Gamow-Teller Strength in the Exotic Odd-Odd Nuclei ^{138}La and ^{180}Ta and Its Relevance for Neutrino Nucleosynthesis

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The Gamow-Teller strength distributions below the particle threshold in ^{138}La and ^{180}Ta, deduced from high-resolution measurements of the (^{3}He, t) reaction at 0°, allow us to evaluate the role of charged-current reactions for the production of these extremely rare nuclides in neutrino-nucleosynthesis models. The analysis suggests that essentially all ^{138}La in the Universe can be made that way. Neutrino nucleosynthesis also contributes significantly to the abundance of ^{180}Ta but the magnitude depends on the unknown branching ratio for population of the long-lived isomer.

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Nuclei with an odd number of protons and neutrons are a rarity amongst stable isotopes (9 out of about 300). The nucleosynthesis of the two heaviest, ^{138}La and ^{180}Ta, is a long-standing puzzle. In particular, for ^{138}La all major nucleosynthesis processes fail. It is too heavy for the α process, it is bypassed in the s process, and is shielded against the r process. Because it lies on the proton-rich side of the valley of stability, p-process production by the ^{138}La$(\gamma, n)^{138}$La reaction might be considered, but the latest data [1] and calculations [2] strongly discourage such a scenario. For ^{180}Ta the situation is slightly more complicated. Despite its isomeric nature, s-process production cannot be excluded [3] and may in fact account for close to 100% of the solar abundance [4]. Also, the p process is a possible source [2,5,6].

The present work focuses on the possibility to produce these rare exotic isotopes through neutrino-induced reactions in core-collapse supernovae (the so-called ν process [7]). Neutrino-nucleus reactions are a topic of current interest in supernova modeling [8,9] with impact on many dynamical aspects (see, e.g., Ref. [10]). Neutrino-induced reactions can also make important contributions to the synthesis of specific isotopes. However, since the weak interaction cross sections are so small, this requires an abundance difference of several orders of magnitude between mother and daughter nuclei. Prime examples are ^{11}B and ^{19}F produced in neutral-current (n.c.) reactions which generally have been conjectured to be the most important, while charged-current (c.c.) reactions were believed to contribute little. This conclusion, however, was based on very simplified assumptions [7] for the neutrino-induced cross sections for the heavier nuclides.

Recently, a refined analysis [2] showed that c.c. reactions can be important and changed the picture of how the rare, odd-odd isotopes ^{138}La and ^{180}Ta are produced. This study followed the neutrino nucleosynthesis in a self-consistent way in complete stellar evolution models (from [11]) including the evolution of all isotopes up to bismuth from the time the star ignited central hydrogen burning through the supernova explosion. It also used improved cross sections for the neutrino-induced reactions on key nuclides based on random phase approximation (RPA) calculations [12]. These calculations predict that ^{138}La is made almost exclusively by the charged-current reaction ^{138}Ba$(\nu_e, e)^{138}$La (as suggested earlier by [13]). Using the supernova progenitor model including heavy nuclei in the reaction network [11], ^{138}Ba was significantly enhanced over previous estimates [7] increasing the ^{138}La yield accordingly. This allows production of ^{138}La proportional to ^{16}O (the most abundant product in massive stars) at a solar abundance ratio, i.e., essentially all ^{138}La in the Universe could be made this way. Furthermore, about half of the solar ^{180}Ta abundance is predicted to be made by the p process and half by the c.c. reaction ^{180}Hf$(\nu_e, e)^{180}$Ta.

The low-energy nuclear response in neutrino-induced reactions is dominated by $\Delta S = 1$, $\Delta T = 1$ spin-isospin-flip excitations [8]. Electron neutrino temperatures T_e are rather low of the order of several MeV (corresponding to mean energies $\langle E \rangle \approx 3T_e$ for a Fermi-Dirac distribution without chemical potential). Thus, Gamow-Teller (GT)

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transitions characterized by angular momentum transfer $\Delta L = 0$ are most important. The main part of the GT response (the so-called GT resonance) is located at excitation energies above the neutron separation energy in the daughter nuclei. This implies a considerable uncertainty in the predictions based on the RPA calculations [2]. Besides the need to introduce an empirical quenching factor [12], a realistic description of the strength distributions requires the inclusion of complex configurations beyond the one particle-one hole excitations considered in RPA. These correlations will fragment the GT strength and can in fact shift some strength over the relevant particle thresholds producing, for example, ^{137}La rather than ^{138}La.

Clearly, experimental information on the GT response in ^{138}La and ^{180}Ta is highly desirable. The GT strength can be extracted from charge-exchange reactions at zero degrees and we have set out to determine it in high-resolution (^{3}He, t) experiments on ^{138}Ba and ^{180}Hf populating states in ^{138}La and ^{180}Ta, respectively. The experiments were performed at RCNP, Osaka University, Japan using a 140 MeV/nucleon ^{3}He beam with typical currents of about 10 nA. Data were taken with isotopically enriched (>99.9%) targets with an areal density of 2 mg/cm^3. Outgoing tritons were detected with the Grand Raiden magnetic spectrometer placed at 0°, covering an angle range $\Theta = 0° \simeq 3°$. At scattering angles close to 0° the selectivity to GT transitions is significantly enhanced over other nuclear transitions and thus only results deduced for a very limited angular range $\Theta = 0°$–$0.5°$ are used in the further analysis. The upper part of Fig. 1 presents the resulting spectrum for the ^{138}Ba(^{3}He, t)^{138}La reaction. Below $E_x \simeq 4$ MeV, resolved transitions are visible while the spectrum is smooth at higher energies. Despite the good energy resolution of about 70 keV full width at half maximum the level density becomes too high to resolve individual transitions.

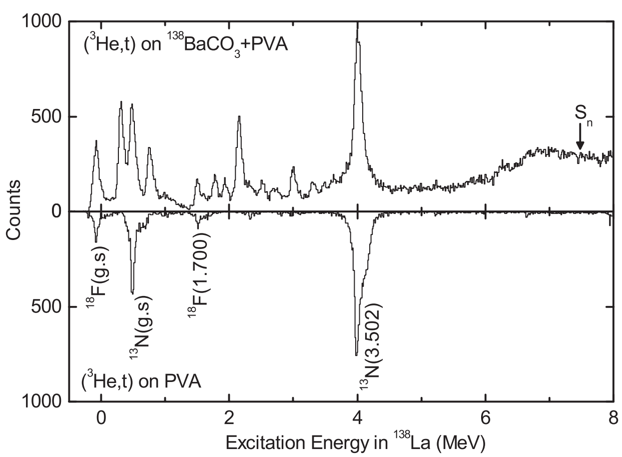

FIG. 1. Top: spectrum of the ^{138}Ba(^{3}He, t)^{138}La reaction at $E_0 = 420$ MeV and $\Theta = 0°$–$0.5°$. The target consisted of ^{138}BaCO$_3$ dissolved in PVA. Bottom: spectrum of the (^{3}He, t) reaction on PVA. S_n denotes the neutron emission threshold.

Because barium is extremely oxidizing, the enriched material (in the form of ^{138}BaCO$_3$) was dissolved in polyvinylalcohol (PVA) to produce a target following the procedure described in [14]. Because of its chemical composition $(C_2H_4O)n$, this causes considerable background lines from (^{3}He, t) reactions on C and O, which completely dominate the spectrum for excitation energies above 10 MeV. Here we take advantage of the large Q-value difference between the ^{138}Ba, ^{180}Hf(^{3}He, t) and ^{12}C, ^{16}O(^{3}He, t) reactions. In the energy range below particle threshold, only a few well-known transitions from the rare ^{13}C and ^{18}O isotopes contribute to the spectrum. These can be identified in a measurement on a pure PVA target under the same kinematical conditions shown in the lower part of Fig. 1. The difference in the relative intensities of the ^{13}N and ^{18}F lines visible in the two spectra results from the use of barium carbonate and has been corrected for before the subtraction of the background contributions.

The same method of target preparation (but using ^{180}HfO$_2$) has been applied for ^{180}Hf. The measured ^{180}Hf(^{3}He, t)^{180}Ta spectrum is presented in Fig. 2, again compared to the PVA spectrum. As ^{180}Ta is a well-deformed heavy odd-odd nucleus and therefore has an extremely high level density, only the ground state (g.s.) and one low-lying transition are resolved.

The properties of the (^{3}He, t) reaction at $E =$ 140 MeV/nucleon as a tool to measure detailed GT strength distributions have been well established in recent years by comparison of the zero degree cross sections with the GT strengths from the isospin-analogous β decays [15]. For an extraction of absolute GT strengths we make use of the so-called R^2 ratio [16] of the g.s. GT and Fermi transition strengths; the latter is deduced from the population of the isobaric analog state. The accumulated data [17] indicate that this normalization is a smooth function of mass number A and is constant within error bars for heavy nuclei with mass number $A > 100$. The normalization is taken for the cases of ^{138}La and ^{180}Ta from measurements of the (^{3}He, t) reaction on the neighboring nuclei ^{140}Ce and

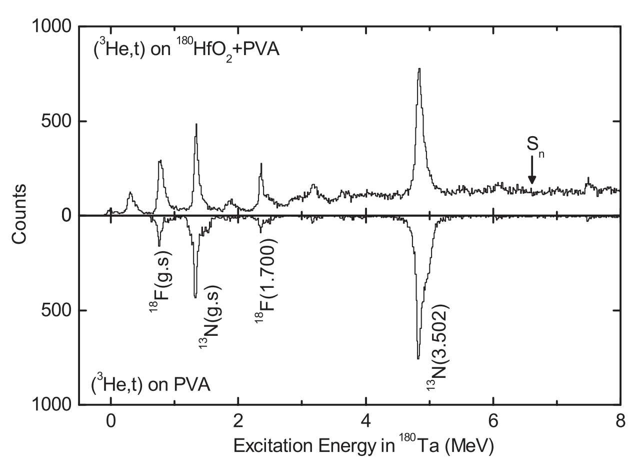

FIG. 2. Same as Fig. 1 but for a ^{180}HfO$_2$ target.

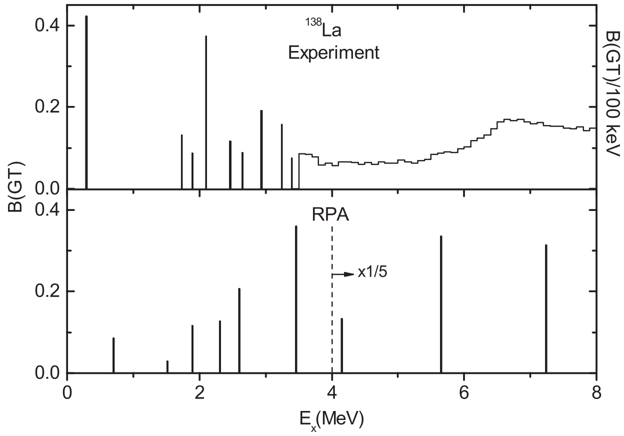

FIG. 3. GT strength distribution in ^{138}La. Top: present work. Bottom: RPA calculation used in Ref. [2].

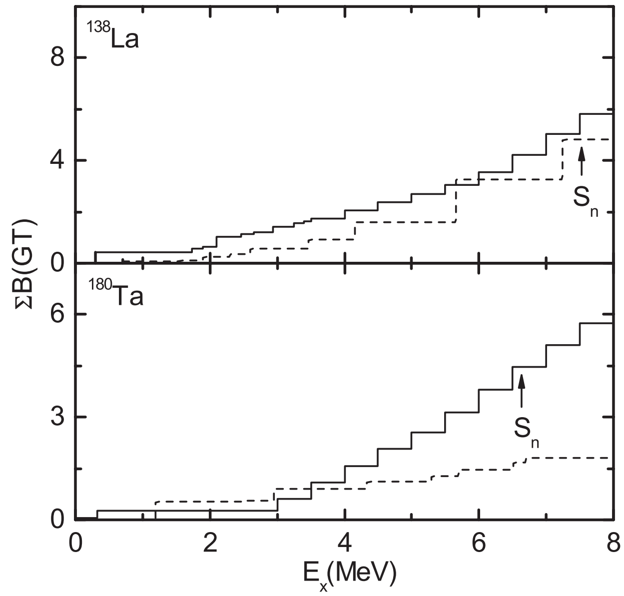

FIG. 4. Summed B(GT) strength in ^{138}La and ^{180}Ta as a function of excitation energy. The neutron emission thresholds (S_n) are indicated by arrows. Solid lines: present experiment. Dashed lines: RPA calculations from Ref. [2].

^{178}Hf, respectively, normalized to the corresponding β decays of the ^{140}Pr and ^{178}Ta ground states [18,19]. Since the smooth mass dependence of R^2 is a purely empirical finding and a few marked deviations are observed in lighter nuclei, the uncertainty of absolute B(GT) values is estimated to be $\pm 20\%$. This error includes possible $L > 0$ contributions in the measured cross sections which were estimated to be at most 5% by repeating the analysis for maximum angles varying between 0.2° and 0.8°.

The experimental B(GT) strength distribution is displayed in Fig. 3 for the case of ^{138}La together with the RPA results [2] used in the calculation of the ^{138}Ba$(\nu_e, e)^{138}$La cross sections. The comparison reveals a strong fragmentation of the experimental strength as opposed to a concentration in a few transitions in the theoretical results. A realistic model calculation of spin-isospin giant resonances requires the inclusion of complex configurations (see, e.g., [20]).

For nuclear astrophysics purposes in the present Letter, however, it is more appropriate to look at the summed B(GT) strengths as a function of excitation energy. The corresponding running sums are plotted in Fig. 4 for ^{138}La and ^{180}Ta. The total experimental GT strengths up to the neutron threshold amount to 5.8(1.6) for ^{138}La and 4.4(0.9) for ^{180}Ta. In the case of ^{138}La, this value corresponds to 126% of the RPA predictions and more strength is found experimentally at low energies. For ^{180}Ta, about 3 times the RPA result is obtained but the experimental strength at low E_x is smaller.

For the production of ^{138}La and ^{180}Hf by neutrino nucleosynthesis one has to know the partial ^{138}Ba(ν_e, e) and ^{180}Hf(ν_e, e) cross sections leading to the ^{138}La g.s. and to the isomeric state in ^{180}Ta. Neglecting small corrections due to finite momentum transfer, the GT contributions to these cross sections below particle threshold can be calculated from the measured B(GT) strength distributions as outlined in [21]. Since for both nuclei the proton thresholds open at energies below the neutron thresholds, the fraction of the B(GT) strength relevant for the ^{138}La and ^{180}Ta production is calculated using the statistical model code SMOKER [22]. While the GT strength dominates the cross sections of interest, other multipoles contribute as well (varying, e.g., for ^{138}La from 15% at $T = 4$ MeV to 25% at $T = 8$ MeV). Here, we adopt the cross sections for these multipoles from the RPA calculations presented in [2]. Table I compares the present ^{138}Ba$(\nu_e, e)^{138}$La and ^{180}Hf$(\nu_e, e)^{180}$Ta cross sections based on the experimental B(GT) strength distributions with the RPA results from [2]. For ^{180}Ta the sum of cross sections to the ground and isomeric states is given.

In Table II we give the post-supernova nucleosynthesis yields based on complete stellar models and explosions [2]. First we list key isotopes (^{16}O, ^{24}Mg, ^{28}Si) used to trace massive star contributions to nucleosynthesis and to the chemical evolution of the Universe which in turn can be used to normalize yields to solar abundances. Then, the yields required to obtain a solar production of ^{138}La and ^{180}Ta relative to ^{24}Mg based on the solar abundance compilation of [23] are compared to those from just the γ process (no neutrino interactions), and from the γ process

TABLE I. Cross sections for the reactions ^{138}Ba$(\nu_e, e)^{138}$La and ^{180}Hf$(\nu_e, e)^{180}$Ta (in units 10^{-42} cm^2) for different ν_e temperatures.

T (MeV)	^{138}La		^{180}Ta	
	present	RPA [2]	present	RPA [2]
4	74	61	151	115
6	226	156	399	272
8	435	281	752	485

TABLE II. Nucleosynthesis yields in solar masses. Top: key isotopes serving as tracers for the massive star contribution to nucleosynthesis. Middle: ^{138}La abundances compared to the solar value: γ process alone, n.c. reactions added (+), and c.c. reactions added (+ +) using either the present GT strength distribution or that from [2]. Bottom: same for ^{180}Ta.

$M_\odot$	15		25	
Ejecta	13.399		23.095	
^{16}O	0.849		3.316	
^{24}Mg	0.040		0.144	
^{28}Si	0.097		0.354	
^{138}La ($\times 10^{-10}$)	present	Ref. [2]	present	Ref. [2]
solar [23] (^{24}Mg)		1.115		4.014
γ-proc. only		0.241		0.525
+ n.c. (6 MeV)		0.353		0.948
++ c.c. (4 MeV)	1.394	1.233	5.143	4.453
++ c.c. (6 MeV)	2.549	2.195	9.465	7.929
++ c.c. (8 MeV)	4.080	3.110	15.29	11.09
^{180}Ta ($\times 10^{-12}$)	present	Ref. [2]	present	Ref. [2]
solar [23] (^{24}Mg)		0.880		3.171
γ-proc. only		0.600		5.402
+ n.c. (6 MeV)		1.016		9.218
++ c.c. (4 MeV)	3.125	2.755	18.25	16.57
++ c.c. (6 MeV)	5.411	4.632	27.95	24.36
++ c.c. (8 MeV)	7.392	6.036	34.00	27.78

plus n.c. interactions (assuming $T_\nu = 6$ MeV). Finally, we present the complete yields including c.c. interactions for different ν_e temperatures, using the cross sections from [2] and from the present work.

For ^{138}La clearly the charged-current interaction is needed to reproduce the solar yields, and a ν_e temperature around 4 MeV seems sufficient. For this energy, the new results give a ~15% higher yield. Both stars show yields above the solar value, however, the solar composition also includes contributions from stars of lower metallicity. Since the production of ^{138}La depends on the abundance of the ^{138}Ba seed nucleus, those stars contribute less and hence stars of around solar metalicity, as simulated here, need a larger-than-solar contribution.

The ^{180}Ta yields do not take into account that a fraction of the isotope (about 65% after freeze-out from temperatures high enough to achieve thermal equilibrium [24]) may be produced in the short-lived ground state and decay quickly; however, a detailed calculation including full reaction kinematics has not been performed and would be limited by our knowledge about the distribution between the g.s. and isomeric state during each of the contributing processes. Like ^{138}La, the production of ^{180}Ta in the ν process is dominated by the charged-current reaction. However, even without charged current ^{180}Ta may already be sufficiently produced.

In conclusion, the B(GT) strength distributions in ^{138}La and ^{180}Ta were deduced from the reactions ^{138}Ba, ^{180}Hf(^{3}He, t) measured at 0° with good energy resolution. The results put models concerning possible production mechanisms of these extremely rare isotopes on safer grounds: essentially all ^{138}La in the Universe can be made in the ν process by charged-current reactions. These also contribute significantly (up to about 50%) to the abundance of ^{180}Ta but the exact magnitude depends on the yet unknown branching ratio between population of the long-lived isomer and the short-lived ground state.

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