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RECENT RESULTS IN EXPLOSIVE AND S-PROCESS NUCLEOSYNTHESIS FROM MEASUREMENTS ON RADIOACTIVE AND STABLE TARGETS

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ABSTRACT

Measurements of (n,p) and (n,α) cross sections are crucial for a better understanding of many scenarios of nucleosynthesis. Current problems in which such reactions play a role include the possible synthesis of heavy elements during the big bang, the production of several rare isotopes in explosive nucleosynthesis, and a better understanding of the role of the s process in the synthesis of light and intermediate mass nuclei. We have recently completed measurements of several (n,p) and (n,α) cross sections of importance to nuclear astrophysics. The cross sections were measured in the range from thermal energy to approximately 1 MeV by using the white neutron source at the Manuel Lujan, Jr. Neutron Scattering Center (LANSCE) in Los Alamos. We have also made complementary measurements at the Karlsruhe Van de Graaff and at the Oak Ridge Electron Linear Accelerator (ORELA). We discuss the impact of the results on nuclear astrophysics as well as recent improvements and future plans.

1. Introduction

Measurements of (n,p) and (n,α) cross sections are crucial for a better understanding of many scenarios of nucleosynthesis. Problems of current interest in which such reactions play a roll include the possible synthesis of heavy elements during the big bang[1], the production of rare stable isotopes in explosive nucleosynthesis[2], and the role of the s process in the synthesis of light and intermediate mass nuclei[3].

2. Examples

Recent examples of measurements of interest to nuclear astrophysics which were made at LANSCE and at Karlsruhe will be described below. The discussion will be divided into subsections dealing with different scenarios of nucleosynthesis.

2.1 *Big Bang Nucleosynthesis*

Recently there has been much interest in the possibility of synthesizing heavy elements in so-called nonstandard models of the big bang. Whereas nucleosynthesis in standard big-bang models effectively stops at A=7, it has been speculated that the large density inhomogeneities possible in nonstandard models may lead to the synthesis of elements with mass A>12. Network calculations indicate that most of the flow towards heavier elements proceeds mainly through a series of neutron captures[1] until ^{17}O is reached. Using previously known resonance parameters and thermal cross sections it was anticipated[4] that the (n,α) reaction on ^{17}O would dominate over (n,γ). As a result, much

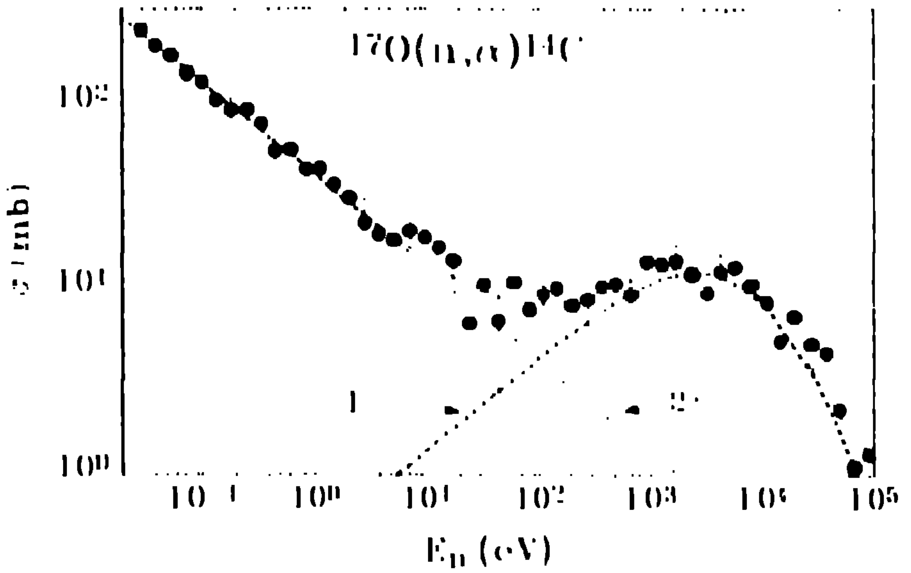

FIG. 1. The ^{17}O(n,α)^{14}C cross section from 0.025 eV to 100 keV. The solid circles are our LANSCE data[4]. The solid curve is a two level fit to the data. The dotted and dashed curves are the separate contributions to this fit from 2^+ and 1^- resonances respectively.

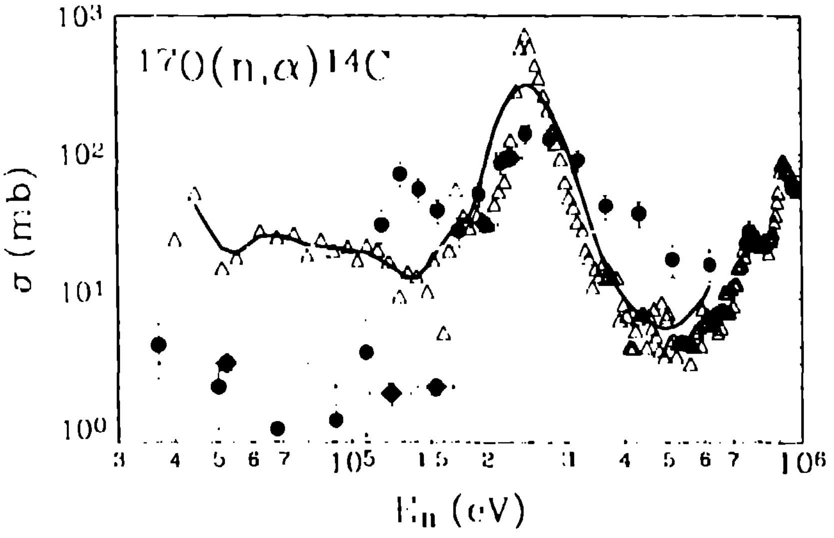

FIG. 2. The $^{17}O(n,\alpha)^{14}C$ cross section from 100 keV to 1 MeV. The solid circles are the data from our LANSCE measurements[4]. The solid diamonds are our data from the measurements at the Karlsruhe Van de Graaff[5]. The open triangles are the inverse data of Sanders[6] which we converted using detailed balance. The solid curve resulted from averaging the data of Sanders over the energy spread of our measurements.

of the nucleosynthesis flow would cycle back to ^{14}C. The severity of cycling was uncertain because no direct measurements of the cross section had been made and because the resonance parameters were not well known. In principal, the $^{17}O(n,\alpha)^{14}C$ cross section could be determined from published measurements[6] of the inverse reaction. Below an energy of a few hundred keV, however, the rapid decrease of the $^{14}C(\alpha,n)^{17}O$ cross section, together with background from the $^{13}C(\alpha,n)^{16}O$ reaction makes these measurements very difficult; hence, a direct measurement of the $^{17}O(n,\alpha)^{14}C$ cross section in this region was desirable.

The results of our recent direct measurement of the $^{17}O(n,\alpha)^{14}C$ cross section at LANSCE[4] are shown in Figs. 1 and 2. Because of the large resonances in this reaction we were able to extend these measurements to almost 1 MeV. Figs. 1 and 2 illustrate several interesting points which are discussed in more detail in Ref. 4. First, the bump in the cross section near 3 keV, which is due to a sub threshold p wave (1) level, leads to about a factor of 10 increase in the astrophysical reaction rate below about 0.2 GK. Second, our results are in fair agreement with the inverse measurements of Sanders[6] except below about 100 keV where the data of Sanders are significantly above ours (This is most likely due to background from the $^{13}C(\alpha,n)^{16}O$ reaction in the inverse measurements of Sanders.), and near 130 keV where we observed a peak which does not correspond to any known resonance in ^{18}O. Because the reaction rate estimated from the previous resonance parameters is in reasonably good agreement with the rate calculated from our data (except for the effect due to the sub-threshold 1^- resonance as discussed above), and because the gamma widths are known[7], the ratio of the (n,α) to (n,γ) rates calculated from the resonance parameters should be fairly reliable at big bang temperatures. The result[4] is that the (n,α) to (n,γ) ratio is approximately 10^4 at big bang temperatures. Hence, cycling between ^{17}O and ^{14}C is expected to be a serious restriction in the path to heavy element synthesis in nonstandard big bang models.

Our LANSCE measurements[4] were made with a single solid state detector subtending a range of angles near 90 degrees. The data were converted from yields to cross sections assuming an isotropic angular distribution. Because the cross section above a few keV is dominated by non-s-wave resonances, this assumption is probably not valid and leads to an unknown systematic uncertainty in the results. Also, the peak we observed near 130 keV does not correspond to any known resonance in ^{18}O. For these reasons we undertook a measurement of this cross section in the energy range from 10 to 250 keV at the Karlsruhe Van de Graaff[5]. Because the Karlsruhe measurements employed an ionization chamber it was possible to cover close to the full 4π solid angle while at the same time measuring the forward-to-backward asymmetry in the emitted alpha particles. The results of these measurements are shown in Fig. 2. The Karlsruhe results are in general in agreement with the LANSCE data except that no peak was observed near 130 keV. The observation of this peak in the LANSCE experiment hence remains a mystery. The Karlsruhe results yield a reaction rate within a factor of two of the LANSCE results despite the large differences in the data near 130 keV. Hence, the conclusion that the ^{17}O(n,α)^{14}C reaction strongly dominates over ^{17}O(n,γ)^{18}O at big bang temperature is unchanged.

2.2 *Explosive Nucleosynthesis*

It has been speculated that rare isotopes are valuable diagnostics that will lead to a better understanding of the properties of the astrophysical environment in which they were produced. Most of the rare isotopes are thought to originate in explosive environments[2]. However, the parameters of explosive nucleosynthesis calculations remain fairly uncertain and new processes are invented occasionally as our knowledge evolves. So it remains important to measure cross sections affecting the production and destruction of these rare nuclei.

One persistent problem with most explosive nucleosynthesis calculations is that the isotope ^{36}S is extremely overproduced relative to the other rare nuclei which are synthesized. The ^{35,36}Cl(n,p)^{35,36}S reactions form a part of the nucleosynthesis network describing the production of ^{36}S. Recently, we have made the first measurements of these cross sections at astrophysically relevant temperatures. Our data[8] show that the ^{35}Cl(n,p)^{35}S reaction probably does not play a significant role in the nucleosynthesis of ^{36}S. A part of our data[9] for the ^{36}Cl(n,p)^{36}S reaction is shown in Fig. 4. The reaction rate calculated from our data is approximately a factor of 2 smaller at astrophysically relevant temperatures than the theoretical rate[10] used in previous nucleosynthesis calculations. The lower rate indicated by our measurements could help to reduce the overproduction of ^{36}S seen in the calculations.

Understanding the origin of ^{26}Al is important because it is one of the very few radioactive products of stellar nucleosynthesis to be observed directly by γ-ray telescopes[11]. ^{26}Al has also been observed indirectly as a ^{26}Mg anomaly in some meteorites[12]. Several scenarios have been proposed for the production of ^{26}Al and most fall into the explosive nucleosynthesis category. The ^{26}Al(n,p)^{26}Mg and ^{26}Al(n,α)^{23}Na reactions are thought to be the major means for the destruction of ^{26}Al in some astrophysical environments, so a knowledge of the cross sections for these reactions is important for a better understanding of the origin of ^{26}Al.

We have measured the ^{26}Al(n,p_1)^{26}Mg and ^{26}Al(n,α_0)^{23}Na cross sections from thermal energy to 50 keV and 6 keV respectively[13]. Most of this energy range has not been explored by previous measurements. We normalized our data to the thermal energy measurement of Trautvetter *et al.*[14] for the (n,p_1) reaction. With this normalization, our data for the (n,α_0) cross section are in good agreement with the inverse measurements of Skelton *et al.*[15]. Our results for the (n,p_1) cross section are shown in Fig. 5. The astrophysical reaction rate calculated from our results is approximately a factor of two larger than the results of Trautvetter *et al.* at astrophysically relevant temperatures. The source of the difference between our results and those of Trautvetter *et al.* is unknown although a similar difference was seen for the ^{14}N(n,p)^{14}C reaction[16]. Our results confirm the speculation of Skelton *et al.* that the (n,α_0) channel is as important as the (n,p_1) channel for the destruction of ^{26}Al in explosive environments. Our results also fill in the gap in the data for the (n,p_1) reaction rate at low temperatures characteristic of the red giant phase in stars.

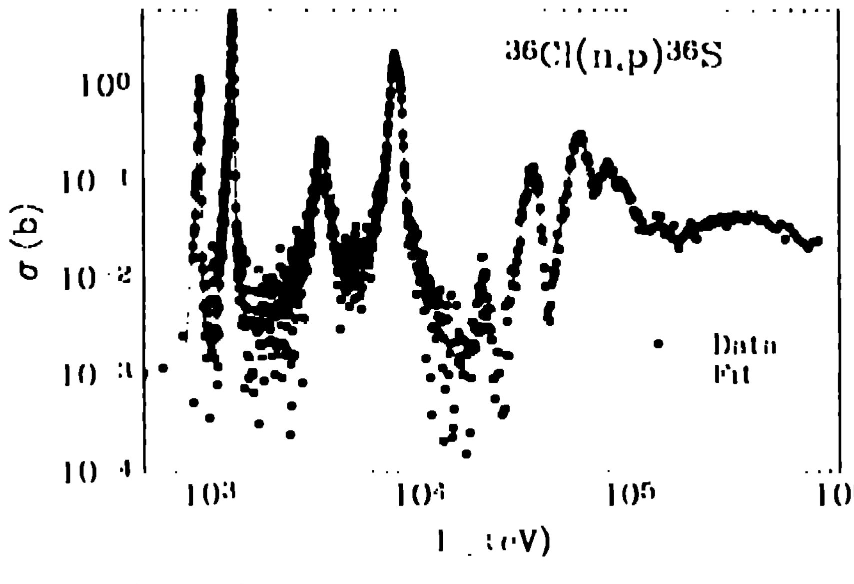

FIG. 4. The ^{36}Cl(n,p)^{36}S cross section for energies between 500 eV and 800 keV from our LANSCE measurements[9]. For clarity the error bars are not shown but can be surmised from the scatter in the data. The curve is from a multilevel fit to the data as described in Ref. 9.

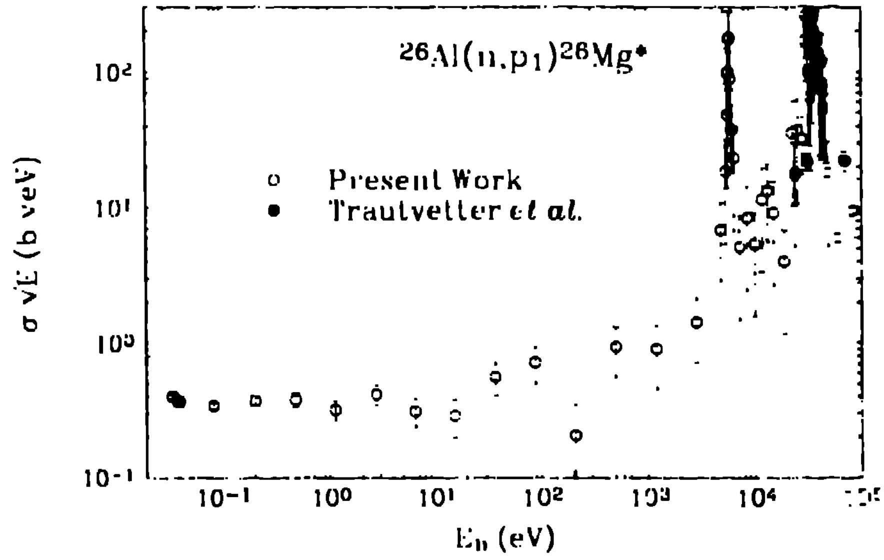

FIG. 5. The ^{26}Al(n,p$_1$)^{26}Mg* reduced cross section from thermal energy to 100 keV. Our new LANSCE data[13] are shown as open circles whereas the data of Trautvetter *et al.*[14] are depicted as solid circles.

2.3 S-process Nucleosynthesis of Light and Intermediate Mass Elements

Although the s process is mainly thought to produce most of the elements heavier than iron, Beer and Penzhorn[3] studied the contribution of the s process to the abundance of lower mass nuclei near ^{40}Ar. One result of their calculation was that (mainly the weak component of) the s process can account for most of the observed ^{36}S abundance. However, their results for ^{36}S are fairly uncertain in part because cross sections for the reactions that lead directly to ^{36}S (i.e., ^{36}Cl(n,p)^{36}S and ^{39}Ar(n,α)^{36}S) had not been measured and so they had to rely on theoretical calculations for the reaction rates. The reduction in the ^{36}Cl(n,p)^{36}S reaction rate indicated by our measurements[9] may significantly reduce the amount of ^{36}S calculated to be synthesized by the s process.

The mass flow in the region affecting the abundance of ^{36}S is complicated by several branchings, so new nucleosynthesis calculations are needed to fully asses the impact of our new rate. Furthermore, the s-process calculations of Ref. 3 were made with an exponential distribution of exposures whereas it is now thought that the weak component of the s process results in a single exposure[17]. Of the remaining unmeasured cross sections of importance to the s process production of ^{36}S several appear to be amenable to direct measurements. These include the ^{39}Ar(n,α)^{36}S, ^{37}Ar(n,α)^{34}S, and ^{36}S(n,γ)^{37}S reactions. The unmeasured ^{36}Cl(n,γ)^{37}Cl reaction is also very important because it competes directly with the ^{36}Cl(n,p)^{36}S reaction. Statistical model calculations[10] of the ratio of cross sections for ^{36}Cl at 30 keV yielded (n,p)/(n,γ) ≈ 20. At thermal energy, our results together with the ^{36}Cl(n,γ)^{37}Cl measurements of Ref. 18 yield a ratio of (n,p)/(n,γ) ≈ 5x10^{-4}, or about 40000 times smaller than the theoretical rate at 30 keV. However, there appears to be some disagreement about the value of the thermal ^{36}Cl(n,γ)^{37}Cl cross section. In the measurements of Ref. 18 this cross section was found to be $\sigma_{th} = 90 \pm 25$ b. On the other hand, the cross section was measured to be $\sigma_{th} < 10$ b in Ref. 19. A direct measurement of this cross section at thermal energy seems feasible with current techniques and is highly desirable in light of the present large uncertainty. A direct measurement of this cross section at astrophysically relevant temperatures appears very difficult if it is as small as the statistical model calculations indicate.

3 *Recent Improvements and Future Plans*

We have been investigating techniques for extending the measurements to isotopes with smaller cross sections and/or which are only available in low enrichment by using detectors which allow larger sample sizes and larger solid angles. The general approach we are pursuing is to cover as close to 4π solid angle as possible and to accommodate samples larger than the 0.5 cm diameter size of our previous LANSCE measurements by placing the detector directly in the incident neutron beam. The main problem to be overcome with this approach is the potential large increase in beam-induced background which arises when the detector is placed within the neutron beam.

The first approach we have tried is to use a parallel-plate compensated ionization chamber. Ion chambers have been used by the Dubna group for (n,p) and (n,α) measurements at their pulsed reactor for several years[20]. The main problem with these detectors is that the beam-induced backgrounds increase rapidly with increasing neutron energy with the result that measurement are typically limited to energies below a few keV. Most of the background is due to the initial burst of high energy particles and γ-rays which pass through the detector at short times. This intense burst can cause the preamplifier and amplifier to saturate for several hundred microseconds making measurements impossible during these times.

The idea of a compensated chamber is an old one[21] although it apparently has not been used before at a white neutron source. In a compensated chamber, on each side of the signal plate there are equal volumes defined by plates at equal but opposite voltages. The sample is placed on, for example, the plate which is negative with respect to the signal plate. Hence when an (n,p) or (n,α) reaction occurs in the sample a negative polarity signal is induced in the signal plate. In contrast, particles which penetrate the entire chamber induce approximately equal but opposite polarity signals. Hence, the potentially large background from the initial beam burst is greatly reduced. Earlier[22] we reported on a successful measurement of the ^{35}Cl(n,p)^{35}S cross section with a compensated ion chamber at LANSCE.

Because further time for the development and use of this detector has not been available at LANSCE we took it to ORELA where similar background problems are encountered. In Fig. 6 we show results of our first attempt at a measurement of the ^{17}O(n,α)^{14}C cross section using this chamber. Instead of the typical limit of a few keV we were able to make measurements to as high as 2 MeV. Compared to our previous

LANSCE measurement using a solid state detector, these new results represent about a factor of 30 increase in the product of sample size times solid angle. Larger increases are possible by using larger beam diameters and/or multiple sample plates. We are still analyzing the data from this experiment. One interesting result so far is that the forward/backward asymmetry appears to be fairly small.

A second approach we have tried is to use the scintillator ZnS mixed with other chemicals as both the target and the detector. This work was inspired by a report of the measurement of the ^{35}Cl(n,p)^{35}S cross section by Popov and Shapiro[23] at a lead-slowing-down spectrometer by using a detector made of ZnS mixed with CCl_4. In our experiment, a layer of ZnS 25 mg/cm^2 thick was deposited from a water solution onto a thin plastic disk which was mounted on a photomultiplier tube. A second detector was made by depositing a equal amount of ZnS mixed with K_2SO_4, which had been enriched in ^{33}S, on another disk. The detectors were placed in the LANSCE beam at a distance of 8 m from the neutron source.

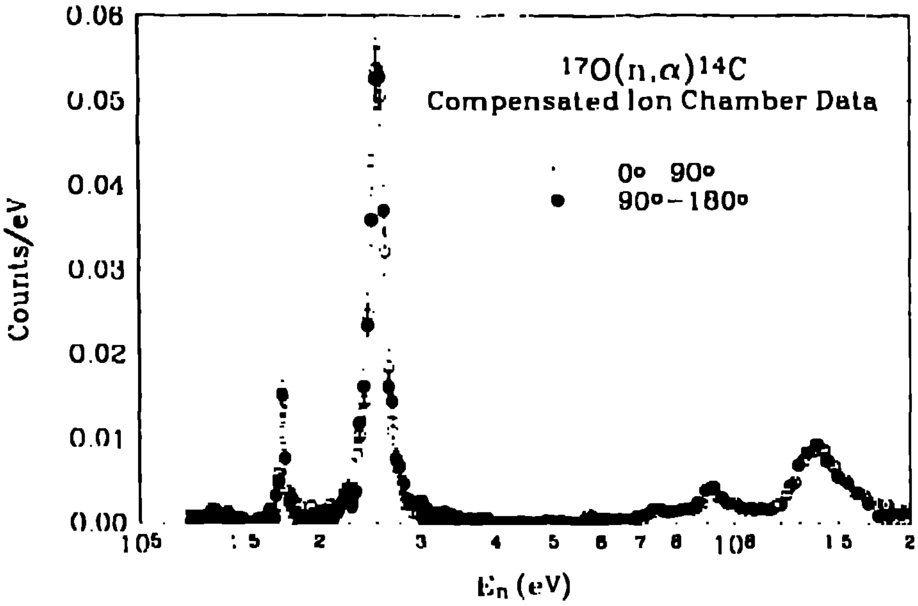

FIG. 5. Yield verses energy for the ^{17}O(n,α)^{14}C reaction measured with a compensated ion chamber at ORELA. The open circles represent data taken with the sample facing towards the forward hemisphere relative to the beam whereas the solid circles represent data taken in the backward hemisphere.

In figure 6 we compare the resulting cross section for the ^{33}S(n,α)^{30}Si reaction obtained by subtracting the spectrum measured with the plain ZnS detector from that measured with the combined ZnS plus K_2SO_4 detector to the previous measurements of Wagemans *et al.*[24]. The two results are in agreement to within the experimental errors except in three regions. The differences seen near 35 and 90 keV are due to the fact that we placed a 10 cm thick aluminum "filter" in the beam ahead of the detector to decrease dead time problems encountered at the highest energies. As a result, there were very few counts in the spectra at these energies due to large resonances in the aluminum. The third area of difference is at about 130 keV where the LANSCE data are higher than Wagemans *et al.* Perhaps this difference is caused by a resonance in the unmeasured $^{39}K(n,\alpha)^{36}Cl$ or $^{33}S(n,p)^{33}P$ reactions. The major problem encountered using ZnS is that this scintillator is apparently available only as a powder, so although the relative light output of ZnS is large, it is difficult to collect the light from the powder. As a result, the pulse height resolution is very poor. A second problem is that we have so far been unable to overcome the dead time problem associated with the initial large flux of high energy particles without using a fairly thick filter in the beam. However, the overall performance of the detector was encouraging and we hope to pursue this idea further by exploring the use of different chemical mixtures for the detector and other methods of decreasing the dead-time problems.

Our future plans are clouded by the uncertain future of LANSCE and ORELA. Also, as a result of new safety regulations the experimental room where this research is undertaken at LANSCE is inaccessible while the beam is being delivered. In addition the experimental room is open for at most two hours a day during the run cycle. These new rules have caused us to suspend work on developing a barium fluoride detector to measure (n,γ) cross sections for radioactive samples. If these difficulties can be overcome there is a rich field of new measurements of interest to nuclear astrophysics which could be accomplished at LANSCE and ORELA.

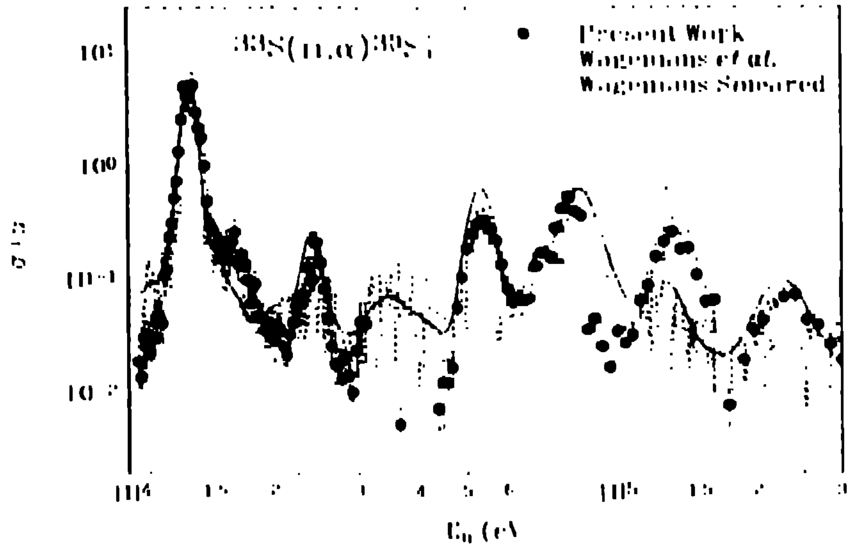

FIG. 6. Cross section for the $^{33}S(n,\alpha)^{30}Si$ reaction from 10 keV to 100 keV. The solid circles are our data from LANSCE obtained with a ZnS detector. The dotted curve represents the data of Wagemans *et al.*[24] The solid curve results from smearing the data of Wagemans *et al.* over the resolution of the LANSCE measurement.

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