Nuclear astrophysics with secondary (radioactive) beams

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ABSTRACT. Some problems in nuclear astrophysics are discussed with emphasis on the ones central to the field which were not solved over the last two decades, including helium burning in massive stars (the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction) and the $^8$B solar neutrino flux problem (the $^7$Be($p, \gamma$)$^8$B reaction). We demonstrate that a great deal of progress was achieved by measuring the time reverse process(es): the beta-delayed alpha-particle emission of $^{16}$N and the Coulomb dissociation of $^8$B, using radioactive beams of $^{16}$N and $^8$B. In this way an amplification of the sought for cross section was achieved, allowing a measurement of the small cross section(s) of relevance for stellar (solar) processes.

RESUMEN. Se discuten algunos problemas de astrofísica nuclear con énfasis en aquellos que son centrales en este campo y que no han sido resueltos en las últimas dos décadas, incluyéndose el consumo de helio en las estrellas masivas (la reacción $^{12}$C($\alpha, \gamma$)$^{16}$O) y el problema del flujo de neutrinos solares de $^8$B (la reacción $^7$Be($p, \gamma$)$^8$B). Demostramos que se han hecho grandes progresos mediante la medición de los procesos de tiempo inverso: la emisión de partícula alfa retardada por beta de $^{16}$N y la dissociación coulombiana de $^8$B, usando haces radioactivos (de $^{16}$N y $^8$B). En esta forma se logró una amplificación de la sección transversal que se busca, permitiendo la medición de las pequeña(s) sección(es) transversales que tienen importancia para procesos estelares (solares).

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1. INTRODUCTION

Nuclear Astrophysics, the study of Nuclear inputs to astrophysics theories, is a mature science [1] that has developed to the point where we can now use stars to probe fundamental physics questions. However, as some critical problems are left unsolved, it presents a formidable challenge to Nuclear Science. In this paper we address two such problems involving key reaction rates: the $^{12}$C($\alpha, \gamma$)$^{16}$O and $^7$Be($p, \gamma$)$^8$B, of importance for understanding helium burning and $^8$B solar neutrino flux, respectively. We demonstrate that a great deal of progress was achieved by using Radioactive Beams to study these reactions in their time reverse process. These new techniques allow us to add useful data and constraints on the studied nuclear processes.

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2. NUCLEOSYNTIIESIS IN MASSIVE STARS

Stars commence their energy generating life cycle by burning hydrogen to form helium. As stars consume their hydrogen fuel in the core, now composed mainly of helium, it contracts, raising its temperature and density. For example, in 25 solar masses stars the hydrogen burning lasts for 7 Million years. At temperatures of the order of 200 MK [2,3], the burning of helium sets in. The first reaction to occur in helium burning is the $\alpha + \alpha \rightarrow ^8\text{Be}$, and due to the short lifetime of $^8\text{Be}$ this reaction yield a small concentration of $^8\text{Be}$ nuclei in the star. However, this reaction is very crucial as a stepping stone for the next reaction that is loosely described as the three alpha-capture process: $^8\text{Be}(\alpha, \gamma)^{12}\text{C}$. The formation of small concentration of $^8\text{Be}$, allows for a larger phase space for the triple alpha-capture reaction to occur. This reaction was originally proposed by sir Fred Hoyle in the 50’s, as a solution for bridging the gap over the mass 5 and 8, where no stable elements exist, and therefore the production of heavier elements. The triple alpha capture reaction is governed by the excited $0^+$ state in $^{12}\text{C}$ at 7.654 MeV. This state was predicted by Fred Hoyle, prior to its discovery (by Fred Hoyle himself) at the Kellog radiation lab [1]. One loosely refers to this $0^+$ state as the reason for our existence, since without it the universe will have a lot less carbon and indeed a lot less heavy elements, needed for life. Extensive studies of properties of this state by nuclear spectroscopists, allow us to determine the triple alpha-capture rate with accuracy better than 10%.

At the same temperature range (200 MK), the produced $^{12}\text{C}$ nuclei can undergo subsequent alpha-particle capture to form $^{16}\text{O}$ via the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction. Unlike the triple alpha-capture reaction this reaction occurs in the continuum. This reaction is governed by the quantum mechanical tail of the bound $2^+$ at 6.92 MeV, and the interference of the tail of the bound $1^-$ state at 7.12 MeV and the tail of the quasi-bound $1^-$ state at 9.63 MeV in $^{16}\text{O}$. These effects eluded measurements of the cross section (and the S-factor $= E\sigma \exp(2\pi \eta)$ and $\eta = e^2 Z_1 Z_2/\hbar \nu$) of the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction for the last two decades, in spite of repeated attempts [4–8], and was only recently measured using the time reverse process of the disintegration of $^{16}\text{O}$, populated in the beta-decay of $^{16}\text{N}$ [9–14]. Helium burning lasts for approximately 500,000 years in a 25 solar masses star [2,3], and occurs at temperatures of approximately 200 MK.

Stars of masses smaller than approximately 8 solar masses complete their energy generating life cycle at the helium burning cycle. At the end of this cycle they are composed mainly of carbon and oxygen and contract to a dwarf, lying forever on the left bottom corner of the H-R diagram. More massive stars at the end of helium burning, commence carbon burning at a temperature of approximately 600–900 MK. Carbon burning lasts for 600 years in 25 solar masses stars [2,3]. The main reaction in carbon burning is the $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ reaction, but elements such as $^{23}\text{Na}$ and some $^{24}\text{Mg}$ are also produced. At temperatures of approximately 1.5 BK (approximately 150 keV) the tail of the Boltzmann distribution allows for the photo-disintegration of $^{20}\text{Ne}$ with an alpha-particle threshold as low as 4.73 MeV. This reaction $^{20}\text{Ne}(\gamma, \alpha)^{16}\text{O}$ serves as a source of alpha-particles which are then captured by $^{20}\text{Ne}$ to form $^{24}\text{Mg}$ and $^{28}\text{Si}$. The neon burning cycle lasts for 1 year in a 25 solar masses stars. These alpha-particles could also react with $^{22}\text{Ne}$, as suggested by Icko Iben [15], to yield neutron flux via the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction and give rise to the slow capture of neutrons and the production of the heavy
Figure 1. Burning stages and onion-like structure of a 25 $M_{\odot}$ star prior to its supernova explosion [2,3].

Elements via the (weak) s-process. At this point the core is rich with oxygen, and it contracts further and the burning of oxygen commence at a temperature of 2 BK, mainly via the reaction $^{16}O(^{16}O, \alpha)^{28}\text{Si}$, with the additional production of the elements sulfur and potassium. The oxygen burning period lasts for approximately 6 months in a 25 solar masses star. At temperatures of approximately 3 BK a very brief (one day or so) cycle of the burning of silicon commence. In this burning period elements in the iron group are produced. These elements can not be further burned as they are the most bound (with binding energy per nucleon of the order of 8 MeV), and they represent the ashes of the stellar fire. The star now resemble the onion like structure shown in Fig. 1.
As the inactive iron core aggregates mass it reaches the Chandrasekhar limit (close to 1.4 solar mass) and it collapses under its own gravitational pressure, leading to the most spectacular event of a supernova. During a supernova the electrons are energetic enough to undergo electron capture by the nuclei and all protons are transposed to neutrons, releasing the gravitational binding energy (of the order of $3/5GM^2/R \approx 3 \times 10^{53}$ ergs) mostly in the form of neutrino’s of approximately 10 MeV (and temperature of approximately 100 BK). As the core is now composed of compressed nuclear matter (several times denser than nuclei), it is black to neutrinos (i.e. absorbs the neutrinos) and a neutrino bubble is formed for approximately 10 sec, creating an outward push of the remnants of the star. This outward push is believed (by some) to create the explosion of a type II supernova. During this explosion many processes occur, including the rapid neutron capture (r process) that forms the heavier elements of total mass of approximately $M \approx \mu M_\odot$.

The supernova explosion ejects into the inter-stellar medium its ashes from which at a later time “solar systems” are formed. Indeed the death of one star gives the birth of another. At the center of the explosion we find a remnant neutron star or a black hole.

It is clear from Fig. 1 that if in the process of helium burning mostly oxygen is formed, the star will be able to take a shorter route to the supernova explosion. In fact if the carbon to oxygen ratio at the end of helium burning in a 25 solar masses star, is smaller then approximately 15% [16], the star will skip the carbon and neon burning and directly proceed to the oxygen burning. For a cross section of the $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$ reaction that is twice the accepted value (but not 1.7 the accepted value), a 25 solar masses star will not produce $^{20}\text{Ne}$, since carbon burning is essentially turned off. This indeed will change the thermodynamics and structure of the core of the progenitor star and in fact such an oxygen rich star is more likely to collapse into a black hole [16] while carbon rich progenitor stars is more likely to leave behind a neutron star. Hence one needs to know the carbon to oxygen ratio at the end of helium burning (with an accuracy of the order of 15%) in order to understand the fate of a dying star and the heavy elements it produces.

Since the triple alpha-particle capture reaction: $^{8}\text{Be} (\alpha, \gamma) ^{12}\text{C}$ is very well understood, see above, one must measure the cross section of the $^{12}\text{C} (\alpha, \gamma) ^{16}\text{O}$ reaction with high accuracy of the order of 15% or better. Unfortunately, this task was not possible over the last two decades using conventional techniques and was only recently tackled using radioactive beams [9–14]. This cross section is needed to be measured at the most effective energy for helium burning (the Gamow window) of 300 keV. At this energy one may estimate [1] the cross section to be $10^{-8}$ nbarn, clearly non measurable in laboratory experiments. In fact the cross section could be measured down to approximately 1.0 MeV and one needs to extrapolate further down to 300 keV. As we discuss below the extrapolation to 300 keV, which in most other cases in nuclear astrophysics could be performed with certain reliability, is made difficult by a few effects.

The cross section at astrophysical energies has contribution from the p and d waves and is dominated by tails of the two bound states of $^{16}\text{O}$, the $1^-$ at 7.12 MeV (p-wave) and the $2^+$ at 6.92 MeV (d-wave). The p-wave contribution arises from a detailed interference of the tail of the bound $1^-$ state at 7.12 MeV and the broad $1^-$ state at 6.93 MeV.
The contribution of the bound $1^-$ state arises from its virtual alpha-particle width, that could not be reliably measured or calculated. Furthermore, the tails of the quasi-bound and bound $1^-$ states interfere in the continuum and the mixing phase angle can not be determined from existing data measured only at higher energies and therefore it does not show sensitivity to the above questions. Due to these reasons the cross section of the $^{12}C(\alpha, \gamma)^{16}O$ reaction could not be measured in a reliable way at 300 keV, and the p-wave S-factor at 300 keV, for example, was estimated to be between 0–500 keV-barn with a compiled value of $S_p(300) = 60 + 60 - 30$ keV-b [17,18] and $S_d(300) = 40 + 40 - 20$ keV-b. This large uncertainty is contrasted by the astrophysical need to know the S-factor with 15% accuracy.

The beta-delayed alpha-emission of $^{16}N$ allows the study of the $^{12}C(\alpha, \gamma)^{16}O$ reaction in its time reverse fashion, the disintegration of $^{16}O$ to $\alpha + ^{12}C$, and it provides a high sensitivity for measuring low energy alpha-particles and the reduced (virtual) alpha-particle width of the bound $1^-$ state in $^{16}O$ at 7.12 MeV. As shown in Fig. 2, low energy alpha-particle emitted from $^{16}N$ correspond to high energy beta's and thus to a larger phase space and enhancement (proportional to the total energy to approximately the fifth
power). In addition the apparent larger matrix element of the beta decay to the bound $1^-$ state provides further sensitivity to that state.

It is clear from Fig. 2 that the beta-decay in this case provides a "NARROW BAND WIDTH HI FI AMPLIFIER", where the high fidelity is given by our understanding of the predicted shape of the beta-decays. As we demonstrate later Radioactive Beams are very essential in providing such "hi fi amplifiers" and allow for a measurement of the small cross sections of relevance for Nuclear Astrophysics. However, in this case one needs to measure the beta decay with a sensitivity for a branching ratio of the order of $10^{-9}$ or better. In this case we have replaced an impossible experiment (the measurement of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction at low energies) with a very hard one (the beta-delayed alpha-particle emission of $^{16}\text{N}$).

Prediction of the shape of the spectra of delayed alpha-particles from $^{16}\text{N}$ were first published by Baye and Descouvemont [19], with an anomalous interference structure around 1.1 MeV, at a branching ratio at the level of $10^{-9}$. The reduced alpha-particle width of the bound $1^-$ state can be directly "read off" the spectra if measured at such low energies. We emphasize that these predictions were published approximately five years prior to the observation of the anomalous interference structure around 1.1 MeV [13,9]. The previously measured beta-delayed alpha-particle emission of $^{16}\text{N}$ [20] was analyzed using R-matrix theory by Barker [21] and lately by Ji, Filippone, Humblet and Koonin [22]. They conclude that the data measured at higher energies is dominated by the quasi bound $1^-$ state in $^{16}\text{O}$ at 9.63 MeV and shows little sensitivity to the interference with the bound $1^-$ state. The data measured at low energies is predicted to have large sensitivity to the anomalous interference with the bound $1^-$ state. Similar prediction were also given by a K-matrix analysis of Humblet, Filippone, and Koonin [23] of the same early data on $^{16}\text{N}$ [20]. We again note that both the R-matrix paper and K-matrix paper were published three and two years, respectively, prior to publication of the spectra from $^{16}\text{N}$ [13,9].

As shown in Fig. 2, the beta decay can only measure the p-wave S-factor of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction, and it also includes (small) contribution from an f-wave. The contribution of the f-wave has to be determined empirically and appears to be very small and leads to some (at most 15%) uncertainty in the quoted S-factor [9,10,12]. The total S-factor of the $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ reaction could be extracted from the knowledge of the $E2/E1$ ratio which is better known than the individual quantities.

An experimental program to study the beta-delayed alpha-particle emission of $^{16}\text{N}$ (and other nuclei) was commenced at Yale University in early 1989. A similar program commenced at about the same time at the TISOL radioactive beam facility at TRIUMF. After some four years of studies and background reduction, the first observation of the interference anomaly was carried out in November of 1992. A preliminary report of the data was given by Zhiping Zhao of Yale University in a seminar at Caltech in January 1992. At that time the anomaly around 1.1 MeV was observed with small statistics (approximately 25 counts in the anomaly). In March of 1992 the TRIUMF collaboration also observed 9 counts in the anomalous structure as reported by Charlie Barnes in the meeting of the AAAS in Ohio, June, 1992. The two collaboration have carried out the required checks and data analyses and in November 1992 both collaborations submitted their papers for publication in the Phys. Rev. Lett. within ten days [13,9]. While the two parallel experiments were very different in their production of $^{16}\text{N}$ and detection methods, and
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hence acquire different systematical error(s), they appear to be in agreement and quote similar S-factors, of similar accuracy and with good agreement. The R-Matrix analysis of the two experiments [9, 24, 14] yield:

Yale Result: \( S_{E1}(300) = 95 \pm 6 \) (stat) \( \pm 28 \) (syst) keV-b

TRIUMF II Result: \( = 79 \pm 21 \) keV-b

In the Yale experiment [9, 10], recoiling \(^{16}\text{N}\) nuclei produced with a 9 MeV deuterium beams with the \(^{15}\text{N}\)(d, p)\(^{16}\text{N}\) reaction, were collected in a Ti\(^{15}\text{N}\) foil (with Au backing), tilted at 7° with respect to the beam. The foil is then rotated using a stepping motor to a counting area where the time of flight between alpha-particles, measured with an array of 9 Si surface barrier detectors, and beta-particles, measured with an array of 12 plastic scintillators, is recorded. The experiment is described in details [9, 10, 12] and it arrived at a sensitivity for the branching ratio of the beta-decay in the range of \(10^{-9}\) (to \(10^{-10}\)), see Fig. 3, where we show one of the cleanest spectrum. Other spectra show background at the level of branching ratio of \(10^{-9}\).

The data measured at Yale University arise from alpha-particle that traverse the production foil and thus need to be corrected for such effects. Hence, we have measured the spectra of beta-delayed alpha-particle emission of \(^{16}\text{N}\) in the absence of foil. This was achieved by implanting radioactive \(^{16}\text{N}\) beams from the MSU A1200 radioactive beam facility [11], into a surface barrier detector and by studying the alpha-decay in the detector. In this experiment the absolute branching ratio for the beta decay to the quasi bound 1\(^{-}\) state was also measured [11].
The spectrum after correction for the foil thickness and response function was fitted with the R-matrix formalism developed by Ji, Filippone, Humblet, and Koonin [22] as shown in Figs. 4a and 4b. Indeed this spectrum appears to be in agreement with the one measured at TRIUMF [13] and more recently at Seattle [25], as shown in Fig. 5.

An attempt to extract the total $(E1 + E2)$ S-factor for the $^{12}C(\alpha, \gamma)^{16}O$ reaction from the abundance of the elements was carried out by Weaver and Woosley [16], by comparing the calculated abundance of the elements to the solar abundance. In this calculation the $^{12}C(\alpha, \gamma)^{16}O$ cross section was varied between 0.5 to 3 times the value tabulated in CF88 [17] and listed in [18]: $S_{E1} = 60 + 60 - 30 \text{ keV-b}$ and $S_{E2} = 40 + 40 - 20 \text{ keV-b}$. As shown in Fig. 6, they can reproduce the observed solar abundances only for a cross section which is $1.7 \pm 0.5$ times CF88. If we assume the ratio $E1/E2 = 1.5$, as suggested in CF88 [17,18], we derive:

\[
\text{Weaver and Woosley's Result: } S_{E1}(300) = 102 \pm 30 \text{ keV-b}
\]

in excellent agreement with laboratory measurements, see above.

3. The COULOMB DISSOCIATION OF $^8B$ AND THE $^8B$ SOLAR NEUTRINO FLUX

The Coulomb Dissociation [26] Primakoff [27] process, is the time reverse process of the radiative capture. In this case instead of studying for example the fusion of a proton plus a nucleus $(A - 1)$, one studies the disintegration of the final nucleus $(A)$ in the Coulomb field, to a proton plus the $(A - 1)$ nucleus. The reaction is made possible by the absorption of a virtual photon from the field of a high $Z$ nucleus such as $^{208}\text{Pb}$. In this case since $\pi/k^2$ for a photon is approximately 1000 times larger than that of a particle beam, the small cross section is enhanced. The large virtual photon flux (typically 100–1000 photons per collision) also gives rise to enhancement of the cross section. Our understanding of QED and the virtual photon flux allow us (as in the case of electron scattering) to deduce the
inverse nuclear process. In this case we again construct a "NARROW BAND WIDTH HI FI AMPLIFIER" to measure the exceedingly small nuclear cross section of interest for nuclear astrophysics. However in Coulomb dissociation since $\alpha Z$ approaches unity (unlike the case in electron scattering), higher order Coulomb effects (Coulomb post acceleration) may be non-negligible and they need to be understood [28-30]. The success of the experiment is in fact hinging on understanding such effects and designing the kinematical conditions so as to minimize such effects.
FIGURE 6. The $^12\text{C}(\alpha, \gamma)^{16}\text{O}$ cross section extracted from the observed solar abundances [16].

Hence the Coulomb dissociation process has to be measured with great care with kinematical conditions carefully adjusted so as to minimize nuclear interactions (i.e. distance of closest approach considerably larger than 20 fm, or very small forward angles scattering), and measurements must be carried out at high enough energies (many tens of MeV/u) so as to maximize the virtual photon flux. Indeed when such conditions were not carefully selected [31, 32] the measured cross sections were found to be dominated by nuclear effects, which can not be reliably calculated to allow the extraction of the inverse radiative capture cross section.

Good agreement between measured cross section of radiative capture through a nuclear state, or in the continuum, was achieved for the Coulomb dissociation of $^6\text{Li}$ and the $^4\text{He}(d, \gamma)^6\text{Li}$ capture reaction [33], and the Coulomb dissociation of $^{14}\text{O}$ and the $^{13}\text{N}(p, \gamma)^{14}\text{O}$ capture reaction [34–36]. In addition we note that a test experiment on the Coulomb dissociation of $^{13}\text{N}$ [34] was also found to be in agreement with the $^{12}\text{C}(p, \gamma)^{13}\text{N}$ capture reaction.

The Coulomb dissociation of $^8\text{B}$ may provide a good opportunity for resolving the issue of the absolute value of the cross section of the $^7\text{Be}(p, \gamma)^8\text{B}$ reaction. The Coulomb dissociation yield arise from the convolution of the inverse nuclear cross section times the virtual photon flux. While the first one is decreasing as one approaches low energies, the second one is increasing (due to the small threshold of 137 keV). Hence as can be seen in Fig. 7 over the energy region of 400 to 800 keV the predicted measured yield is roughly constant. This is in contrast to the case of the nuclear cross section that is dropping very fast at low energies, see Fig. 7. Hence measurements at these energies could be used to evaluate the absolute value of the cross section.

The Coulomb Dissociation process measured at lower energies is insensitive to the $M1$
component of the cross section, since the $M1$ virtual photon flux is smaller by a factor (smaller than) $\beta^2$. In this case the $1^+$ state in $^8B$ at $E_{cm} = 632$ keV, is not expected to be observed. The $M1$ contribution is predicted to be approximately 10% of the $^7Be(p, \gamma)^8B$ cross section [37] measured just below 1 MeV, which yield to a 10% correction of the $S_{17}$-factor extracted from the radiative capture work [38], but not the $S_{17}$ factor extracted from the Coulomb dissociation.

An experiment to study the Coulomb dissociation of $^8B$ was performed during March-April, 1992, at the RIKEN-RIPS radioactive beam facility. The experiment is a Rikkyo-RIKEN-Yale-Tokyo-LLN collaboration [39]. The radioactive beams extracted from the RIPS separator are shown in Fig. 8. Indeed the results of the experiment allow us to measure the cross section of the $^7Be(p, \gamma)^8B$ radiative capture reaction and preliminary results are consistent with the absolute value of the cross section measured by Filippone et al. [40] and by Vaughn et al. [41], as shown in Fig. 9.

3.1. Is there evidence for an $E2$ component?

The much publicized [42] paper of Langanke and Shoppa (LS) [43] infers that the data analysis performed by the RIKEN collaboration is invalid due to the model dependent prediction of LS of a large $E2$ component in the CD of $^8B$, which was ignored in our paper [39]. In the following we show that their assertion arose from a misunderstanding of the experimental procedures of the RIKEN experiment.

We first note that I have pointed to LS that they have used and published (before the
RIKEN collaboration!) incorrect data, including wrong error bar. Langanke and Shoppa now attempt to correct it in a form of (a revised) Erratum. More crucial is however the fact that LS appear to ignore the angular resolution of the RIKEN experiment. The finite angular resolution implies that the acceptance (or response) of the RIKEN detector is not the same for $E_1$ and $E_2$. This invalidates the basic assumption of LS that "Assumes the detector efficiency is the same for $E_1$ and $E_2$ contributions" [43]. As it turns out the angular averaging tends to push the predicted $E_1$ cross section to large angles, where the $E_2$ dominates. And the large $E_2$ predicted by LS appears to be a compensation for their neglect of the angular resolution of the RIKEN experiment.

A search for $E_2$ component in the RIKEN data was performed by Cai and Bertulani [44]. When the experimental resolutions are correctly taken into account, together with the correct RIKEN data (!) the best fit of the angular distributions is obtained with $E_1$ amplitude alone, as shown in Fig. 10. Our analysis invalidates the claims of LS and support the analysis performed by Dr. Iwasa and his advisor Professor Motobayashi, as presented in Ref. [39].

In conclusion we demonstrate that the Coulomb dissociation provides a viable alternative method for measuring small cross section of interest for nuclear-astrophysics. First results on the CD of $^8$B are encouraging for a continued effort to extract $S_{17}(0)$, of importance for the SSM. Our initial results are consistent with the lower value of the cross section measured by Filippone et al. and suggest a small value for the extracted $S_{17}(0)$; smaller than 20 eV-barn, and considerably smaller (30%) than assumed in the SSM of Bahcall et al.
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Figure 10. The reduced $\chi^2$ obtained from fitting the 600 keV angular distribution with: $\sigma_{CD}(E1) + \sigma_{CD}(E2)$. The best fit is obtained with $E1$ amplitude only, with $S_{17} = 18$ eV-b (for the 600 keV angular distribution) [44].

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