

**$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  Reaction in the Energy Regime of Supernova Nucleosynthesis**

H. Nassar,<sup>1</sup> M. Paul,<sup>1,\*</sup> I. Ahmad,<sup>2</sup> Y. Ben-Dov,<sup>3</sup> J. Caggiano,<sup>2</sup> S. Ghelberg,<sup>1</sup> S. Goriely,<sup>4</sup> J. P. Greene,<sup>2</sup> M. Hass,<sup>5</sup> A. Heger,<sup>6,7</sup> A. Heinz,<sup>2</sup> D. J. Henderson,<sup>2</sup> R. V. F. Janssens,<sup>2</sup> C. L. Jiang,<sup>2</sup> Y. Kashiv,<sup>1</sup> B. S. Nara Singh,<sup>5</sup> A. Ofan,<sup>1</sup> R. C. Pardo,<sup>2</sup> T. Pennington,<sup>2</sup> K. E. Rehm,<sup>2</sup> G. Savard,<sup>2</sup> R. Scott,<sup>2</sup> and R. Vondrasek<sup>2</sup>

<sup>1</sup>*Racah Institute of Physics, Hebrew University, 91904 Jerusalem, Israel*

<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439, USA*

<sup>3</sup>*Physics Division, NRC-Negev, P.O. Box 9001, 84190 Beer-Sheva, Israel*

<sup>4</sup>*Université Libre de Bruxelles, CP-226, 1050 Brussels, Belgium*

<sup>5</sup>*Department of Particle Physics, Weizmann Institute, 76100 Rehovot, Israel*

<sup>6</sup>*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

<sup>7</sup>*University of California at Santa Cruz, Santa Cruz, California 95064, USA*

(Received 31 August 2005; published 3 February 2006)

The  $^{44}\text{Ti}$  ( $t_{1/2} = 59$  yr) nuclide, an important signature of supernova nucleosynthesis, has recently been observed as live radioactivity by  $\gamma$ -ray astronomy from the Cas A remnant. We investigate in the laboratory the major  $^{44}\text{Ti}$  production reaction  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  ( $E_{\text{c.m.}} \sim 0.6\text{--}1.2$  MeV/ $u$ ) by direct off-line counting of  $^{44}\text{Ti}$  nuclei. The yield, significantly higher than inferred from previous experiments, is analyzed in terms of a statistical model using microscopic nuclear inputs. The associated stellar rate has important astrophysical consequences, increasing the calculated supernova  $^{44}\text{Ti}$  yield by a factor  $\sim 2$  over previous estimates and bringing it closer to Cas A observations.

DOI: 10.1103/PhysRevLett.96.041102

PACS numbers: 26.30.+k, 24.60.Dr, 25.55.-e, 95.85.Pw

The radionuclide  $^{44}\text{Ti}$  ( $t_{1/2} = 59$  yr) is considered an important signature of explosive nucleosynthesis in core-collapse supernovae (SN) [1], where multiple  $\alpha$  capture is the path for SN nucleosynthesis from  $^{28}\text{Si}$  to  $^{56}\text{Ni}(\text{Fe})$ .  $^{44}\text{Ti}$  is produced mainly during an  $\alpha$ -rich freeze-out phase, the ratio  $^{44}\text{Ti}/^{56}\text{Ni}$  being sensitive to the explosion conditions. Stellar production of  $^{44}\text{Ti}$  determines the abundance of stable  $^{44}\text{Ca}$  and contributes to that of  $^{48}\text{Ti}$  (fed by  $^{48}\text{Cr}$  on the  $\alpha$  chain). Live  $^{44}\text{Ti}$  has been directly observed from a point source identified as Cassiopeia A (Cas A) by  $\gamma$ - and x-ray telescopes (CGRO, RXTE, BeppoSAX) and very recently by the INTEGRAL mission (see [2,3]). Cas A is believed to be the remnant of a core-collapse SN whose progenitor mass was in the range  $(22\text{--}25)M_{\odot}$  ( $M_{\odot}$  denotes a solar mass) [4]. Using known values of the distance and age of the remnant, half-life of  $^{44}\text{Ti}$ , and the combined  $\gamma$  flux from all observations, an initial  $^{44}\text{Ti}$  yield of  $160 \pm 60 \mu M_{\odot}$  is implied [3]. This value is larger by a factor of 2–10 than  $^{44}\text{Ti}$  yields calculated in current models (e.g., [5,6]), and various explanations have been proposed [4,7–9].  $^{44}\text{Ti}$   $\gamma$ -ray emission from SN1987A in the near Large Magellanic Cloud galaxy, the closest known SN remnant in the past two centuries, is below detection limits. But its present lightcurve is believed to be powered by  $^{44}\text{Ti}$  radioactivity, and the inferred initial  $^{44}\text{Ti}$  yield is estimated to be  $(100\text{--}200) \mu M_{\odot}$  (see [2]), similar to that of Cas A. Using the  $^{56}\text{Ni}$  yield of SN1987A directly measured by  $\gamma$ -ray astronomy, the implied  $^{44}\text{Ti}/^{56}\text{Ni}$  ratio is larger by a factor  $\sim 3$  than estimated by stellar calculations [2]. No other source of  $^{44}\text{Ti}$  activity has been confirmed so far, despite a number of candidates and the improved sensitivity of the INTEGRAL  $\gamma$ -ray telescope [2]. Although many nuclear reactions play roles in determining the SN

yield of  $^{44}\text{Ti}$  [9,10], the major production reaction is  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$ , and its importance has been emphasized [11]. Experimental information about this reaction is incomplete, and theoretical estimates are made less reliable by the suppression of dipolar  $T = 0 \rightarrow 0$  transitions in self-conjugate ( $N = Z$ ) nuclei. The reaction was studied in the 1970s by  $\alpha$  bombardment of Ca targets and prompt- $\gamma$  spectroscopy down to  $E_{\text{c.m.}} \sim 3$  MeV, yielding energies, spins, and strengths of isolated resonances [12,13]. Rauscher *et al.* [14] used this information (together with that for lighter  $N = Z$  nuclei) to build an empirical model and calculate an astrophysical rate for the reaction, currently adopted in SN-nucleosynthesis codes. The aim of the present work is to provide new experimental information on the cross section of the  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  reaction and on the astrophysical rate of production of  $^{44}\text{Ti}$  in the energy range of SN nucleosynthesis. We use accelerator mass spectrometry (AMS), with which we determine the integral number of ground-state residual nuclei produced in an activation run. This method has been used to measure cross sections of astrophysical interest producing long-lived nuclides [15,16]. We measure for the first time the yield of the  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  reaction integrated over a large range of energies in the explosive-nucleosynthesis regime, allowing us to validate or scale the results of current theoretical models and derive an astrophysical rate compatible with laboratory experiment.

Our measurements were performed by bombarding a He-gas target cell with a  $^{40}\text{Ca}$  beam and implanting forward-recoiling reaction products in a Cu catcher acting also as beamstop. This inverse-kinematics approach has the advantage of using a high-purity target able to sustain

high beam power, where the thickness can be accurately controlled by monitoring the gas pressure. In the conditions of our experiment, the power deposited in the gas ( $<10$  mW/mm) is not expected to change its stopping power [17]. After irradiation,  $^{44}\text{Ti}$  atoms are chemically extracted from the catcher with a  $^{\text{nat}}\text{Ti}$  carrier. The abundance  $r_{44} = ^{44}\text{Ti}/\text{Ti}$  (in the  $10^{-13}$ – $10^{-12}$  range) is then measured by AMS, and the total number ( $n_{44}$ ) of  $^{44}\text{Ti}$  nuclei produced in the catcher is obtained by the relation  $n_{44} = r_{44}n_{\text{Ti}}$ , where  $n_{\text{Ti}}$  denotes the number of Ti carrier atoms used. Importantly, this result, based on the  $^{44}\text{Ti}/\text{Ti}$  isotopic ratio, is independent of chemical or counting efficiencies [15]. The experimental scheme was tested by producing a copious number of  $^{44}\text{Ti}$  nuclei ( $\sim 2.7 \times 10^9$ ) via the reaction  $^{34}\text{S}(^{12}\text{C}, 2n)^{44}\text{Ti}$  [18]. The  $^{44}\text{Ti}$  yield measured by AMS analysis and the derived cross section are consistent with those calculated by the evaporation code PACE2 [19].

The  $^{40}\text{Ca}$  irradiations were performed at two different accelerators. Using the electron-cyclotron ion source and the ATLAS linac at Argonne National Laboratory, an intense  $^{40}\text{Ca}^{11+}$  beam ( $\sim 1$  e  $\mu\text{A}$  on target) was produced. The irradiation was set up in a 32 cm-diameter chamber used as a gas cell. The vacuum window, made of a 1.5 mg/cm<sup>2</sup> pinhole-free Ni foil mounted eccentrically to the beam, was rotated at  $\sim 1$  Hz using a ferrofluidic vacuum seal to dissipate the power loss of the beam. He gas (99.995%) was circulated at room temperature in the large-volume chamber at constant pressure (12 Torr) during the  $^{40}\text{Ca}$  irradiation. The catcher, at a distance of 18 cm from the entrance Ni foil, was made of a 6.4 mm thick, 4.5 cm-diameter Cu (99.99%) disk, clamped to a chilled-water-cooled housing. The beam intensity was periodically measured during the irradiation run in an electron-suppressed Faraday cup situated 2 m upstream of the gas cell and continuously monitored by a beam scanner in front of the gas cell. In addition, a small Bragg-chamber detector viewed the Ni window through a 0.8 mm-diameter collimator at a scattering angle of  $49^\circ$  to monitor ions elastically scattered off the foil. Ion identification allowed for the discrimination between the main  $^{40}\text{Ca}$  beam and a  $(8.3 \pm 0.4)\%$  contamination of  $^{40}\text{Ar}$ . A correction to the ion beam charge was applied, using the monitored  $^{40}\text{Ca}$  fraction. It should be noted that the  $^{40}\text{Ar}$  projectiles cannot produce  $^{44}\text{Ti}$  from the  $^4\text{He}$  target. The incident laboratory energy (70.9 MeV) and He pressure (run R1, Table I) were tuned to populate a strong resonance ( $E_{\text{c.m.}} = 4.10$  MeV,  $J^\pi = 2^+$ ) in  $^{44}\text{Ti}$ , known from prompt  $\gamma$ -ray study [13]. Using an Enge magnetic spectrograph available on another beam line, the energy of the  $^{40}\text{Ca}$  beam after the Ni foil was measured before the irradiation (46.1 MeV, FWTM = 2.8 MeV). The energy loss is well reproduced by calculations performed with the SRIM-2003 code [20], which was used throughout our work to estimate specific energy loss. Irradiations under different conditions (see Table I and Fig. 1) were performed to verify that production of  $^{44}\text{Ti}$

TABLE I.  $^{40}\text{Ca}$  irradiations and  $^{44}\text{Ti}$  AMS analysis results.

Run	$E_{\text{lab}}$ (MeV) <sup>a</sup>	Target/ $\mu\text{g}/\text{cm}^2$	Irr. acc. <sup>b</sup>	$^{40}\text{Ca}$ dose ( $10^{16}$ )	$^{44}\text{Ti}$ AMS counts	$^{44}\text{Ti}/\text{Ti}$ ( $10^{-13}$ ) <sup>c</sup>	$n_{44}$ ( $10^6$ )
R1	46.1	He/51	L	6.9(14)	20	1.7(5)	6.4(17)
B1	46.1	Ar/106	L	3.9(8)	0	$<0.1$	$<0.3$
B2	42.5	He/42	L	2.6(5)	1	0.1(1)	0.3(3)
B3 <sup>d</sup>	...	...	L	...	0	$<0.1$	...
R2	46.4	He/590	T	3.06(12)	33	5.6(10)	21(4)
R3	46.4	He/590	T	4.00(20)	28	7.7(15)	30(6)
S1 <sup>e</sup>	...	...	...	...	377	380(20)	...
B4 <sup>f</sup>	...	...	...	...	0	$<0.1$	...

<sup>a</sup> $^{40}\text{Ca}$  incident energy after pressure foil.

<sup>b</sup>Irradiation accelerator: L = Linac, T = tandem.

<sup>c</sup>3.0 mg  $^{\text{nat}}\text{Ti}$  carrier used for each catcher.

<sup>d</sup>Unirradiated catcher.

<sup>e</sup>Calibration sample [ $^{44}\text{Ti}/\text{Ti} = (3.66 \pm 0.12) \times 10^{-11}$ ].

<sup>f</sup>Blank AMS cathode ( $^{\text{nat}}\text{Ti}$ ).

by background reactions is negligible: In run B1, the He gas was replaced by pure Ar (with similar incident energy loss), and in run B2 (with He gas) the incident energy was shifted downward ( $\Delta E_{\text{c.m.}} = -0.25$  MeV) off the resonance. The other irradiations were performed at the Koffler tandem accelerator (Weizmann Institute), using a (isobarically pure)  $^{40}\text{Ca}^{8+}$  beam with an average intensity of  $\sim 120$  enA on target. The He (99.999%) gas target and the water-cooled Cu catcher were contained in an electrically insulated and secondary-electron-suppressed chamber acting as a Faraday cup for beam charge integration. Catchers made of the same high-purity Cu material and a vacuum window made of the same Ni foil as in the ATLAS experiment, were used. In order to dissipate the power loss,

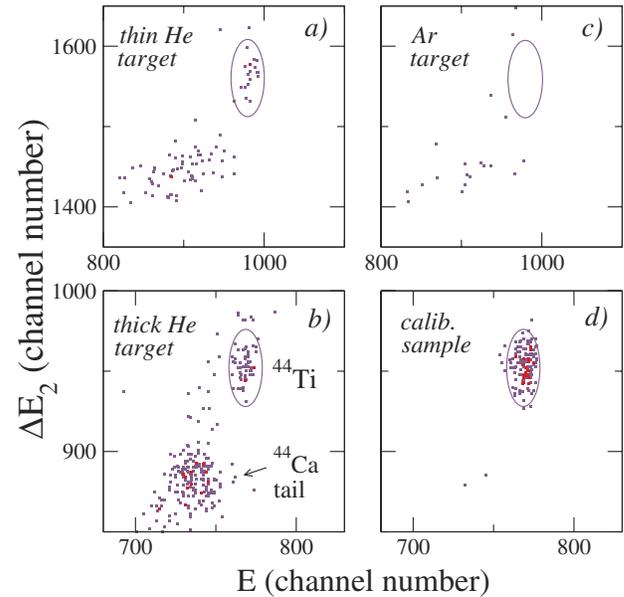


FIG. 1 (color online). Identification spectra of  $^{44}\text{Ti}$ :  $E$  and  $\Delta E_2$  are energy and energy-loss signals, respectively. The data shown have been filtered through a software condition set by additional energy-loss signals ( $\Delta E_1$ ,  $\Delta E_4$ ) and correspond to runs (a) R1; (b) R2, R3; (c) B1; (d) S1 (see Table I).

the beam was magnetically steered onto the vacuum window in a periodic ( $\sim 1$  Hz) spiral motion. The incident energy of the beam was set to 72.0 MeV, and the thickness of the  $^4\text{He}$  gas target (110 Torr, 23 cm) was selected to integrate the reaction yield from  $E_{c.m.} = 4.2$  MeV (after the vacuum window) down to  $E_{c.m.} = 2.1$  MeV, covering a large part of the SN-nucleosynthesis energy range. Two independent irradiation runs were performed under the same conditions, using different catchers (R2 and R3; see Table I).

After activation, a 10  $\mu\text{m}$ -thick layer was etched off each Cu catcher in a  $\text{HNO}_3$  solution containing 3 mg of Ti carrier.  $\text{Ti}^{4+}$  ions were separated from Cu by ion-exchange techniques, and Ti was finally converted to  $\text{TiO}_2$ . The  $^{44}\text{Ti}$  analysis and measurement of the isotopic ratios  $r_{44}$  were performed using the Hebrew University AMS facility [21] at the Koffler accelerator.  $^{44,46}\text{Ti}^-$  ions were alternately accelerated at a terminal voltage of 12 MV and  $^{44}\text{Ti}^{10+}$  ions transported to the detection system.  $^{44}\text{Ti}$  was discriminated from the dominant  $^{44}\text{Ca}$  isobaric background in a multianode ionization chamber (Fig. 1) and the  $^{46}\text{Ti}^{10+}$  charge current was measured, leading to the  $^{44}\text{Ti}/\text{Ti}$  ratio. In order to reduce systematic errors in the final  $r_{44}$  values, the ratios were normalized to those measured for a calibration sample (Table I; see [18,22] for information on the  $^{44}\text{Ti}$  source material). Blank samples (having gone through the same chemical procedures but containing no  $^{44}\text{Ti}$ ) were used to ensure that no background is present in the measurements. More details on the AMS analysis and the experiments can be found in Refs. [21,23,24].

The experimental results are summarized in Table I. We derive from run R1 a resonance strength  $\omega\gamma$  (see, e.g., [23] for a relation between yield and  $\omega\gamma$ ) of  $8.8 \pm 3.0$  eV, consistent with the results of prompt- $\gamma$  measurements [13] for the two close-by resonances in  $^{44}\text{Ti}$  at  $E_x = 9.227$  and 9.239 MeV ( $\omega\gamma = 5.8$  and 2.0 eV, respectively). Runs R2 and R3 (thick He target) give consistent  $^{44}\text{Ti}$  yields. If we interpret these yields as the sum over isolated resonances in the experimental range of energies, we derive lower and upper limits for the total resonance strength of 30 and 63 eV, respectively, depending on the energies of the resonances. Experimentally known resonances [12,13] in this energy range, and those used in the empirical model [14], sum to a total strength of 12.5 eV only. Considerations based on the energy dependence of the Wigner limit for the  $\alpha$  widths and of Weisskopf units for  $\gamma$  transition intensities require that isolated resonances with total strength of the order 30–60 eV ought to be centered above  $E_{c.m.} \sim 3.6$  MeV. Such resonances have not been observed so far, although this energy range has (at least in part) been investigated by prompt- $\gamma$  spectroscopy. The additional yield measured in the present experiment may result from unobserved resonances but more likely from closely spaced states in the  $^{44}\text{Ti}$  compound nucleus [ $E_x(^{44}\text{Ti}) = 7.2\text{--}9.3$  MeV], unresolved in previous experiments. We derive the experimental average cross section (thick He

target) over the measured energy range  $\sigma_{\text{ave}}^{\text{exp}} = n_{44}/(N_{\text{proj}}n_T) = (8.0 \pm 1.1) \mu\text{b}$  ( $N_{\text{proj}}$  is the number of incident projectiles and  $n_T$  the He target thickness in atoms/ $\text{cm}^2$ ) and compare it in Fig. 2(a) with the expression  $\sigma_{\text{ave}} = \int_{E_{\text{min}}}^{E_{\text{max}}} \sigma(E)(dE/dx)^{-1} dE/\Delta x$ , using values from current models for  $\sigma(E)$ . The present data strongly support the BRUSLIB statistical model [25], which incorporates a microscopic model of nuclear level densities [26] and of the  $\gamma$ -ray strength function [27], and a global  $\alpha$ -nucleus optical-model potential [28]; the NON-SMOKER [29] and empirical [14] models underestimate the average cross section. In the BRUSLIB model, the  $\gamma$  widths ( $\Gamma_\gamma$ ) are determined on the basis of a quasirandom phase approximation calculation (for details, see [27]) built on a Hartree-Fock description of the ground state, assuming complete isospin mixing. For  $N = Z$  nuclei, the standard prescription of Ref. [30] is adopted to account for the suppression of dipolar  $T = 0 \rightarrow 0$  transitions by reducing the corresponding  $\Gamma_\gamma$ 's by a factor  $f_{\text{iso}} = 5$ . The scaled BRUSLIB calculation [Fig. 2(a)] was modified to reproduce the experimental average cross section by adjusting the suppression factor to  $f_{\text{iso}} = 8$ . This value, an experimental measure of the degree of mixing of the  $T = 0$  into the  $T = 1$  states, confirms the large reduction of  $E1$  strength in a  $N = Z$  nucleus. It is close to the value ( $f_{\text{iso}} = 6\text{--}8$ ) derived in Ref. [31] for the  $^{24}\text{Mg}$  and  $^{32}\text{S}$  compound nuclei from a comparative analysis of the cross sections of ( $\alpha, \gamma$ ) reactions on  $N = Z$  and ( $Z, N = Z + 2$ ) target nuclei. The cross section  $\sigma(E)$  obtained from the scaled BRUSLIB calculation was integrated to yield the astrophysical rate of the  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  reaction [Fig. 2(b)]. The rate is higher by a factor 5–10 than that calculated with the model [14] over the range of temperatures of SN nucleosynthesis. It is well fitted by the expression  $N_A \langle \sigma v \rangle (\text{cm}^3 \text{s}^{-1} \text{mole}^{-1}) = \exp(107.92 - 2.254x^{-1} + 34.19x^{-1/3} - 167.81x^{1/3} + 6.867x - 0.2649x^{5/3} + 82.15 \ln(x))$ , where  $x = T_9$  in the range  $0.1 < T_9 < 10$  [ $T_9$  denotes the temperature (K) divided by  $10^9$  K].

We have used this new rate in SN-nucleosynthesis models and performed calculations as those described in Ref. [32] with the KEPLER code [33]. For 15 and 25  $M_\odot$  stars (models S15 and S25), we find that, while the  $^{56}\text{Ni}$  yield is kept at  $0.1M_\odot$ , the SN  $^{44}\text{Ti}$  yield in the ejecta increases by a factor  $\sim 2$  from  $14\mu M_\odot$  to  $27\mu M_\odot$  and from  $16\mu M_\odot$  to  $24\mu M_\odot$ , respectively. Due solely to the new reaction rate, both the absolute  $^{44}\text{Ti}$  yield and the  $^{44}\text{Ti}/^{56}\text{Ni}$  ratio are thus brought closer to the values inferred from  $\gamma$ -ray astronomy observations. The higher estimated  $^{44}\text{Ti}/^{56}\text{Ni}$  ratio is particularly important since it fits better the solar  $^{44}\text{Ca}/^{56}\text{Fe}$  ratio. Our calculations follow self-consistently spherical-symmetry hydrodynamics to determine the mass cut (the surface dividing the ejected mass from that falling back onto the compact object). Increase by a factor  $\sim 2$  in  $^{44}\text{Ti}$  is found also in the calculated fall back material. The yields of multidimensional SN explosion calculations proposed to explain the

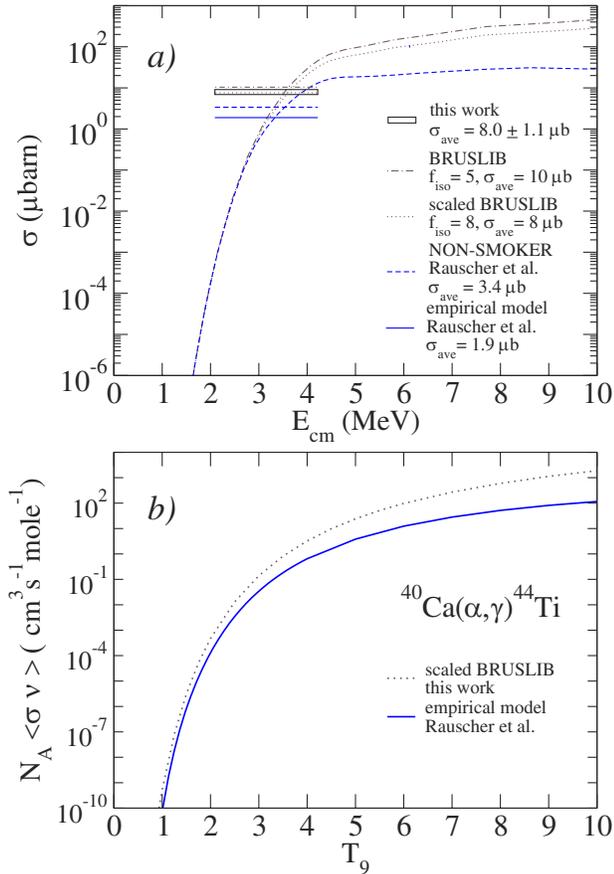


FIG. 2 (color online). (a) Comparison of the average cross section of the  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  reaction measured in the present experiment (open box) with current models. The horizontal bars represent the average cross section over the energy range, calculated with the different models (see text). (b) Astrophysical rate of the reaction calculated with scaled BRUSLIB (this work) and with the empirical model of Rauscher *et al.* [14], currently used in stellar calculations. See text.

observed  $^{44}\text{Ti}$  yield of Cas A [7], in which parts of deeper layers can be ejected while some of the outer layers fall back, are thus expected to be enhanced in  $^{44}\text{Ti}$  as well. The  $^{48}\text{Cr}$  production increased in our calculations only by 13% and 5.3%, increasing, after decay, the total stellar  $^{48}\text{Ti}$  yield of models S15 and S25 by 10% and 4%, respectively.

In summary, we have measured the integral yield and average cross section of the  $^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$  reaction over a large range of incident energies compatible with explosive nucleosynthesis by off-line counting of  $^{44}\text{Ti}$  ground-state nuclei. The yield is well reproduced by statistical calculations using microscopic nuclear inputs. It would be interesting to study the reaction in finer energy steps and investigate whether some prominent resonances also contribute to the yield. The associated astrophysical rate of the reaction is significantly larger than the one adopted in previous stellar calculations and increases the predicted SN  $^{44}\text{Ti}$  yield by a factor of  $\sim 2$ . The new estimates may account for the measured yield for the Cas A remnant and

support the prospect of identifying additional  $^{44}\text{Ti}$  localized sources in the Galaxy.

We gratefully acknowledge the participation of J. Görres, S. K. Hui, and M. Wiescher in early stages of this experiment. We thank A. Glasner, J. P. Schiffer, J. Truran, and S. Woosley for stimulating discussions and C. Feldstein and N. Trubnikov for their work on the chemistry procedure. This work was supported in part by the U.S. DOE, Office of Nuclear Physics, under Contract No. W-31-109-ENG-38, by the DOE Program for Scientific Discovery through Advanced Computing (SciDAC; DE-FC02-01ER41176), by DOE Contract No. W-7405-ENG-36 to the Los Alamos National Laboratory, and by the U.S.–Israel Binational Science Foundation (BSF).

\*To whom correspondence should be addressed.

Electronic address: paul@vms.huji.ac.il

- [1] D. Arnett, *Supernovae and Nucleosynthesis* (Princeton University Press, Princeton, 1996).
- [2] R. Diehl *et al.*, Nucl. Phys. A (to be published).
- [3] J. Vink, Adv. Space Res. **35**, 976 (2005).
- [4] J. Vink, New Astron. Rev. **48**, 61 (2004).
- [5] S. E. Woosley and T. A. Weaver, Astrophys. J. Suppl. Ser. **101**, 181 (1995).
- [6] F.-K. Thielemann *et al.*, Astrophys. J. **460**, 408 (1996).
- [7] S. Nagataki *et al.*, Astrophys. J. Lett. **492**, L45 (1998).
- [8] Y. Mochizuki *et al.*, Astron. Astrophys. **346**, 831 (1999).
- [9] L.-S. The *et al.*, Astrophys. J. **504**, 500 (1998).
- [10] A. A. Sonzogni *et al.*, Phys. Rev. Lett. **84**, 1651 (2000).
- [11] R. D. Hoffman *et al.*, Astrophys. J. **521**, 735 (1999).
- [12] E. L. Cooperman *et al.*, Nucl. Phys. **A284**, 163 (1977).
- [13] W. R. Dixon *et al.*, Phys. Rev. C **15**, 1896 (1977); Nucl. Phys. **A363**, 173 (1981).
- [14] T. Rauscher *et al.*, Nucl. Phys. **A675**, 695 (2000).
- [15] M. Paul *et al.*, Phys. Lett. **94B**, 303 (1980).
- [16] H. Nassar *et al.*, Phys. Rev. Lett. **94**, 092504 (2005).
- [17] J. Görres *et al.*, Nucl. Instrum. Methods **177**, 295 (1980).
- [18] S. K. Hui *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **172**, 642 (2000).
- [19] A. Gavron, Phys. Rev. C **21**, 230 (1980).
- [20] J. F. Ziegler, SRIM-2003, <http://www.srim.org/>.
- [21] D. Berkovits *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **223**, 161 (2004).
- [22] I. Ahmad *et al.*, Phys. Rev. Lett. **80**, 2550 (1998).
- [23] M. Paul *et al.*, Nucl. Phys. **A718**, 239c (2003).
- [24] H. Nassar *et al.*, Nucl. Phys. **A758**, 411c (2005).
- [25] M. Arnould and S. Goriely, Nucl. Phys. A (to be published).
- [26] P. Demetriou and S. Goriely, Nucl. Phys. **A695**, 95 (2001).
- [27] S. Goriely and E. Khan, Nucl. Phys. **A706**, 217 (2002).
- [28] P. Demetriou *et al.*, Nucl. Phys. **A707**, 253 (2002).
- [29] T. Rauscher and F.-K. Thielemann, At. Data Nucl. Data Tables **79**, 47 (2001).
- [30] J. A. Holmes *et al.*, At. Data Nucl. Data Tables **18**, 305 (1976).
- [31] H. L. Harney *et al.*, Rev. Mod. Phys. **58**, 607 (1986).
- [32] T. Rauscher *et al.*, Astrophys. J. **576**, 323 (2002).
- [33] T. A. Weaver *et al.*, Astrophys. J. **225**, 1021 (1978).