How Well Do We Know the Beta-Decay of $^{16}$N and Oxygen Formation in Helium Burning?

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Abstract. Contrary to claims that the problem has been solved, the astrophysical E1 S-factor of $^{12}$C($\alpha, \gamma$)$^{16}$O is not yet well known. R-Matrix analyses of elastic scattering data, $^{12}$C($\alpha, \gamma$)$^{16}$O data, and data on the beta-delayed alpha-particle emission of $^{16}$N are not consistent and a small S-factor solution [$S_{E1}(300)$] cannot be ruled out. In particular, data on the beta-delayed alpha-particle emission of $^{16}$N do not agree. The unaltered Mainz data do not agree with TRIUMF, but agree with both Seattle and Yale-UConn. The TRIUMF collaboration has recalibrated the Mainz('71) data; however, we dispute both the alteration of the Mainz data performed by the TRIUMF collaboration and the very justification for the recalibration.

1 Introduction

Recently, a measurement of the beta-delayed alpha-particle emission of $^{16}$N was performed at TRIUMF [1, 2, 4], which, together with an R-Matrix analysis of these and related data, was used to extract a value for the p-wave astrophysical S-factor of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction. Such an analysis relies upon accurate knowledge of the line-shape of the spectrum of the beta-delayed alpha-particle emission of $^{16}$N. In the same paper [1] a comparison with the Mainz('71) data is shown, as communicated to Dr. F.C. Barker by Dr. H. Waffler [3] and published [7, 8, 9], and it is claimed [1] that the Mainz('71) spectrum "...is difficult to fit..." due to a broader line-shape. Hence the Mainz('71) data have been largely ignored by these and other authors. In this paper we demonstrate the validity of the original Mainz('71) calibration, with which two additional experiments [5, 11] agree quite well, see Fig. 1.

2 The Recalibration of the Mainz('71) Spectrum

While the unaltered Mainz('71) data disagree with the TRIUMF('94) experiment on both the high and low energy sides of the broad 1− peak, the TRIUMF group [1, 2, 4] has produced a recalibration of the Mainz spectrum leading to a very different spectrum with "The difference ranges from 6.5 keV at the low end to 18 keV at the higher energies" [10]. The altered Mainz data agree with the later TRIUMF data [1] on the high energy side, but disagree even more significantly on the low energy side. It is claimed "...the Mainz spectrum shows evidence of an enhancement on the low energy side of the peak that is likely to be the result of the low energy tail of the system response function. Hence the Mainz('71) data have been considered faulty.

Azuma et al. [2] make the claim that the energy calibration (10.60 kev/ch) contained in Waffler's communication to Barker [3] is wrong, and that the Mainz('71) spectrum can be self-calibrated with high accuracy. They use Waffler's statement (in
his letter) that "...channel 37 corresponds to 1281 keV...") and claim that the centroid of the $2^+$ state is accurately extracted from the Mainz('71) spectrum. Using only the well known energy of the $2^+$ state they derive a different energy dispersion ($10.45 \text{ keV/ch}$).

At first we note that it seems arbitrary that Azuma et al. adopt part of Wäffler's calibration (channel 37 is 1281 keV), but reject the very dispersion ($10.60 \text{ keV/ch}$) used to calibrate it. Even accepting this, their recalibration depends upon the ability to precisely extract the centroid of the $2^+$ state in the Mainz('71) spectrum. In Fig. 2a we show the Mainz('71) data over the region of interest. The raw data show a very strong energy dependence, and in the vicinity of channel 106 one observes a minuscule excess of counts, most likely due to a contribution from the $2^+$ state. An accurate extraction of a centroid for this excess is very dependent on the choice of background and requires data with extremely good statistics. The exact energy dependence of the background cannot be calculated ab initio as it is a convolution of the beta-decay phase space with contributions from the broad $1^-$ state plus non-calculable background states.

In Fig. 2a we show the original Mainz('71) data with a fourth order polynomial background fit ($\chi^2/\nu = 0.7$ for ch 92-100 and $\chi^2/\nu = 5.2$ for ch 110-114). The background subtracted data are shown in Fig. 2b together with a fit to a gaussian with a centroid fixed at the expected energy of the $2^+$ state ($E_{\alpha} = 2.0115 \text{ MeV}$ expected at channel 105.9). The resultant fit is not inconsistent with the expected shape of the $2^+$ state when allowing for undulations in the background. This fit casts a strong
Figure 2: (a) The Mainz(‘71) data with a background fit, (b) and subtracted from the data with a gaussian fit. This gaussian fit for the expected $2^+$ state is consistent with the original Mainz(‘71) calibration.

Figure 3: An example of the original Mainz(‘71) calibration with a signal to noise ratio of 12:1. This should be compared to the spectrum shown in Fig. 2 with a signal to background ratio of a few percent used by the TRIUMF group to recalibrate the Mainz data.
doubt on the necessity of the recalibration. In addition, we emphasize that the choice of background leads to a systematic uncertainty in the extracted centroid (ch 105.2 to 107.5) greater than the correction introduced in Ref. [1, 2, 3]. We emphasize that this is a systematic uncertainty and thus different from statistical uncertainties (derived from chi-square considerations).

In Fig. 3 we show the original calibration data from the Mainz('71) experiment [7, 8, 9], using the \( ^{10}\text{B}(n, \alpha)^{7}\text{Li} \) procedure which resulted in an energy uncertainty of \( \pm10\text{keV} \). In contrast to the spectrum used for the recalibration with a signal a few percent above background, the original calibration spectrum has a signal to noise ratio of 12. We strongly doubt the stated accuracy of the recalibration procedure as given by the TRIUMF collaboration. While they use data with a signal to background ratio nearly 1000 times worse (i.e. 12:1 vs about 1% above background see Figs. 2 and 3) the TRIUMF collaboration claims to extract a centroid with a factor of 5 better precision (\( \pm2\text{keV} \) vs. \( \pm10\text{keV} \)).

3 Conclusion

It is most important to evaluate the effect of the various data sets on the extracted p-wave astrophysical S-factor of the \( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction. This question is beyond the scope of this short contribution, but we remark that the \( ^{16}\text{N} \) spectrum allows for extracting the reduced alpha-particle width of the bound \( 1^- \) state at 7.12 MeV, but it can not determine a priori whether the interference between the bound and quasi-bound \( 1^- \) states is constructive or destructive, and cannot rule out the small S-factor solution (i.e \( S_E < 20\text{keV-b} \) [6]). Clearly a change in the line shape by as much as a factor of two at 1.4 MeV (the region of the interference minimum, see Fig. 1 is expected to, for example, significantly alter the f-wave contribution and thus the extracted p-wave astrophysical S-factor of the \( ^{12}\text{C}(\alpha, \gamma)^{16}\text{O} \) reaction.

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