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NUCLEAR ASTROPHYSICS FROM NEUTRON CROSS-SECTION MEASUREMENTS ON RADIOACTIVE SAMPLES

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ABSTRACT

Reaction rates for both big-bang and stellar nucleosynthesis calculations can be obtained from the measurement of (n,p) (n,α) and (n,γ) cross sections for radioactive nuclei. In the past, large backgrounds associated with the sample activity limited these types of measurements to radioisotopes with very long half lives. The advent of the high-intensity neutron source at the Los Alamos Neutron Scattering CEnter (LANSCE) has greatly increased the number of nuclei which can be studied. Results of recent measurements on samples with half lives as short as fifty-three days are given. Plans for future measurements are discussed.

1. INTRODUCTION

Many cross sections of importance to both big-bang and stellar nucleosynthesis calculations have been measured in the laboratory. These cross sections have been converted into reaction rates and then integrated into the reaction networks used in the calculations and have improved the general understanding of several types of nucleosynthesis events. At present, the rates for several important reactions have not been measured, necessitating the use of theoretical estimates[1]. This may lead to large uncertainties in the results of nucleosynthesis calculations. Many of the unmeasured rates involve neutron-induced reactions on radioactive nuclei. Previous measurements[2-4] of this type have been limited to nuclei with very long half lives due to potentially large backgrounds associated with the sample activity. The advent of the pulsed spallation neutron source at LANSCE[5] has opened up the possibility of making cross-section measurements for neutron-induced reactions on nuclei with short half lives. In this paper, we will give some examples of recent measurements of this type and briefly discuss the nuclear astrophysics to be learned. We will then discuss our plans for additional measurements, briefly outlining the techniques involved and the nuclear astrophysics we hope to learn. We expect that these measurements will greatly aid in the understanding of the astrophysical environments in which nucleosynthesis occurs.

2. EXPERIMENTAL TECHNIQUE

The experimental technique[6] for these measurements requires a large peak neutron intensity and a properly designed detector so that the detected rate for the reaction of interest is larger than the background rate associated with the decay of the sample under study. For our experiments, LANSCE provides the high peak neutron intensity. At design intensity (100 μA, at 12 Hz), the water moderated neutron intensity at 1 eV for our flight path of 7 m is 4×10^6 neutrons/(eV cm^2 sec), and the neutron spectrum of this "white" source is approximately proportional to $1/E_n$. This high neutron intensity allows measurements to be made with sample sizes in the approximately 100 ng to a few hundred μg range. The small sample size means that the necessary radioactive samples are easier to produce and that only relatively modest activities must be handled. Even these small samples can still present some rather large background problems, but a properly designed detector can reduce the sample-related backgrounds to acceptable levels. Because the requirements for the detectors differ, we will discuss (n,p) and (n,γ) measurements separately below.

2.1 A^*(n,p) and A^*(n,α) Measurements

For A^*(n,p) and A^*(n,α) measurements, where A^* is a radioactive nucleus, the sample-related backgrounds can be reduced to manageable levels by choosing a charged-particle detector of minimal thickness. The detection efficiency for radioactive decay emissions from the sample can thus be reduced to order 10^{-6} of the proton detection efficiency. For all of our measurements so far, we have detected the charged particles with silicon surface-barrier detectors. More details of the apparatus are given in ref. 6. Because very few nuclei emit charged particles under bombardment by slow neutrons, the sample can be of relatively low specific activity, and can even be a chemical compound. To demonstrate the quality of the measurements possible, pulse-height spectra from our ^{22}Na(n.p)^{22}Ne and ^{22}Na(n,α)^{19}F measurements[7] are shown in fig. 1. These measurements were made with a sample containing 75 ng of ^{22}Na. To our knowledge, these were the first measurements of the relatively small ^{22}Na(n,α)^{19}F cross sections at any energy.

2.2 A^*(n,γ) Measurements

A^*(n,γ) measurements require a separated isotope on a low mass backing as a sample because many nuclei have sizable (n,γ) cross sections at low neutron energy. This requirement should not be too difficult to meet for the very small samples sizes required. Another problem is that pileup of the low-energy decay γ-rays from the radioactive sample can result in a signal the same size as that from a neutron-capture event. To overcome this potentially large background one can make use of the fact that the γ-ray decay energy, E_d, is almost always much lower in energy than the total energy, E_c, of the neutron capture cascade. Hence, a detector which registers all of the energy from the capture cascade, and which has a very short output pulse width ,τ, can effectively overcome this background. Of course, the size of this background is a very strong function of the ratio, E_d/E_c, and of τ, and one can always think of very difficult cases for which measurements are still not possible. Our calculations[8] indicate that measurements on many interesting samples with half lives as short as a few months can be made.

We feel that the relatively new scintillator barium fluoride (BaF_2) is the best choice as a detector for these measurements. Monte Carlo calculations we have made using the computer code CYLTRAN[9] indicate that a thickness of roughly 15 cm of BaF_2 is adequate to make an approximately 100% efficient detector in essential agreement with the calculations of Wisshak *et al.*[10] In our application, the small sample size allows us to have a very small neutron beam (0.5 cm diameter). Hence, a 30 cm cube of BaF_2 with a 4 cm beam hole is sufficient to make a detector which is approximately 100% efficient. The fast component of BaF_2 ($\tau \approx 20$ ns for 15 cm crystals)[11] provides for effective pileup rejection. We are currently constructing such a detector composed of eight 15 cm cubes. More details can be found in refs. 8 and 12. At present, two of the eight 15 cm cubes have been delivered and preliminary tests reveal them to be of good quality. The remaining crystals are scheduled to be delivered by November 1988.

3. NUCLEAR ASTROPHYSICS FROM A^* + n MEASUREMENTS

Many of the as yet unmeasured cross sections of importance to nuclear astrophysics involve neutron-induced reactions on radioactive nuclei[13,14]. At Los

Alamos, the very high peak intensity of the LANSCE white neutron source can be combined with laboratory facilities[15] for the production and separation of radioactive samples to open up new opportunities for nuclear astrophysics studies on unstable nuclei. For example, establishing a program to systematically measure the (n,γ) cross sections for radioactive branching points on the s-process nucleosynthesis path would help to finally reveal the physical conditions during stellar helium burning[16]. In addition, using these data to refine analyses will provide information on the dynamical aspects of the s-process, a problem where present stellar models fail to reproduce the observed isotopic abundances[17]. Also, measurements of (n,p) and (n,α) cross sections for unstable nuclei will help reveal the conditions prevailing during explosive nucleosynthesis[18] and perhaps also during the s-process[19]. This should aid in the explanation of the origin of radioisotopes observed by γ-ray telescopes[20], of the various isotopic anomalies observed in meteorites[21], and of the production of several very rare stable isotopes[13]. Finally, measurements from this program will aid in the interpretation of several cosmochronometers, which will be useful in refining current estimates of the age of the universe.

A first example of an important A^*+n reaction rate is $^7Be(n,p)^7Li$. This reaction is important to the primordial nucleosynthesis[22-24] of ^7Li. Our recent measurements[6], which were made with a 90 ng sample of ^7Be, have substantially reduced (by a factor of almost ten at thermal energy) the uncertainty in the reaction rate. Furthermore, the rate based on our data is only 60% to 80% of the old rate[25] in the temperature range of interest in big-bang calculations. This difference can lead to as much as a 20% increase in the amount of ^7Li calculated to be produced in the big bang[6].

Our $^{22}Na(n,p)^{22}Ne$ measurements[7] are a second example of a reaction involving a radioactive target which can be important in nucleosynthesis calculations. This reaction may play a role in the nucleosynthesis of ^{22}Na and/or ^{22}Ne in explosive environments. An understanding of the nucleosynthesis of these isotopes is important because the origin of the Neon-E anomaly in meteorites[21] is not well understood, and because ^{22}Na has been suggested as a candidate for observation by γ-ray telescopes[26]. The astrophysical reaction rate calculated from our data is compared to the theoretical rate[1] in fig. 2. The theoretical rate is about a factor of ten lower than the experimentally determined one at very low temperatures. However, due to a resonance at E_n=170 eV, the two rates cross at 0.05 GK, and the theoretical rate is about a factor of six low at the highest temperatures measured. If this difference between the experimental and theoretical rates persists to higher temperatures, it may result in a significant increase in the calculated production of ^{22}Na in explosive environments.

Our $^{36}Cl(n,p)^{36}S$ data are a third example of how our measurements can contribute to nuclear astrophysics. These measurements were made with 410 μg of ^{36}Cl. Because the half life for this sample is very long, a high peak neutron intensity is not essential to the measurements, but the relatively high average neutron intensity available from LANSCE is still important to measuring this comparatively small cross section within a reasonable time. Our preliminary data for energies greater than 700 eV are displayed in fig. 3. Because we have yet to complete our measurement of the thermal cross section, we display yields rather than cross sections. The data reveal several resonances for energies greater than 800 eV. This reaction is denoted by an asterisk in Howard *et al.*[13], a mark which they reserve for rates important to the nucleosynthesis of rare stable nuclei (^{36}S in this case) in explosive carbon burning. Alternatively, Beer and Penzhorn[19] calculate that most or all of the ^{36}S may have been produced in the s process, in which case the $^{36}Cl(n,p)^{36}S$ reaction is also important. It remains to be seen how our measurements will affect the results of future nucleosynthesis calculations.

As a final example, our very recent (n,p) measurements on the stable sample ^{14}N indicate that this cross section has very close to a 1/v shape from thermal energy to approximately 30 keV. The reaction rate[27] based upon an interpolation between direct measurements at thermal energy[28] and for E_n>150 keV (ref. 29), and upon measurements made using the inverse reaction[30] for E_n>29 keV, is in fairly good agreement with our data. These results are in disagreement with a recent direct measurement[31] which is a factor of 2 to 3 lower than the rate[27] based on the previous measurements. With the larger reaction rate indicated by our data and previous data[28-30], it appears that, in contrast to the claim in ref. 31, ^{14}N acts as an effective neutron poison in many scenarios in which the $^{13}C(\alpha,n)^{16}O$ reaction might otherwise be a viable s-process neutron source.

4. FUTURE PLANS

There are a few more (n,p) and (n,α) cross sections of interest to nuclear astrophysics which should be measurable at LANSCE. Potential samples include both the stable nuclei ^{25}Mg, ^{33}S, and ^{35}Cl, and the radioactive samples ^{37}Ar and ^{41}Ca. These measurements could have a significant impact on our understanding of nucleosynthesis both in explosive environments and during the s process. For example, the $^{22}Ne(\alpha,n)^{25}Mg$ reaction is often cited as the best candidate for the neutron source during the s process. However, there have been no measurements of this cross section low enough in energy to correspond to the s-process temperature. Furthermore, it is unlikely that direct measurements will ever be made at the very low s-process temperature and hence an extrapolation from higher energy measurements will be necessary. This problem could be circumvented by measuring the cross section for the inverse, $^{25}Mg(n,\alpha)^{22}Ne$ reaction, and then using detailed balance to convert to the desired cross section. Such a measurement should be feasible at LANSCE, although it may require the development of a new detector which allows for a larger sample and solid angle (e.g. an ionization chamber) than our present apparatus, because this cross section is predicted to be very small.

Potentially, the largest number of future measurements to be made are of $A^{*}(n,\gamma)$ cross sections which are mainly of interest for a better understanding of the dynamics of s-process nucleosynthesis. Our planned measurements on radioactive samples, coupled with the anticipated very precise measurements on stable isotopes[32], and new calculational approaches[17] should lead to a much better understanding of the s-process, including its dynamics.

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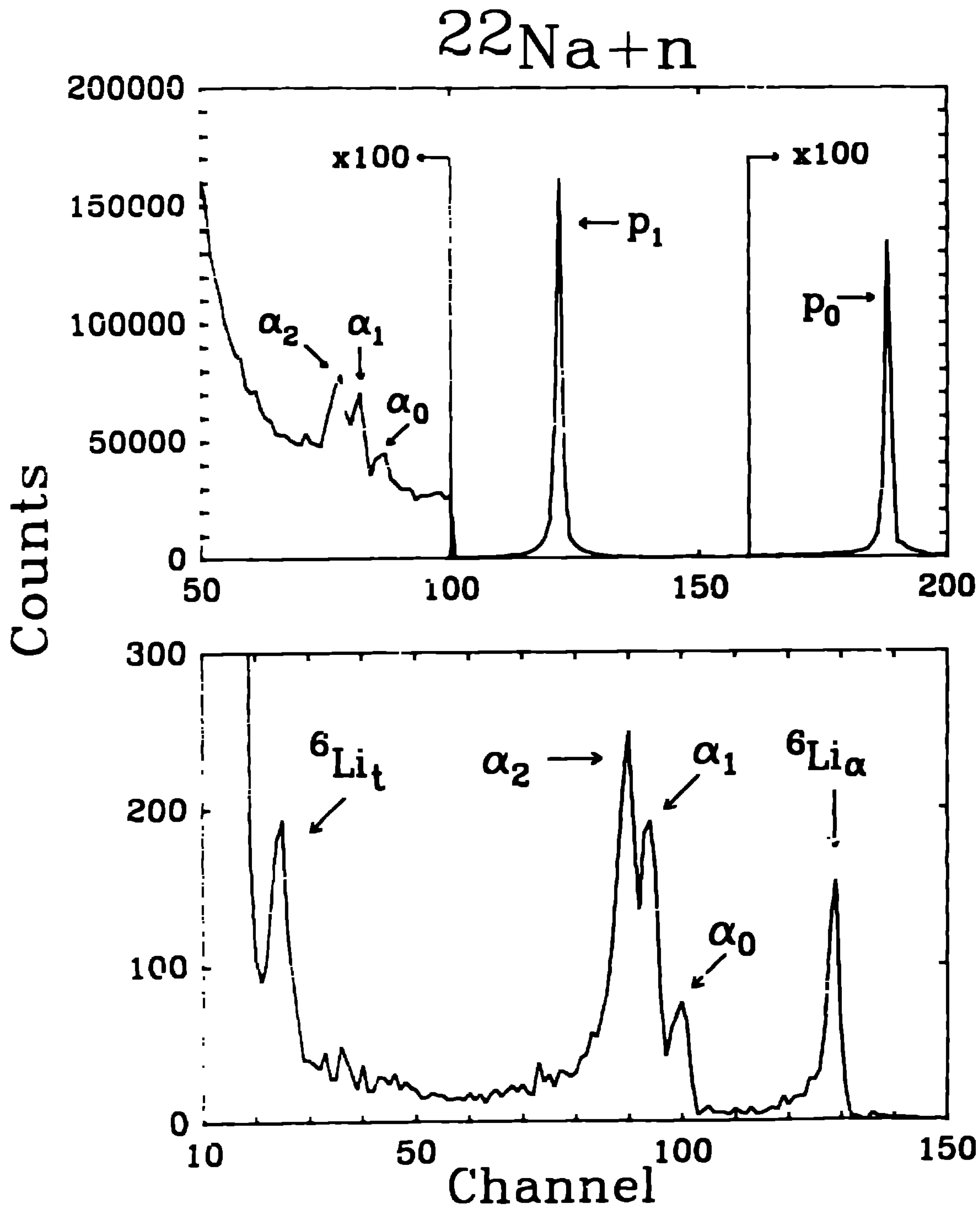
FIGURE CAPTIONS

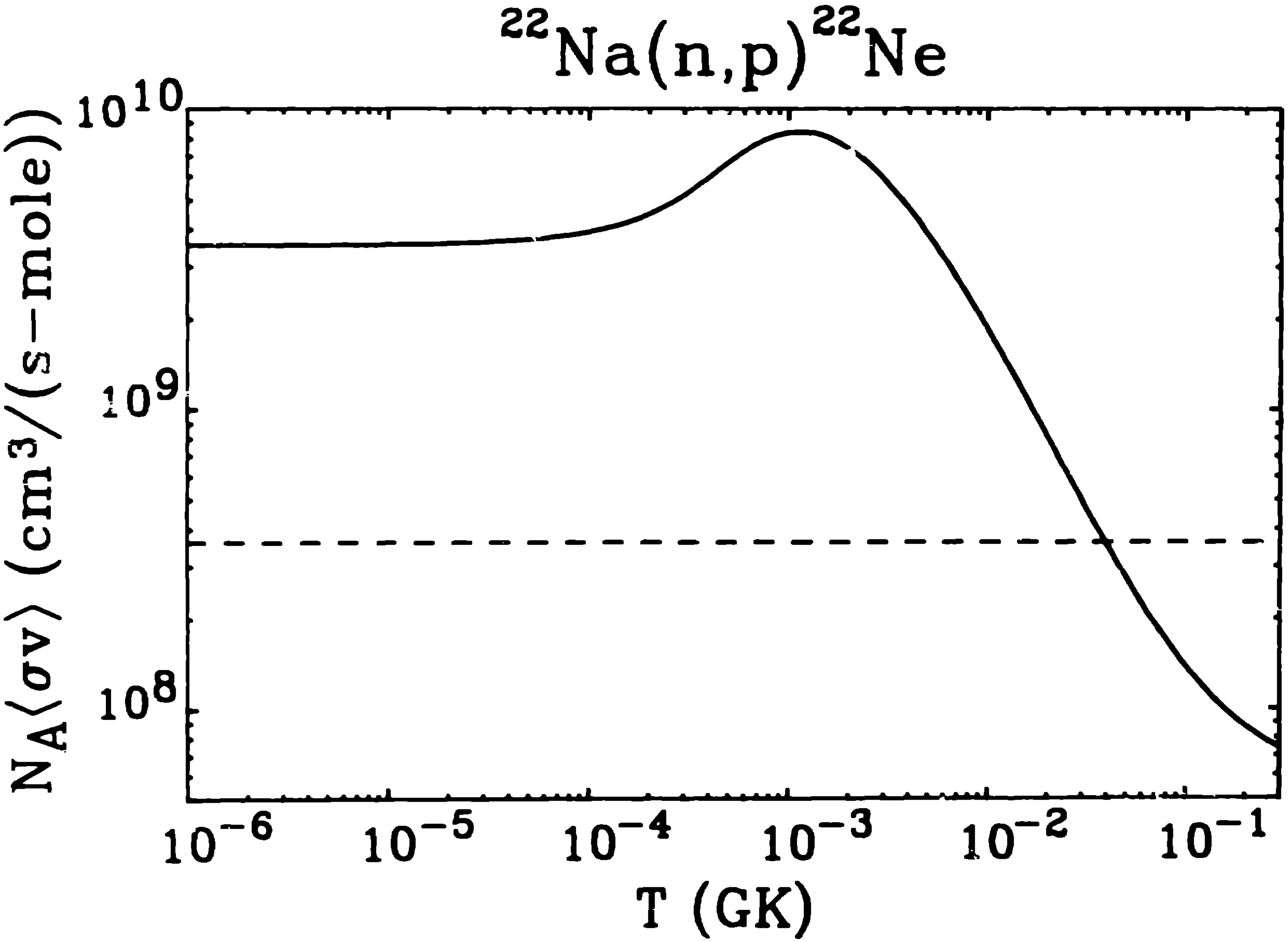
Fig. 1. Pulse-height spectra at thermal neutron energy from our ^{22}Na+n measurements (ref. 7). The peaks are labeled according to the outgoing particle. The upper spectrum was taken with a detector which was 150 μm thick by 25 mm^2 in area. The lower spectrum was taken with a detector of 10 μm thickness by 50 mm^2 in area.

Fig. 2. The $^{22}Na(n,p)^{22}Ne$ reactivity verses temperature. The solid curve is the rate calculated from our measurements (ref. 7), while the dashed curve is the theoretical rate of ref. 1.

Fig. 3. Preliminary yield verses neutron energy from our $^{36}Cl(n,p)^{36}S$ measurements. The yield has not been corrected for the variation with energy of the neutron flux.

Figure 1. Koehler and O'Brien





$^{22}Na(n,p)^{22}Ne$
10^{10}
10^{9}
10^{8}
$N_A\langle\sigma v\rangle$ $(cm^3/(s-mole))$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
T (GK)

Figure 5. Koehler and O'Brien