PROCEEDINGS OF SCIENCE

The ^{22}Ne(α,n)^{25}Mg neutron source: latest experimental results and prospects.

Claudio Ugalde*
University of North Carolina at Chapel Hill
E-mail: cugalde@unc.edu

The current status of the reaction rate of ^{22}Ne(α,n)^{25}Mg is summarized. Among the latest new results, probably the most relevant is the conclusion that the E_x=11.15 MeV state in ^{26}Mg has a non-natural parity, so it does not contribute to the rates of the α + ^{22}Ne reactions. Here we make an account of some of the experimental work in the literature that is relevant to this state. Indeed, it would have been possible to avoid the controversy regarding this state before it even started.

10th Symposium on Nuclei in the Cosmos
July 27 - August 1 2008
Mackinac Island, Michigan, USA

*Speaker.

PoS(NIC X)038

1. Introduction

The ^{22}Ne(α,n)^{25}Mg reaction is considered to be the main neutron source for the s process in core He-burning massive stars and also is of relevance in He-shell burning in AGB stars. By influencing the abundance of low mass s-process nuclei, this reaction also affects the seeds for the p process. For example, some of these nuclei, like the light Mo and Ru isotopes, are underproduced unless the rate for the ^{22}Ne(α,n)^{25}Mg reaction is somehow enhanced[5].

The ^{22}Ne(α,n)^{25}Mg reaction competes with the ^{22}Ne(α,γ)^{26}Mg process for the available ^{22}Ne. These nuclei are produced by the ^{14}N(α,γ)^{18}F(β)^{18}O(α,γ)^{22}Ne chain of reactions in a stellar environment rich both in ^{4}He and ^{14}N nuclei left from hydrogen burning via the CNO cycle. The temperature at which the neutron production is activated is such that the ratio of the two reaction rates is close to unity[15]. Therefore, the efficiency of this neutron source is regulated by this ratio, so both reaction rates need to be determined simultaneously.

Inside the Gamow peak in these stellar scenarios, the ^{22}Ne+α processes are mostly resonant and involve the formation of the ^{26}Mg compound nucleus. Direct measurements of the cross section are challenging due to the Coulomb barrier, so currently available reaction rates require an extrapolation to the lowest energies. Also, a guess of the cross section requires information of the structure of ^{26}Mg at excitation energies in the Gamow peak, such as excited states, their energies, spins, and parities. On the other hand, partial widths (or spectroscopic factors) of the different channels involved in the process need to be known as well.

Here, a summary of what is known about the ^{22}Ne(α,n)^{25}Mg reaction at temperatures relevant to nucleosynthesis in the s process will be given.

2. The reaction rate

Several direct measurements have been performed to determine the reaction rates at energies that may have relevance in stellar scenarios (for example, see [2, 11, 22, 12, 7, 8, 10, 13]). So far, the best sensitivity has been achieved by Jaeger et al.[13] at $\sigma \sim 10^{-11}$ barn. Experiments have reached energies inside the Gamow window, but still, uncertainties surrounding the direct measurements in this region and uncertainties in the spectroscopic α-particle strengths of the threshold resonances introduces important uncertainties to the extrapolated rate estimate.

It has long been thought that a resonance at E_{lab}=635 keV dominates the stellar reaction rates. Berman et al.[4] first proposed its existence based on their observation of a state in ^{26}Mg at E_x=11.15 MeV. They claimed the state to have $J^{\pi}=1^-$ based on a couple of arguments. First, a comparison of their 90^o and 135^o photo-neutron cross section measurements favored a π=- assignment over π=+ [1]. Second, they compared electron inelastic scattering measurements by Titze and Spamer[18] and Bendel et al. [3] at two angles and various energies. Their analysis of the distribution of the strengths between magnetic and electric transitions suggested $J^{\pi}=1^-$, a result that contradicted Bendel et al.'s own conclusion the previous year.

It is likely that the first indication of the M1 nature of the ground state transition for the E_x=11.15 MeV state in ^{26}Mg comes from the parallel works of Titze and Spamer, and Bendel et al.

[1]This fact is only mentioned in their paper but the cross section at 90^o is not shown, so the actual comparison can not be assessed by the reader.

However, the resolution of their experiments was such that it is not possible to establish a clear 1 to 1 correspondence between their state and that from Berman et al.'s high resolution work.

The confirmation of the spin-parity nature of the E_x=11.15 MeV state came years later when Crawley et al.[6] performed inelastic proton scattering experiments on ^{26}Mg at 201 MeV. They measured angular distributions in the range $2.5^o \leq \theta_{c.m.} \leq 12.5^o$ and based on distorted wave Born approximation (DWBA) and distorted wave impulse approximation (DWIA) analyses, were able to identify 19 states with $J^\pi=1^+$. The state at E_x=11.15 MeV was among them.

Soon after Crawley et al.'s result was published, experimental efforts for measuring this resonance directly via the ^{22}Ne(α,n)^{25}Mg reaction were presented. For example, Harms et al.[12] found some evidence of the existence of the resonance by measuring the neutron yield at one single beam energy (E_α=635 keV). Drotleff et al.[7] also reported a resonant structure found with their windowless gas target system at E_α=623 keV, but later concluded it to belong to the background ^{11}B(α,n)^{14}N reaction [8]. Since both ^{22}Ne and α-particles have a ground state with $J^\pi=0^+$, only natural parity states in ^{26}Mg can be populated via ^{22}Ne + α reactions. Therefore, the ^{22}Ne(α,n)^{25}Mg and ^{22}Ne(α,γ)^{26}Mg reactions can not show the resonant structure at E_{lab}=635 keV. However, this state could be of importance in the competing neutron poison reaction ^{25}Mg(n,γ)^{26}Mg.

Data reanalyses and compilations have also been published since then. The works of the NACRE collaboration[1], Käppeler et al.[14], Koehler[16], and Karakas et al.[15] have all computed the reaction rates assuming the E_x=11.15 MeV state in ^{26}Mg to have a natural parity, following Berman et al.'s[4] suggestion. The most recent direct measurement available (Jaeger et al.) and the indirect measurements below the neutron threshold of Ugalde et al.[21] provide a calculation of the reaction rate for the (α,n) and (α,γ) processes, respectively, under the same assumption.

There are other recent experiments that support the non-natural parity assignment of Crawley et al. For example, Tamii et al.[17] developed a technique to measure proton inelastic scattering angular distributions at forward angles with high resolution using the Grand Raiden spectrometer at Osaka. For ^{26}Mg(p,p')^{26}Mg their resolution was 17 keV, good enough to identify the E_x=11.15 MeV state in ^{26}Mg and then assign to it a $J^\pi=1^+$[9]. Tonchev et al.[19] performed a ^{26}Mg(γ,γ)^{26}Mg experiment with the Free Electron Laser facility at Duke University. Their polarized γ-ray beam impinged on a ^{26}MgO target and the outgoing photons were observed both at parallel and perpendicular positions with respect to the beam polarization plane with Ge detectors. They determined the transition from the E_x=11.15 MeV state to the ground state of ^{26}Mg to be of an M1 character. Finally, Ugalde et al.[20] searched for the E_x=11.15 MeV state in ^{26}Mg with the ^{22}Ne(^{6}Li,d)^{26}Mg α-particle transfer reaction and obtained a negative result, concluding that either the state has non-natural parity or the α-particle spectroscopic factor is very small. Either way, this state does not contribute to the rates for the ^{22}Ne + α reactions.

A calculation of the reaction rate for ^{22}Ne(α,n)^{25}Mg based on Crawley et al.'s conclusion is shown in figure 1. For example, this rate is in good agreement with the lower values suggested by the NACRE collaboration. However, NACRE's upper value can be rejected [20]. One of the main consequences of this result is that, as discussed by Costa et al. [5], the production of the light isotopes of Ru and Mo may require also a contribution from nucleosynthesis in accreting neutron stars or black holes.

There are other states around the E_x=11.15 MeV state that may contribute to the (α,n) and (α,γ) reaction rates. Based on new experimental results, this possibility will be discussed by Ugalde

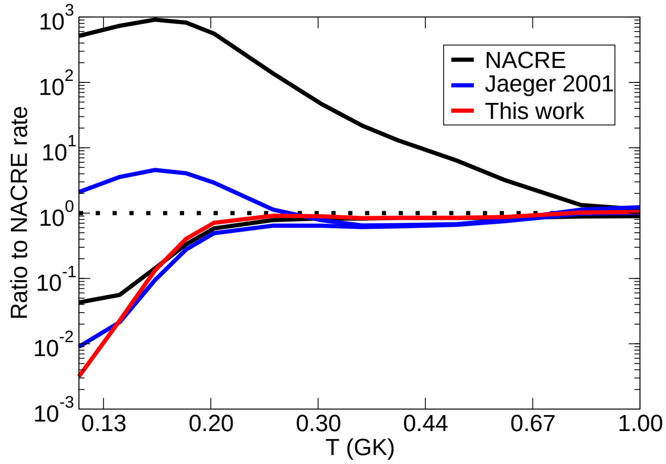

Figure 1: (Color) Rate for the $^{22}Ne(\alpha,n)^{25}Mg$ reaction normalized to the values adopted by the NACRE collaboration[1]. For comparison, the rate values computed in the direct measurement of Jaeger et al. are shown as well. Upper and lower limits of the new rate are presented and discussed in [20].

et al.[20].

3. Conclusion

We have discussed some of the latest experimental results relevant to the reaction rate of $^{22}Ne(\alpha,n)^{25}Mg$. In particular, it has been shown how it is possible to resolve the controversy regarding role of the state at E_x=11.15 MeV in ^{26}Mg to the rate. This is interesting as experimental work conclusive enough has existed almost as long as the controversy itself. It is important to stress too, that a lot of work remains to be done, specially with the $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction.

References

[1] C. Angulo et al. A compilation of charged-particle induced thermonuclear reaction rates. *Nucl. Phys.*, A656:3, 1999.

[2] D. Ashery. Study of the $^{22}Ne(\alpha,n)^{25}Mg$ reaction: a possible source of stellar neutrons. *Nucl. Phys.*, A136:481–495, 1969.

[3] W. L. Bendel, L. W. Fagg, R. A. Tobin, and H. F. Kaiser. Inelastic electron scattering from ^{26}Mg at 180^{o}. *Phys. Rev.*, 173:1103–1107, 1968.

[4] B. L. Berman, R. L. Van Hemert, and C. D. Bowman. Threshold photoneutron cross section for ^{26}Mg and a source of stellar neutrons. *Phys. Rev. Lett.*, 23:386–389, 1969.

[5] V. Costa, M. Rayet, R. A. Zappalá, and M. Arnould. The synthesis of the light Mo and Ru isotopes: how now, no need for an exotic solution? *Astron. Astrophys.*, 358:L67–L70, 2000.

[6] G. M. Crawley, C. Djalali, N. Marty, M. Morlet, A. Willis, N. Anantaraman, B. A. Brown, and A. Galonsky. Isovector and isoscalar spin-flip excitations in even-even s-d shell nuclei excited by inelastic proton scattering. *Phys. Rev. C*, 39:311–323, 1989.

[7] H. W. Drotleff, A. Denker, J. W. Hammer, H. Knee, S. Küchler, D. Streit, C. Rolfs, and H. P. Trautvetter. New ^{22}Ne(α,n)^{25}Mg resonances at very low energies relevant for the astrophysical s process. *Z. Phys. A*, 338:367–368, 1991.

[8] H. W. Drotleff, A. Denker, H. Knee, M. Soiné, G. Wolf, J. W. Hammer, U. Greife, C. Rolfs, and H. P. Trautvetter. Reaction rates of the s-process neutron sources ^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg. *Astrophys. J.*, 414:735–739, 1993.

[9] Y. Fujita. Private communication. 2008.

[10] U. Giesen, C. P. Browne, J. Görres, S. Graaff, C. Iliadis, H. P. Trautvetter, M. Wiescher, W. Harms, K .L. Kratz, B. Pfeiffer, R. E. Azuma, M. Buckby, and J. D. King. The astrophysical implications of low-energy resonances in ^{22}Ne+α. *Nucl. Phys.*, A561:95–111, 1993.

[11] F. X. Haas and J. K. Bair. Total neutron yield from the (α,n) reaction on ^{21,22}Ne. *Phys. Rev. C*, 7:2432–2436, 1973.

[12] V. Harms, K. L. Kratz, and M. Wiescher. Properties of ^{22}Ne(α,n)^{25}Mg resonances. *Phys. Rev. C*, 43:2849–2861, 1991.

[13] M. Jaeger, R. Kunz, A. Mayer, J. W. Hammer, G. Staudt, K. L. Kratz, and B. Pfeiffer. ^{22}Ne(α,n)^{25}Mg: The key neutron source in massive stars. *Phys. Rev. Lett.*, 87:202501, 2001.

[14] F. Käppeler, M. Wiescher, U. Giesen, J. Görres, I. Baraffe, M. El Eid, C. M. Raiteri, M. Busso, R. Gallino, M. Limongi, and A. Chieffi. Reaction rates for ^{18}O(α,γ)^{22}Ne,^{22}Ne(α,γ)^{26}Mg, and ^{22}Ne(α,n)^{25}Mg in stellar helium burning and s-process nucleosynthesis in massive stars. *Astrophys. J.*, 437:396–409, 1994.

[15] A. I. Karakas, M. A. Lugaro, M. Wiescher, J. Görres, and C. Ugalde. The uncertainties in the ^{22}Ne+α-capture reaction rates and the production of the heavy magnesium isotopes in Asymptotic Giant Branch stars of intermediate mass. *Astrophys. J.*, 643:471–483, 2006.

[16] P. E. Koehler. Constraints on the ^{22}Ne(α,n)^{25}Mg s-process neutron source from analysis of ^{nat}Mg+n total and ^{25}Mg(n,γ) cross sections. *Phys. Rev. C*, 66:055805, 2002.

[17] C. Tamii et al. Study of M1 excitations by high-resolution proton inelastic scattering experiment at forward angles. *Nucl. Phys.*, A788:53c–60c, 2007.

[18] O. Titze and E. Spamer. Inelastic electron scattering from levels with 7 to 15 Mev excitation energy in ^{24}Mg and ^{26}Mg. *Z. Naturforschg.*, 21a:1504–1506, 1966.

[19] A. Tonchev, A. Champagne, J. deBoer, C. Iliadis, R. Longland, G. Rusev, C. Ugalde, and M. Wiescher. In preparation. 2008.

[20] C. Ugalde, A. E. Champagne, J. A. Clark, C. Deibel, C. Iliadis, R. Longland, P. D. Parker, C. Wrede, and C. Wood. In preparation. 2008.

[21] C. Ugalde, A. E. Champagne, S. Daigle, C. Iliadis, R. Longland, J. R. Newton, E. Osenbaugh-Stewart, J. A. Clark, C. Deibel, A. Parikh, P. D. Parker, and C. Wrede. Experimental evidence of a natural parity state in ^{26}Mg and its impact to the production of neutrons for the s process. *Phys. Rev. C*, 76:025802, 2007.

[22] K. Wolke, H. W. Harms, J. W. Becker, J. W. Hammer, K. L. Kratz, C. Rolfs, U. Schröder, H. P. Trautvetter, M. Wiescher, and A. Wöhr. Helium burning of ^{22}Ne. *Z. Phys. A*, 334:491–510, 1989.