Enhanced neutron production from pyroelectric fusion

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The pyroelectric effect has been utilized as a means of producing x rays, electrons, positive ions, and neutrons. Pyroelectric sources have advantages over conventional sources, in that they are low cost, only consume a few watts of power, and are smaller than most sources. While pyroelectric x ray sources are already mature enough to be sold as commercial devices, the current generation of pyroelectric neutron sources is too low in intensity to be useful for commercial applications. This report demonstrates techniques which increase neutron production by a factor of 5.6 over previously published data. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2731310]

It has been demonstrated that the electric field resulting from the pyroelectric effect in lithium tantalate ($LiTaO_3$) crystals is sufficient to eject electrons, ionize gas, and create x rays when the crystals are heated or cooled in a vacuum.[1–5] Pyroelectric crystals have already been used to generate >200 keV x rays,[4] 150 keV electrons,[3,5] and 100 keV positive ions.[5] Recently, it has been shown that the pyroelectric effect is also useful for neutron generation via D–D fusion.[6,7]

Fusion neutrons are produced by heating and cooling two crystals in opposite geometry (i.e., the $z+$ surface of one crystal facing the $z-$ surface of the other crystal) in ~3 mTorr of D_2 gas.[6] During heating, the crystals become depolarized, resulting in a negative charge on one crystal and a positive charge on the other crystal. The charge Q generated due to the temperature change is given by

$$\frac{dQ}{dT} = \gamma A, \tag{1}$$

where γ is the pyroelectric coefficient and A is the crystal area. Assuming no losses due to relaxation current, screening charges, electrostatic discharge, or charge emission, the total charge due to the pyroelectric effect per unit area is therefore

$$\frac{Q}{A} = \gamma \Delta T, \tag{2}$$

where ΔT is the total temperature change from equilibrium. The potential between a semi-infinite $d_c=1$ cm thick lithium tantalate crystal ($\varepsilon_r=46$) and its target can then be found by modeling the crystal and the gap between the crystal and the target as a system of capacitors:[4]

$$V = \frac{Q}{C}. \tag{3}$$

$$V = \frac{\gamma \Delta T}{\varepsilon_0 (1 + \varepsilon_r d_{\text{gap}}/d_c)}. \tag{4}$$

For a crystal and target separated by $d_{\text{gap}}=1$ cm and $\gamma=190\ \mu C/(m^2\ K)$,[8] we can see that this gives a potential of 100 kV from a single 1 cm thick crystal with a mere 22 °C change in temperature. In reality, charge losses reduce this potential, but 1 cm thick $LiTaO_3$ crystals heated by $\Delta T=100$ °C have been shown to provide 100 kV of potential per crystal.[3–5]

Using paired crystals allow us to superimpose the field from two crystals, increasing our maximum potential to above 200 kV.[4] A sharp tip mounted to the positively charged crystal becomes polarized and ionizes the deuterium gas.[7] The deuterons are then accelerated into a deuterated target mounted to the negatively charged crystal. As the incident deuterium ions slow down in the plastic, they interact with the deuterium ions in the target, thereby producing fusion. As the ions lose energy, the cross section σ for fusion is reduced until the ion energy reaches zero several micrometers into the target (depending on the initial energy). By integrating the cross section over the penetration depth d and multiplying by the target deuterium atom number density N, we can find the probability P_{neutron} that an incident ion will produce a fusion neutron

$$P_{\text{neutron}} = \frac{1}{2} N \int_0^d \sigma(x) dx. \tag{5}$$

The factor of one-half is included because only approximately one-half of D–D fusion reactions produce neutrons. The total neutron production rate can then be obtained by multiplying P_{neutron} by the number of incident ions.

Pyroelectric fusion sources have thus far not reached the neutron yield available from electrostatic confinement sources or portable neutron generators (PNGs). However, they share the advantage of being able to be turned off to eliminate shielding concerns, and can be very compact and inexpensive.

In this experiment, we used 10 mm thick × 20 mm diameter $LiTaO_3$ crystals. The crystals were mounted to thermoelectric coolers using electrically conductive epoxy, such that the $z+$ surface of one crystal was exposed, and the $z-$ surface of the other crystal was exposed. The back of each crystal was grounded, and the crystals faced each other at a separation distance of 25 mm. The distance between the catwhisker ionizing tip and the target was ~20 mm, depending on the tip length, which was typically 3–4 mm. The thermoelectric coolers were attached to a copper heat sink using nylon screws. Cooling water flowed through a cold finger in the base of the heat sink.

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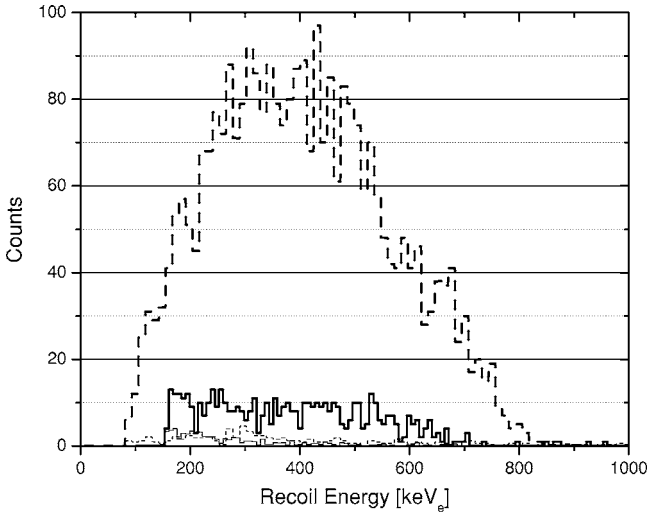

FIG. 1. Spectra showing the advantage of a nonconductive interface between the crystal and the conducting disk holding the ionizing tip. The thick dash line shows a single spectrum from a system with a nonconductive interface; the thick solid line shows the sum of three such spectra from a system with a conductive interface. The thin lines show the corresponding background counts.

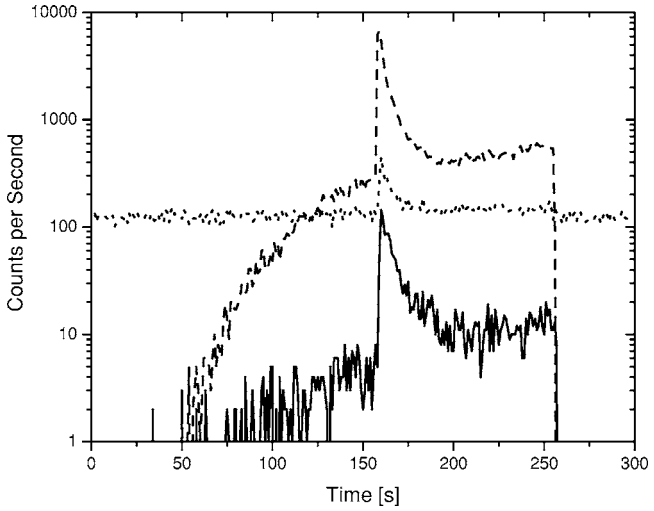

FIG. 2. Multichannel scaler spectra of the yield from a pyroelectric fusion experiment, showing a spurious increase in neutron and x ray count rate. After the initial spike, the count rate slowly returned to its original trend. The dashed line shows the counts from a CdTe x-ray detector, the dotted line shows the counts from the proton recoil detector without pulse-shape discrimination (PSD), and the solid line represents the proton recoil detector counts with PSD (neutron counts).

The crystal with the exposed $z+$ surface was partially covered by a 16 mm diameter copper disk, to which the 70 nm radius catwhisker tip was soldered. In early experiments, we used a conductive epoxy to attach the copper disk to the crystal, but we found that the results were greatly improved by using a nonconductive epoxy (J-B Weld). The crystal with the exposed $z-$ surface was coated with a thin layer of deuterated polyethylene, $-(C_2D_4)_n-$. This deuterated plastic layer served as a target for the ions emitted by the opposing crystal. We had previously published results from experiments in which we used deuterated polystyrene, $-(C_8D_8)_n-$, but deuterated polyethylene is favorable due to its higher deuterium density.

The neutron detector used in this experiment was a 5×3 in.^{2} Eljen EJ-301 proton recoil detector, located 8.1 cm above the axis of the crystals and centered relative to the crystals. Pulse-shape discrimination was used to eliminate counts due to gamma events. A 1.7 mm lead shield was also placed between the detector and source to discriminate against photons. X rays were detected using an Amptek XR-100T CdTe detector $\sim$10 cm away from the crystals.

The crystals were heated with $\sim$10 W of power from room temperature to a temperature of 160 °C, and then were allowed to cool naturally via conduction and radiation back to room temperature.

A previous publication of pyroelectric fusion showed that we could produce $10\,600\pm500$ fusion neutrons per cooling phase.[6] This was significant as a verification of the ability of pyroelectric crystals to generate neutrons. However, we sought to identify crucial aspects of our experiment which could be corrected to improve our yield. We found that by attaching the copper disk to the crystal with nonconductive epoxy instead of conductive epoxy, we could increase our neutron yield dramatically. Figure 1 shows a single spectrum from an experiment using nonconductive epoxy versus three summed spectra from experiments using conductive epoxy. While the detection efficiency was better for the nonconductive epoxy experiment (5.1% vs 1.3%), after correcting for efficiency, we find that our net neutron yield per cooling phase improved to $59\,000\pm1000$ neutrons. While the reason for this improvement is still uncertain, we believe that the use of nonconductive epoxy allows the potential to build to a higher value by restricting charge emission. Therefore, the ion energy (and cross section for D–D fusion) is improved. Experiments conducted with no fill gas, or with air in place of deuterium, yielded high x ray yield but no neutron counts above background.

Another phenomenon which may be exploited to improve neutron yield is the spurious increase in neutron count rate observed in some experiments. Figure 2 shows a plot of observed x ray, neutron and photon, and neutron yield as a function of time during a cooling phase. All three plots show a spike, in which the count rate instantly jumped by more than one order of magnitude and then slowly decreased back to the original curve. A possible interpretation of this result is that, when a certain set of conditions are met, a plasma forms around the tip, giving an increased number of ions (hence the increase in neutron yield), as well as an increase in the number of x rays. Over time, the plasma is depleted, and the count rate returns to its original curve, in which all of the neutrons are due to ions produced via individual field ionization events.Additional evidence that this phenomenon is caused by plasma formation can be gathered by noticing that the x ray and neutron yield increase by approximately the same factor. This can be explained by a simultaneous increase in both the production of ions and electrons. It should be noted, however, that calculation of the Debye length for the plasma shows that the experiment is of smaller size than the Debye length, and therefore it is not certain that this is the phenomenon that causes our spurious increase in count rate.

Finally, we have conducted experiments using tip radii of 70, 200, and 600 nm. So far, we have observed the greatest neutron yield from the 70 nm tip, with the 200 nm tip producing less neutrons, and the 600 nm tip producing no neutrons at all. This result may seem trivial, since the strength of the electric field near a sharp tip is greater for

narrower tips. However, the field may fall below the critical ionization field strength over a smaller radius for a sharp tip than for a wide tip, which can reduce the ionization volume. This effect can be illustrated by comparing the field around charged spheres of different radii. Furthermore, the tip radius will have an effect on the production of D^+ relative to D_2^+. Since the energy per deuteron (and hence the fusing cross section) is higher for D^+ than D_2^+, this could greatly affect the neutron yield. Therefore, it is important to continue to try to optimize the tip radius.

The use of pyroelectric crystals to generate neutrons has progressed rapidly over the past two years, with an improvement in maximum neutron yield of more than a factor of 5. The use of a tritium fill gas would result in an additional increase in yield of over two orders of magnitude. The greatest improvement to date has come from using nonconductive epoxy to attach the conducting disk to the ion-emitting crystal, which resulted in a factor of 5.6 improvement in neutron yield.

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