed a crossed beam facility for colliding these two beams, with which we can step into so-far unexplored areas of nuclear syntheses. The E arena at JHP would be quite a unique place where we could promote the realization of such a new tool.

Acknowledgement

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References

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Figure Captions

Fig.1 Schematic layout of the neutron source with a spallation target and a D_2O moderator.

Fig.2 Calculated time distribution of thermal neutrons near the production target.

Fig.3 Calculated spatial distribution of thermal neutrons at various times.

Fig.4 Schematic layout of a RNB neutron cross beam facility.
Proton beams of 1 GeV produce unstable nuclear atoms in a thick target as well as fast neutrons in a lead beam stopper. The unstable nuclear atoms are ionized and accelerated by a heavy-ion linac, and are then injected into a storage ring by ionization using a laser. Fast neutrons and secondary neutrons from the beam stopper are thermalized in D_2O, and are then used as a "neutron target" to collide with the unstable nuclear beam. Neutron capture products are detected by Detector 1 and 2, depending on the product charge states.

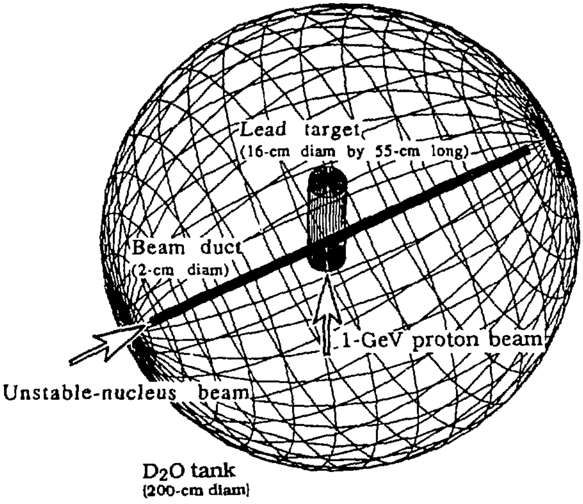
Lead target
(16-cm diam by 55-cm long)
Beam duct
(2-cm diam)
1-GeV proton beam
Unstable-nucleus beam
D_2O tank
(200-cm diam)

Fig. 1

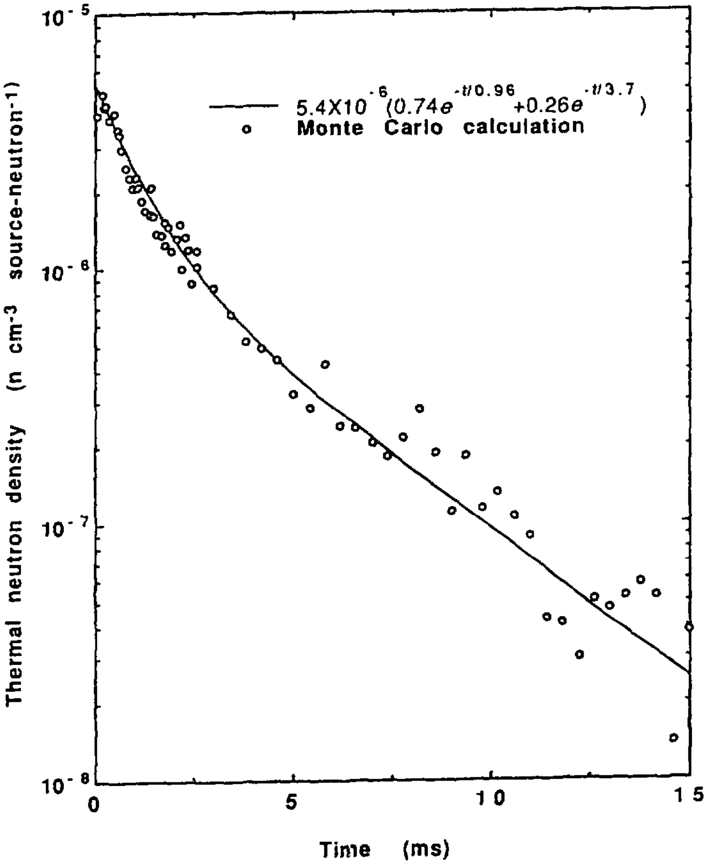
5.4X10^{-6}(0.74$e^{-t/0.96}$+0.26$e^{-t/3.7}$)
Monte Carlo calculation
Thermal neutron density (n cm^{-3} source-neutron^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
5
10
15
Time (ms)

Fig. 2

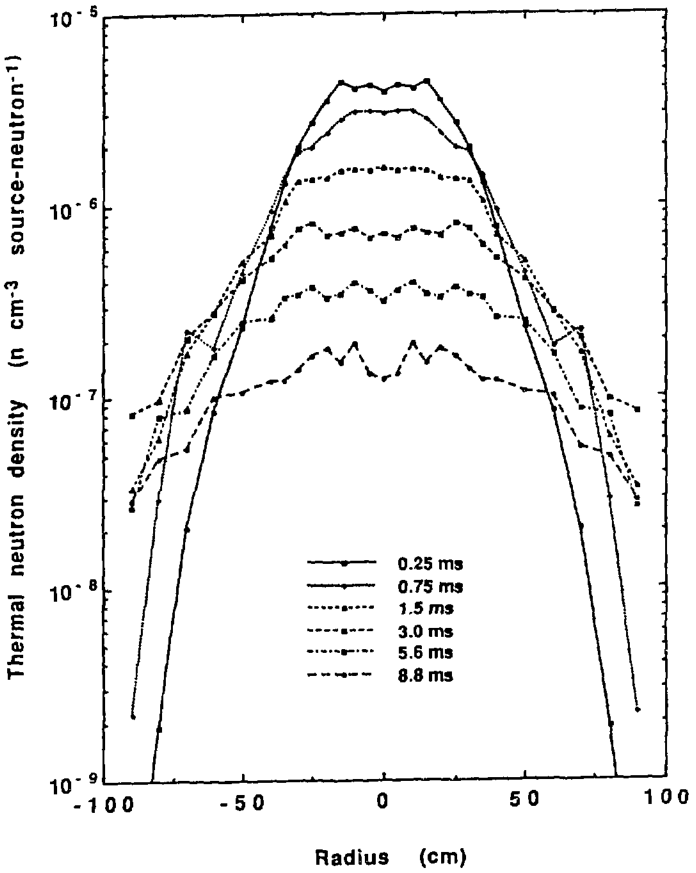
Thermal neutron density (n cm^{-3} source-neutron^{-1})
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
-100
-50
0
50
100
Radius (cm)
0.25 ms
0.75 ms
1.5 ms
3.0 ms
5.6 ms
8.8 ms

Fig. 3

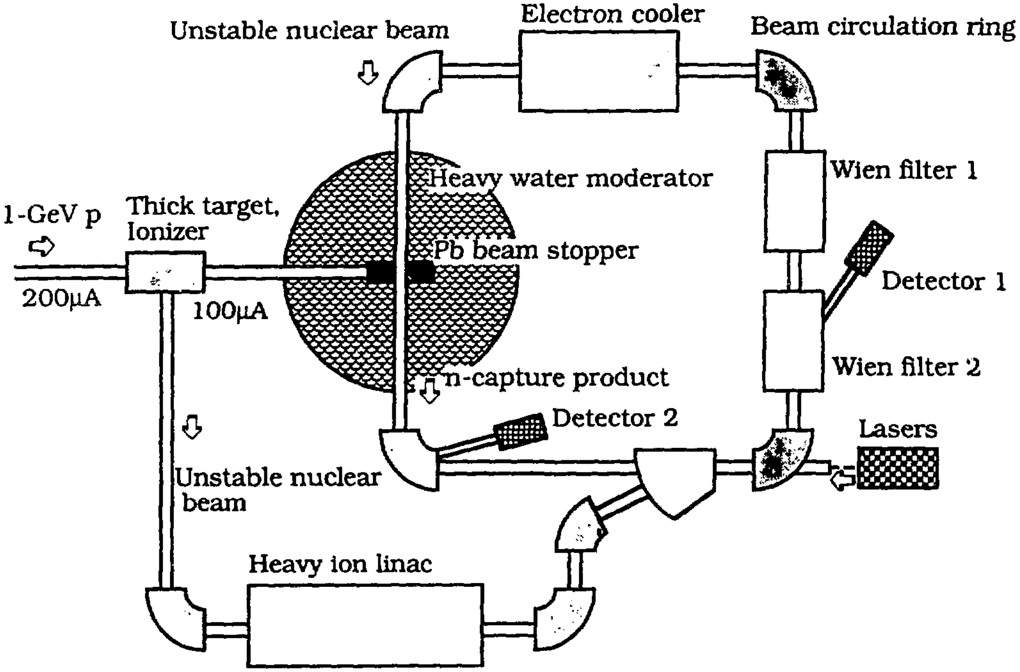
Unstable nuclear beam
Electron cooler
Beam circulation ring
Heavy water moderator
Wien filter 1
1-GeV p
Thick target,
Ionizer
Pb beam stopper
Detector 1
200μA
100μA
Wien filter 2
n-capture product
Detector 2
Lasers
Unstable nuclear
beam
Heavy ion linac

Fig. 4