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Light transport in long, plastic scintillators

M. Gierlik *, T. Batsch, R. Marcinkowski, M. Moszyński, T. Sworobowicz

The Sołtan Institute for Nuclear Studies, PL 05-400 Świerk-Otwock, Poland

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ABSTRACT

As a form of the input into the collaboration the group from the Andrzej Sołtan Institute for Nuclear Studies undertook a task of investigating the validity of the design of a compact detector for Gamma Ray Bursts photon polarization measurements, known as POLAR. The authors focused at the scintillation and light transport properties of $(200 \times 6 \times 6)\,\mathrm{mm}^3$ BC400 plastic bars as well as of other samples of BC408 plastic in the attempt to determine whether the assembled instrument is going to achieve the performance criteria bestowed upon it by the project. The investigation revealed a strong dependence between the amplitude of a signal and distance between the precursor interaction in a scintillator and the photodetector. Accordingly to this finding an attempt has been made to determine the influence of the surface polishing quality on the overall scintillator performance. The authors consider that proper machining of scintillator pieces, adequate choice of their packaging, and proper software analysis may overcome the revealed disadvantages.

1. Introduction

POLAR experiment [1] aims at constructing and launching the dedicated instrument for measuring polarization of photons in Gamma Ray Bursts (GRB). The proposed mechanism takes the advantage of the Compton scattering distribution anisotropy of polarized quanta. Thus the desired detector, apart from being optimized for Compton scattering phenomenon, should also have the ability to determine the relative direction of scattered photons (γ-quanta). The accepted design consists of 1600 or 2304, $(200 \times 6 \times 6)\,\mathrm{mm}^3$ plastic bars coupled to the array of 25 or 36 multi-anode (8×8) H8500 Hamamatsu photomultiplier tubes (PMT). Even though the detailed description of the instrument properties are given in Ref. [1], we remind some of them in this paper for easier reference.

The chosen scintillation material, BC400 plastic from Bicron, was selected for its cost efficiency, tested performance as well as prompt signal, the latter allowing efficient readout of high event rates that are unavoidable in a high background environment. Even though the energy resolution is not crucial, some basic level of energy identification is going to be required. The design defines the requirement of ability of setting low energy threshold at 5 keV for a single bar, the latter being the energy of electrons from Compton scattering. It also demands the ability to identify and reject high energy particles of cosmic radiation which deposit at least 800 keV in a single bar. The cosmic rays must be decisively distinguishable from scattered Compton γ-rays of energy of about 300 keV. This energy may be deposited in more than one bar though. The above might be summarized to the ability of identifying at least the order of magnitude of the deposited energy in the range between 1 keV and 1 MeV. Such a criterion seems to be quite lax, however, as we have learned in the case of the particular geometry of the investigated instrument, it may not be an easy task to fulfill this condition.

2. Experimental technique

2.1. Light attenuation in long rods

From the partners from Paul Scherrer Institute we have received two pieces $(200 \times 6 \times 6)\,\mathrm{mm}^3$ of BC400 plastic scintillators, later referred as bar A and B. In order to focus on the properties of scintillators only we decided to couple them to the excellent Photonis XP5200/B spectroscopy PMT (photocathode blue sensitivity $13.0\,\mu\mathrm{A\,lm}^{-1}\,\mathrm{F}^{-1}$). The set-up was mounted vertically with a collimated γ-source aiming perpendicularly at the desired point of the scintillator, as can be seen in Fig. 1. The collimator was made of a lead cylinder with a $\phi = 10$, 70 mm long well, and the muzzle about 25–30 mm from the scintillator. In order to separate the signal from the background noise we used strong ^{241}Am or 137^{Cs} γ-sources, 0.5 GBq each. Whereas the energy of 59 keV line from ^{241}Am is low enough to offer a chance of detecting its full absorption peak in such a low Z, low volume material as the investigated plastic bars, in the case of ^{137}Cs we

* Corresponding author.
E-mail address: m.gierlik@ipj.gov.pl (M. Gierlik).

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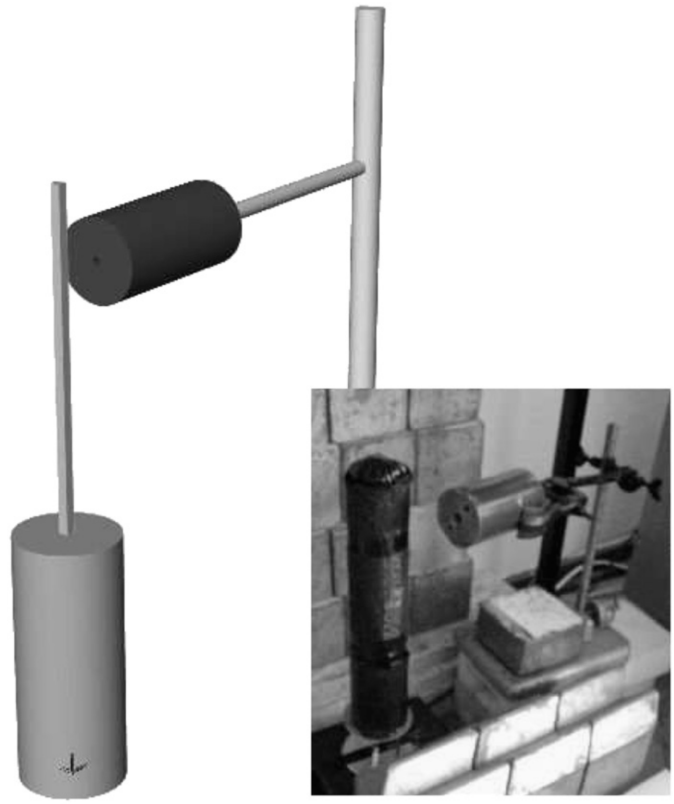

Fig. 1. The schematics of the experimental set-up. The plastic scintillator is attached perpendicularly to the photomultiplier tube. A collimated γ-source can be moved up and down aiming at various parts of the scintillator. The collimator well is 70 mm long and its diameter is 10 mm. The photograph in the inset depicts the real situation. The detector is covered with a light protecting cap. During measurements the muzzle of the collimator is closer to the detector then it is shown in the photograph, the distance is not longer then 30 mm.

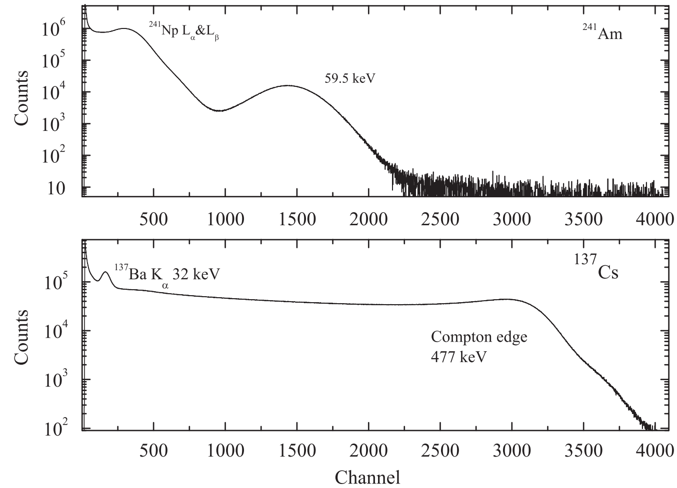

Fig. 2. Good quality spectra obtained with a well shaped piece of BC408 plastic scintillator. The upper panel depicts a spectrum of ^{241}Am with nicely separated 59.5 keV full absorption peak while the lower one shows the Compton edge of the 662 keV line of ^{137}Cs. The small hump visible on the Compton edge is an effect of pileup.

Fig. 3. The Photonis XP5200/B photomultiplier tube with the reference plastic tile attached to the PMT by means of silicon optical coupling.

had to use the Compton edge of the 662 keV line. In the ideal case the former can be assigned to the energy of 477 keV, but exact determination of any Compton edge requires quite a complex procedure of fitting a spectrum with a response function of a given detector [2]. Such precision was not required here, so we estimated the position of a Compton edge being at the 90% of the height of the Compton slope. The advantage of ^{137}Cs over ^{241}Am lies in the amount of light generated in a scintillator by interacting γ-rays. The caesium source was used whenever experimental conditions prevented the application of, otherwise better, americium. In fact, for the sake of comparability, all measurements with plastic bars, results of which have been published in this paper, were performed with the ^{137}Cs source. Typical spectra of ^{241}Am and ^{137}Cs accumulated with a small $(21 \times 21 \times 5)\,\mathrm{mm}^3$ plastic rectangular prism can be seen in Fig. 2. The light yield of the prism, made of BC408 plastic, which properties are nearly identical to BC400 (it has a lower self absorption coefficient), served as a reference and estimation of a maximum available light yield for this kind of scintillator. Due to the flat shape of the sample, the self absorption is negligible, while good ratio of contact face to total area, and the Teflon reflecting cap assure the light collection efficiency is close to 100%. Both the scintillator sample and the photomultiplier are well visible in Fig. 3.

For the sake of comparability we decided to recalculate measured signal amplitudes to the number of photoelectrons emitted from the PMT photocathode. We took the advantage of the single photoelectron method [3,4], in which the amplitude of the given signal is compared to the position of the single photoelectron peak.

As we were interested in finding an optimum coating for bars we have tested a couple of most promising materials and compared the results to the case where a naked sample was simply enclosed, without any optical contact, in a black, light absorbing container made of black paper. In the latter case, later referred as black box variant, light transport in a scintillator toward a photodetector is primarily affected by the reflectivity of the scintillator's walls. In this paper we presented only results of applying Teflon reflecting tape and 3 M Vikuiti™ specular reflector. Teflon is an example of material reflecting light isotropically whereas 3 M foil enhances light guide capabilities of the investigated bars. Other materials, such as Tyvec or aluminum foil show close resemblance to either the former or the latter, while being generally worse. The results presented in the next section are averaged over up to four independent measurement series.

Finally, we made some auxiliary measurements with the $(330 \times 20 \times 20)\,\mathrm{mm}^3$ bar of CsI(Tl), wrapped with Teflon to check whether the observed results are related to scintillator material or are purely a geometrical effect.

2.2. Polishing

Preliminary results of our measurements led us to an idea to make an approach to estimate the impact of polishing quality on the overall light output in the applied set-up. We have chosen the black box variant in order to maximize the investigated effect and 3 M coating for comparison. For three sets of BC400 plastic bars samples that were given three different degrees of polishing, series of measurements identical to those described in the previous section was performed. The degree of polishing can be quantitatively appraised by the grinder granularity of '800', '1200' and '2000', the latter combined with fine diamond paste (the higher the number, the better the polishing). By measuring the dependence of light transport distance on the output signal amplitude over the full length of the scintillator, rather than focusing at its furthest point, we have demonstrated three relations:

(a) the influence of surface polishing on the absolute signal amplitude;
(b) the influence of surface polishing on the differences between the signal amplitudes generated by interaction in the far ends of the samples;
(c) the influence of wrapping on compensating the polishing imperfections.

3. Results and discussion

3.1. Light attenuation in long rods

In general the phenomenon of light attenuation in a scintillator, the geometry and properties of which make it similar to a long light guide is not new. On the other hand this type of set-ups is usually used in detectors (counters), rather than spectrometers, what explains the lack of publications dedicated to this issue. Kurata et al. [5] was the closest to the topic tackled by us in this paper when he described the impact of light transport in plastic scintillators, some of them as long as 3 m, on the signal amplitude and timing properties. His results match quite well those we received for naked (black box) bars, see Fig. 4, where light escaping scintillators is lost. This case can be easily reproduced by a very simple model where the loss of light is proportional to the travelled distance, and thus the total dependence is an exponential function. This model is true if the light transport in a scintillator is only due to internal reflections, or at least the distance between an interaction (the light generating event) and a photodetector is large comparing to the diameter of the scintillator. The addition of reflective wrapping not only dramatically increases the overall light output but also decreases the rate at which the light is being lost during the transport through the length of a scintillator. Fig. 5 depicts, apart from the black box case, two opposite examples. Commonly used Teflon tape reflects light uniformly, just like snow does. If the problem is analyzed in a photon by photon way, it is easy to notice, that the chances of reaching a photodetector are proportional to the number of reflections a photon must undergo on its way from the point

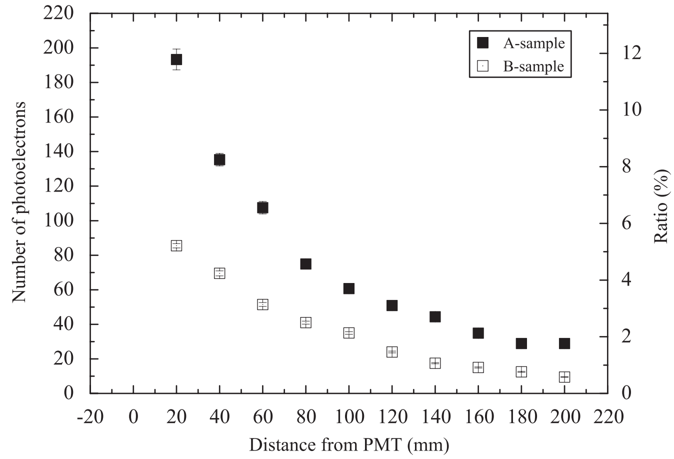

Fig. 4. Dependence between the signal amplitude, measured as the number of photoelectrons emitted from the PMT photocathode, and the distance between the γ-ray interaction and the surface of photodetector. Measurements with the ^{137}Cs source were performed for A and B plastic scintillator samples in the black box variant (see the leading text). The right axis of ordinates denotes the values in relation to the yield of the plastic reference sample. Assuming that the transmission properties of a sample in this set-up variant are defined mostly by the quality of the sample's surface polishing, it seems that the A sample is much better than B. The points' uncertainties are of the size of the symbols or smaller, and should be considered in relation to the left axis of ordinates.

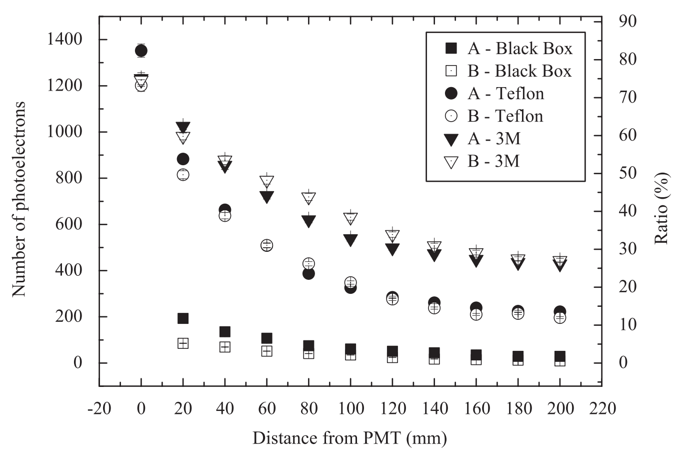

Fig. 5. Comparison of coating performance for the tested plastic samples. See the caption of Fig. 4 and the leading text.

of creation to its destination. That is why we can observe over 6 times increase of the signal amplitude between interaction points that are 20 cm apart. The increase of amplitude does not change the unfortunate fact that we still would not be able to decisively distinguish two events with energies separated from each other by almost the order of magnitude. The solution is to apply a mirror-like coating material and for this purpose we took the advantage of the 3 M Vikuiti™ Enhanced Specular Reflector Film [6]. This material, while offering an otherwise lost photon just another chance, does not reflect it completely randomly and thus does not increase the mean number of reflections of a photon on its way toward a photodetector. We were surprised to notice that while fulfilling our expectations regarding light transport, the 3 M reflective film revealed to be as good as Teflon at close distances.

The results obtained for the CsI(Tl) crystal were not very different, at least qualitatively, from those described earlier. Here we also observed a very rapid drop in the signal amplitude, over two times at the distance of 20 cm from a photodetector, see Fig. 6. This drop is significantly lower, when the sample is wrapped in

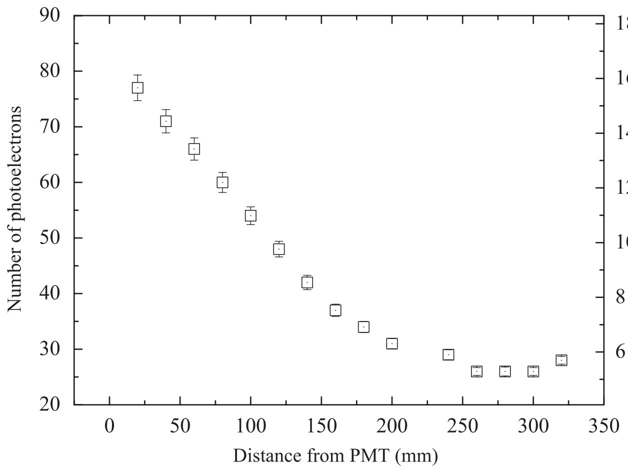

Fig. 6. Results similar to those shown in the Fig. 4, but with the $(330 \times 20 \times 20)\,mm^3$ bar of CsI(Tl) and ^{241}Am source instead of plastic and ^{137}Cs source. The right axis of ordinates denotes the values in relation to the yield of the CsI(Tl) reference sample.

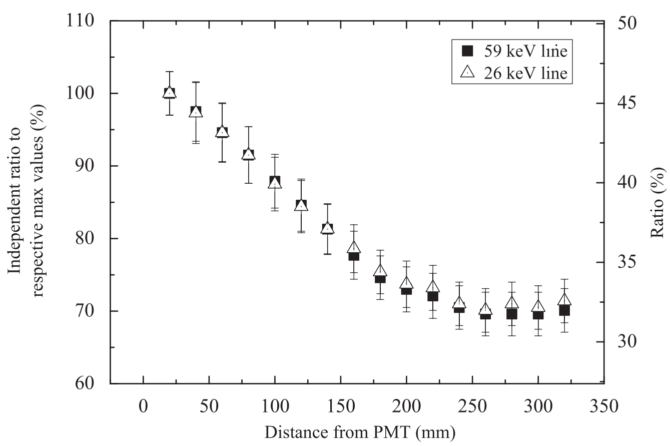

Fig. 7. The CsI(Tl) crystal wrapped in Teflon is checked for differences in light transmission between two energies. The almost identical behavior of the visible two curves proves that there is no obvious correlation between the transmission efficiency and the photon flux generated in a scintillator.

reflecting material, see Fig. 7. The latter figure additionally depicts a comparison between two different energies, when different number of photons is generated in a scintillator, pointing out that the discussed phenomenon is related to the light distribution issue only and does not depend on the ways γ-rays interact with a scintillator.

Quantitatively, the results differ from those obtained for plastic samples, but this is obviously due to different geometrical proportions. Also, the maximum yield of 46% of the reference sample obtained for low distances for the CsI(Tl) crystal wrapped in Teflon is somewhat lower than about 50% measured for plastic bars (for the 20 mm distance). This difference however can be easily explained by better geometry of the CsI(Tl) reference crystal being the flat 9 mm × 1 mm cylinder. Better geometry translates to better contact face-to-total area ratio and negligible self absorption, and in consequence a better light yield.

3.2. *Polishing*

We were not particulary surprised corroborating the assumption that polishing scintillator walls improves light guiding properties of the former. Surprising, however, was the impact scale of careful polishing. Fig. 8 summarizes the results obtained

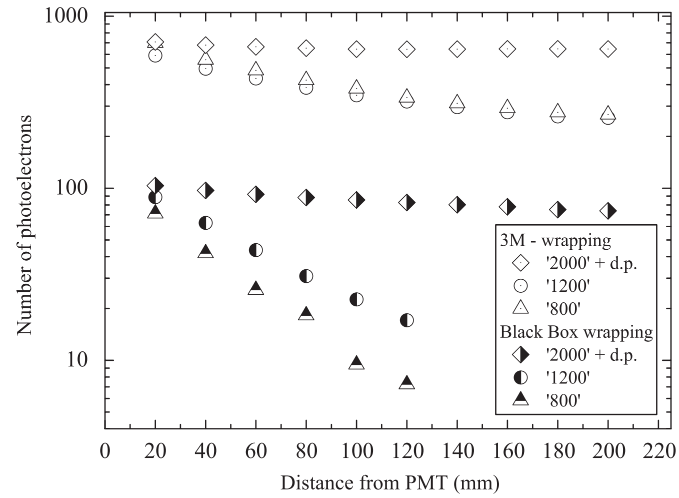

Fig. 8. Effects of polishing on plastic bars. The numbers by symbols denote the grinder granularity while d.p. stays for diamond polishing paste. Note the logarithmic scale of the axis of ordinates applied to emphasize the differences in uniformity of light transport rather than overall light output. The ^{137}Cs source was used in these series of measurements.

in the experiment described in the Section 2.2. Black-and-white points denote those of the measurement series that were performed in the black box set-up variant where the light transport capabilities of the tested sample depend solely on reflectivity of its walls. We may observe a dramatic change of performance, defined as light loss along the scintillator or the difference between signal amplitudes measured for γ interactions at both ends of a sample (more precisely at the distances 20 mm and 200 mm from PMT window, see Fig. 8). This difference exceeds the order of magnitude for the roughly polished samples but is only 30% for the finely polished one (the smaller value is 70% of the greater).

The hollow points denote results measured in the same experimental conditions as the black-and-white ones were, the difference being the reflective wrapping applied instead of the black box. As we already know from the investigations described in the Section 3.1 such a wrapping can improve the overall light output by over a factor of magnitude. Its presence, however, while compensating to some degree, does not cure all the ailments caused by the rough surface machining (polishing). The light loss for poorly polished samples decreases to 60% (from over the order of magnitude). The change is not so impressive for the finely polished sample, even though 9% loss of light on 18 cm path is everything one could expect from a plastic scintillator used as its own light guide.

4. Summary

During our investigation we identified and focused at two aspects related to using long plastic scintillators in the semi-spectroscopic application as described in the Introduction. Definitely, the correct wrapping is the key to success defined as ability to get stable and uniform gain along the entire length of the scintillator. Material of high reflectivity can decrease the influence of the bar walls polishing quality to the level enabling desired separation of energies throughout the space mission period. The Vikuiti™ film from 3 M has proven its usefulness, however we imagine that an aluminium casing with carefully machined and polished nests for scintillator bars could offer similar reflecting properties while simultaneously being a rigid

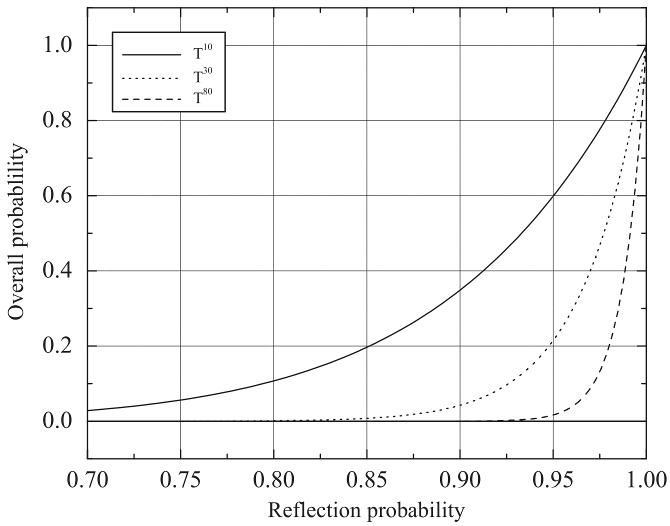

Fig. 9. Function plots $P(T,n)=T^n$, where T is the average probability of reflecting a photon, and n is the average number of successful reflections a photon must undergo on its way toward the photodetector.

mounting firmly pressing the bars to a photomultiplier, and optically separating scintillators from each other.

As far as surface polishing is concerned, the key is the correct estimation of the final instrument requirements against the overall cost of applied material. To illustrate the issue let us consider a very simple model of a photon travelling along a light guide toward the PMT (a light detector/amplifier). The probability of reaching the photodetector is given as $P(T,n)=T^n$, where T is the probability of reflecting the incident photon by the light guide wall (averaged over all angles), and n is the average number of successful reflections a photon must pass on its way from the point of emission to the photodetector. The latter n argument is an obvious function of distance and the light guide geometry, while the former T is related to the surface roughness. In Fig. 9 some examples of the described function have been drawn for different values of n. One can notice that for a given n, starting from $T_c = \sqrt[n-1]{n-1}$, $(\partial P(T_c,n)/\partial T = 1)$, probability P grows faster than T. Assuming linear correlation between T and surface roughness this means that after crossing the critical value T_c further polishing can be very rewarding in terms of light guide performance. If sufficient level of polishing cannot be achieved, the investment of available resources in better reflecting wrapping will be a better choice.

Acknowledgments

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