in the same direction. After this alignment the collaborators plan to introduce pinning sites in a controlled way by irradiating the samples with particles such as electrons, protons and neutrons. Such irradiation has proved to be an effective way to increase the irreversibility line in other materials. A group at the University of Illinois led by Justin Schwartz reports that neutron irradiation of a polycrystalline sample of Hg-1201 has increased both the irreversibility line and the critical-current density.[8]

The band structure of the normal state of Hg-1201 has already been calculated by David Singh (Naval Research Laboratory) and, independently, by Dimtrij Novikov and Arthur J. Freeman (Northwestern).[9] The computations indicate that the undoped Hg-1201 material, like stoichiometric La_2CuO_4 (the basis for the original 40-K copper oxide superconductor), is an antiferromagnetic insulator, requiring doping to become a superconductor. Novikov and Freeman report seeing a saddle point in the energy band, known as a van Hove singularity, quite close to the Fermi surface. According to their calculations, only a small amount of doping is needed to make this van Hove singularity coincide with the Fermi surface. The role that these singularities might play in superconductivity is still being debated.

References

1. S. S. P. Parkin *et al*, Phys. Rev. B **38**, 6531 (1988).
2. A. Schilling, M. Cantoni, J. D. Guo, H. R. Ott, Nature **363**, 56 (1993).
3. R. J. Cava, Nature **362**, 204 (1993).
4. S. N. Putilin, E. V. Antipov, O. Chmaissem, M. Marezio, Nature **362**, 226 (1993).
5. L. Gao, J. Z. Huang, R. L. Meng, G. Lin, F. Chen, L. Beauvais, Y. Y. Sun, Y. Y. Xue, C. W. Chu, to be published in Physica C.
6. J. L. Wagner, P. G. Radaelli, D. G. Hinks, J. D. Jorgensen, J. F. Mitchell, B. Dabrowski, G. S. Knapp, M. A. Beno, Physica C **210**, 447 (1993).
7. U. Welp, G. W. Crabtree, J. L. Wagner, D. G. Hinks, P. G. Radaelli, J. D. Jorgensen, J. F. Mitchell, B. Dabrowski, to appear in Appl. Phys. Lett. **63** (1993).
8. J. Schwartz, S. Nakamae, G. W. Raban Jr, J. K. Heuer, S. Wu, J. L. Wagner, D. G. Hinks, submitted to Nature.
9. D. Singh, Physica C **212**, 228 (1993). D. L. Novikov, A. J. Freeman, to appear in Physica C.

NEW DATA STRENGTHEN WEAK LINK IN STELLAR NUCLEOSYNTHESIS

According to the standard model of the Big Bang, the only elements created during that event were hydrogen, helium and some lithium; the rest were brewed in the stars. Over the past few decades nuclear astrophysicists have sorted out the complex chain of stellar reactions responsible for the observed abundances of the isotopes, with remarkable success in all the most critical reactions but one: $^{12}C(\alpha,\gamma)^{16}O$. This reaction is a key stepping-stone in the synthesis of heavier elements, linking the stage that burns helium to produce carbon and oxygen with the later stages fueled by those elements. If helium burning yields more or less oxygen or carbon, it is predicted that the later stages will be strongly affected, and so will the ultimate fate of massive stars.

Although a number of experiments have studied the $^{12}C(\alpha,\gamma)^{16}O$ reaction, the reported astrophysical rates have failed to converge within an acceptably narrow range. The problem is that astrophysicists need to know the reaction rate at an energy of about 0.3 MeV, where stellar helium burning occurs, but the radiative α-capture cross sections are far too low at that energy to be measured in the lab. The researchers must measure the cross sections at higher energies and then extrapolate down to 0.3 MeV. And the extrapolations are far from easy. That's why there's lots of interest in the results of two new experiments that have succeeded in reaching low enough energies to place useful constraints on the extrapolations. The values determined by the two experiments agree with each other, and they both fall in the same range as the results of a computer simulation.

Computer predictions

All stars burn hydrogen and then helium in their cores early in their development. The main reactions in helium burning are one that combines three α particles to produce ^{12}C and the α-capture reaction, $^{12}C(\alpha,\gamma)^{16}O$. The relative strengths of these reactions determines the ratio of oxygen and carbon at the end of helium burning. If a star's mass is greater than 6–8 solar masses the star gets hot enough to burn the carbon, yielding heavier nuclei. There follow stages characterized successively by the burning of neon, oxygen and silicon.

With the exception of $^{12}C(\alpha,\gamma)^{16}O$, the reactions in this complex chain are sufficiently well known that one can begin to do some calculations. "Nucleosynthesis is getting to be a good quantitative theory," says Stan Woosley (University of California, Santa Cruz). Together with Thomas Weaver of Lawrence Livermore National Laboratory and other colleagues, he has spent 15 years developing a computer code to calculate stellar nucleosynthesis. He and Weaver used[1] that code to explore the $^{12}C(\alpha,\gamma)^{16}O$ rate, feeding various values for it into their program and looking at the abundances of isotopes that resulted.

Woosley and Weaver found that the reaction rate for $^{12}C(\alpha,\gamma)^{16}O$ must fall within a narrow range if it is to account for the observed abundances. The rate required by their computer calculations is 1.7 ± 0.5 times the "best estimate" of the reaction rate as measured up through 1988, and it is consistent with the results of the two new measurements. Woosley and Weaver spoke about their results in 1991 at the 80th birthday symposium for William Fowler (Caltech), one of the pioneers of nuclear astrophysics.

If the rate is larger than Woosley and Weaver have calculated, so much carbon would be turned into oxygen that the star would essentially skip both carbon and neon burning. The star would acquire a much larger iron core and would be more likely to end up as a black hole.

The backdoor approach

The two new experiments were done by groups working at TRIUMF, the meson factory at the University of British Columbia, Vancouver, and at Yale University. The TRIUMF collaboration[2] included researchers from TIRUMF, the University of Toronto, Caltech, Simon Fraser University in Burnaby, and the University of Alberta in Edmonton; it was headed by Lothar Buchmann (TRIUMF) and Richard Azuma (University of Toronto) The Yale experiment[3] was done by a team of researchers from Yale and the University of Connecticut led by Moshe Gai and Zhiping Zhao of Yale.

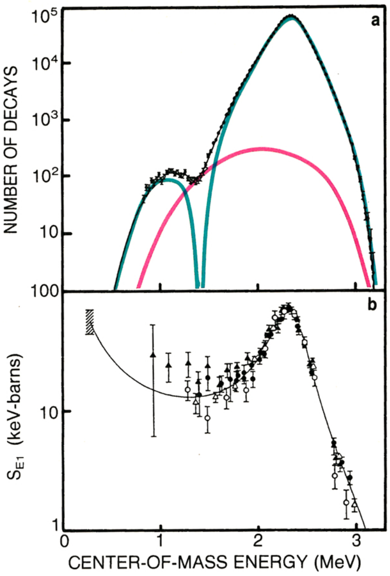
These two collaborations did not study the α capture by a ^{12}C nucleus but rather used a different way of producing an excited state of ^{16}O: They formed ^{16}N, which is unstable and β-decays to an excited state of

^{16}O. The ^{16}O nucleus in turn decays by α emission to ^{12}C, but only about once in every 10^5 β decays. Despite this low branching ratio the rate for this so-called β-delayed α decay is much easier to measure than that for the direct α-capture reaction on ^{12}C at center-of-mass energies for the ^{12}C–α system below about 1 MeV. At these low energies the latter reaction is strongly inhibited by the Coulomb barrier, while the rate for the β-delayed α decay to the low-energy region is actually enhanced.

The downside of the β-delayed α decay is that it does not determine the complete $^{12}C(\alpha,\gamma)^{16}O$ reaction: The ^{16}O nucleus formed directly by radiative α capture can decay by emission of either electric dipole (E1) or electric quadrupole (E2) radiation, but selection rules cause the β-delayed α decay to proceed only through emission of dipole radiation.

Knowledge of the E1 part of the cross section is nevertheless very helpful in extrapolating the cross section to low energies. In discussing nuclear reactions of astrophysical interest one usually does not talk about the cross section but rather the shape factor, or S factor, which is like a cross section with the steepest energy dependence removed. (The S factor is the cross section multiplied by the energy and by the exponential Gamow factor that compensates for the barrier penetration factor.) The S factor for the E1 component of the $^{12}C(\alpha,\gamma)^{16}O$ reaction features a large, broad peak above a center-of-mass energy of 2 MeV that has been well traced by previous experiments. But below about 1.4 MeV, an interference between several partial waves that contribute to the decay amplitude causes the ^{16}N β-delayed α-decay spectrum to have a small bump. Measuring this bump gives a handle on the partial waves that contribute to it and is the key to more accurate extrapolations.

The usefulness of the β-delayed α-decay reaction was suggested over 20 years ago in separate publications by Fred Barker (Australian National University, Canberra) and Carl Werntz (Catholic University).[4] In 1988, Daniel Baye and Pierre Descouvemont (Université Libre de Bruxelles) did a microscopic calculation of the physics involved in this reaction and predicted that the β-decay spectrum would show an interference bump at low energy.[5] More recently, Jean Humblet (University of Liège, Belgium), with Xiangdong Ji, Bradley W. Filippone and Steven Koonin (Caltech),[6] showed by calculations the key role that a lower-energy measurement of the α spectrum from ^{16}N β-decay might play in delineating the interference term. The message was, as Koonin puts it, "If you can find the bump, you can nail down the cross section."



Results of the TRIUMF experiment. Top: Yield of events from the β-delayed α decay of ^{16}N. Blue and red curves are fits to the p and f waves, respectively, that contribute to the cross section. Bottom: Dipole component of the S factor determined by fits to the TRIUMF cross section and to data for the $^{12}C(\alpha,\gamma)^{16}O$ reaction measured by other groups (data points). (Adapted from ref. 2.)

The β-delayed α decay has been measured in several experiments, including a series of studies with particularly thin targets and good statistics done around 1970 by a group at the Max Planck Institute for Chemistry in Mainz, Germany.[7] Those measurements did not go below about 1.5 MeV and could not have seen the interference bump, whereas the recent experiments at TRIUMF and Yale extend down to 0.83 MeV and 1.058 MeV, respectively.

The TRIUMF experiment

The real challenge for the experimentalists was to measure a reaction with a minuscule decay rate. First the experiment has to pick out the tiny fraction of ^{16}N β-decay events that are followed by an α decay. (Most of the time ^{16}N goes into a stable ^{16}O.) Then it has to distinguish the low-energy α particles that constitute the bump of interest from those α's in the large peak above 2 MeV, whose yield is about three orders of magnitude larger. If a higher-energy α particle from the large peak loses energy before it is detected, it could easily be miscounted as a low-energy particle. Both of the recent experiments had to be designed to surmount these difficulties.

The TRIUMF collaboration used protons from the meson factory's 500-MeV beam to produce the ^{16}N ions. The protons bombarded a zeolite target, producing a range of reaction products that included the molecular ions $(^{16}N^{14}N)^+$. These ions were separated from the other reaction products by the TRIUMF Isotrope Separator on Line and then struck a thin collector foil.

Four collector foils were arranged on the arms of a pinwheel. While one of the foils was in the beam line collecting radioactive nitrogen nuclei, the other three were sitting between pairs of detectors, which counted decays from previously collected nuclei. The pinwheel was rotated 90°every 3 seconds (^{16}N has a halflife of 7.1 sec).

The detectors were so thin that the copious β particles passed through them without being detected. The detectors were then able to measure the energies of the α particles and the ^{12}C nuclei and could determine whether there were coincidences between an α emerging on one side of the collector foil and a ^{12}C nucleus emerging on the other side. The members of the TRIUMF collaboration collected one million coincident events and three million "singles" events.

The α-particle spectrum measured at TRIUMF is shown in the top panel of the figure on this page, which exhibits the predicted interference bump. The researchers fitted that spectrum by assuming that it resulted from the coherent sum of two p-wave states plus an f-wave amplitude. Those partial wave components are shown as colored curves in the figure.

To determine the E1 S factor from the β-decay spectrum and to extrapolate it down to the energy of astrophysical interest, the TRIUMF team used a technique known as a K-matrix analysis. The researchers first fit the parameters in that analysis to their data and then used the parameters to extend the S factor to the lower energies. They included in this analysis data gathered over more than 20 years on the $^{12}C(\alpha,\gamma)^{16}O$ reaction. Contributing to the accumulation of data on the $^{12}C(\alpha,\gamma)^{16}O$ reaction as well as on the elastic scattering of α's off ^{12}C were experimental groups from Caltech, Westfälische Wilhelms Universität in Münster, Germany (the same group is now at Ruhr University in Bochum) and Queens University in

Kingston, Canada.

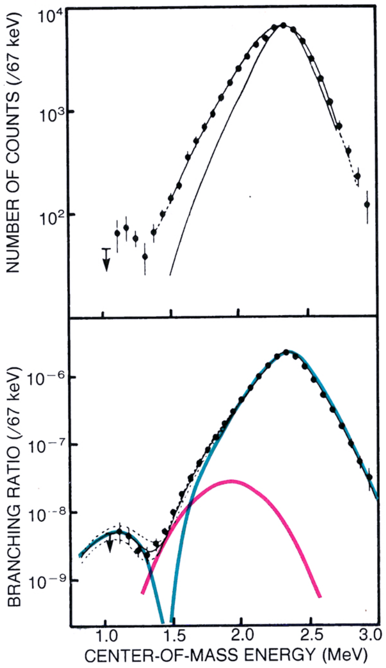
The *S* factor curve determined by the K-matrix analysis for the $^{12}C(\alpha,\gamma)^{16}O$ reaction is shown in the lower panel of the figure on page 24. Based on this analysis the TRIUMF group reported a value for the *S* factor at 0.3 MeV of 57 ± 13 keV-barns (shown as the shaded region in the figure).

The Yale experiment

Across the continent from TRIUMF researchers at Yale conducted an experiment of very different design, using low-energy (9 MeV) deuterons to form the ^{16}N ions. The experiment collected about 55 000 events, so its statistics are not as good as those of the TRIUMF measurement, but the results of the two experiments overlap within error bars.

The ^{16}N nuclei were formed in the $^{15}N(d,p)^{16}N$ reaction when a deuterium beam from Yale's Extended Stretch Transuranium tandem accelerator struck a $Ti^{15}N$ target. After a 10-sec beam exposure the target was transferred to a counting area. There 12 detectors were used to record β particles while 9 others, located farther from the target, registered the energy of α particles. By measuring the time of flight between the arrivals of the β and α particles at their respective detectors, Gai and his colleagues could eliminate all those β's that were not associated with an α particle. As a guide to subtracting the background of random events, the Yale group measured the line shape for the time of flight for a similar reaction, the β-delayed α decay of ^8Li.

A major concern of the Yale group was to correct for the energy loss suffered by the α particles as they left the target. The top panel of the figure on this page shows the measured spectrum of α particles together with a smooth curve representing the data from the older Max Planck experiment, which used a thin target.[7] Gai and his colleagues used those "zero target thickness" data to correct for the effects of target thickness in their experiment. The resulting spectrum is shown in the bottom panel. Also shown in that panel are the p-wave curve that was fit to their data, together with an "*ad hoc*" f wave (it was not determined by a fitting procedure). The Yale team combined its data with the elastic scattering and $^{12}C(\alpha,\gamma)^{16}O$ data in a framework called an R-matrix analysis to extrapolate down to 0.3 MeV. The final result is an *S* factor for the E1 component of 95 keV-barns with statistical and systematic errors of ± 6 and ± 28 keV-barns, respectively.



Yale experiment results. Top: Yield of β-delayed α-decay events (data points and line fit to them), along with the results from an experiment in which the target had essentially no thickness.[7] (In the Yale experiment α particles lost energy exiting from the target.) Bottom: Yale data after correction for target thickness, together with the fitted p wave (blue) and an *"ad hoc"* f wave (red). (Adapted from ref. 3.)

Comparing results

How do the E1 *S* factors of 57 and 95 keV-barns measured at TRIUMF and Yale, respectively, stack up against earlier measurements? In a 1988 compilation of nuclear reaction rates relevant to astrophysical nucleosynthesis, Georgeanne A. Caughlan (Montana State University) and Fowler chose 100 keV-barns as the central value for the *total S* factor for $^{12}C(\alpha,\gamma)^{16}O$ at 0.3 MeV. For the E1 component in particular they gave a range of 30–120 keV-barns with 60 keV-barns as the preferred value. The new E1 measurements certainly fall within that range. Noting that the values for the total *S* factor reported in the past have ranged from nearly 0 to 500 keV-barns, Charles Barnes of Caltech, a member of the TRIUMF group who has pursued the $^{12}C(\alpha,\gamma)^{16}O$ reaction cross section for over 20 years, called the new values for the E1 component a fabulous improvement.

Still, the work is far from over. Some technical issues related to the new experiments must be cleared up. One is the uncertainty over which formalism to trust: the K-matrix analysis used by the TRIUMF group or the R-matrix analysis used by the Yale group. Both parametrizations in principle do the same thing, but there are technical differences in how they accomplish the task. The R-matrix approach has usually been observed to give higher results. More precise numbers must await an understanding of which analysis—K or R—gives the truer result. In addition, there is a continuing dialogue concerning the data analysis and the assignment of errors.

The other work that must be done is to measure the E2 component of the astrophysical *S* factor. Barnes told us that one way[8] to do this is to study the dissociation of ^{16}O into ^4He and ^{12}C in the presence of the strong Coulomb field of a high Z nucleus such as ^{208}Pb. The quadrupole component is greatly enhanced relative to the dipole component in such a dissociation. But Barnes admits that this experiment poses severe difficulties. Another approach is to make more accurate measurements of the ratio of the rates, S_{E2}/S_{E1}, as a function of energy; One could then combine these rates with the new, firmer determinations of the E1 rate to get the E2 rate. A new direct measurement of the α-capture reaction is already under way at the Ruhr University, where the precision of the experimental setup has been improved by about two orders of magnitude compared with previous measurements.

—BARBARA GOSS LEVI

References

1. T. A. Weaver, S. E. Woosley, Phys. Rep., to be published.
2. L. Buchmann, R. E. Azuma, C. A. Barnes, J. M. D'Auria, M. Dombsky, U. Giesen, K. P. Jackson, J. D. King, R. G. Korteling, P. McNeely, J. Powell, G. Roy, J. Vincent, T. R. Wang, S. S. M. Wong, P. R. Wrean, Phys. Rev. Lett. **70**, 726 (1993).
3. Z. Zhao, R. H. France III, K. S. Lai, S. L. Rugari, M. Gai, E. L. Wild, Phys. Rev. Lett. **70**, 2066 (1993).
4. F. C. Barker, Aust. J. Phys. **24**, 777 (1971). C. Werntz, Phys. Rev. **4**, 1591 (1971).
5. D. Baye, P. Descouvemont, Nucl. Phys. A **481**, 445 (1988).
6. X. Ji, B. W. Filippone, J. Humblet, S. Koonin, Phys. Rev. C **141**, 1736 (1990). J. Humblet, B. W. Filippone, S. E. Koonin, Phys. Rev. C **44**, 2530 (1991).
7. H. Hättig, K. Hünchen, H. Wäffler, Phys. Rev. Lett. **25**, 941 (1970).
8. G. Bauer, M. Weber, Nucl. Phys. A **504**, 352 (1989). T. D. Schoppa, S. E. Koonin, Phys. Rev. C **46**, 382 (1992). ■