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# Secondary Gamma Radiation from Neutral Particle Beams

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The results of a proton-induced gamma-ray emission experiment are presented. Such data can be used to simulate the effects of a neutral particle beam within the context of proposed midcourse-phase target discrimination schemes. A summary of the calculations is presented in order to support the general conclusion that the physical limitations on such a system are prohibitive.

It is the purpose of this research note to provide some data we have obtained for the production of gamma rays by an incident beam of protons. Such a beam can simulate a neutral particle beam (NPB) that has been proposed for use as a nondestructive discriminator in the midcourse phase of a ballistic missile defense scheme.

In principle, the discriminator would operate as follows: a particle beam is produced in an accelerator in space. It is then directed and focused on the object to be investigated and transformed into a beam of neutral atoms. When the atoms hit the target, nuclear reactions occur producing gamma radiation as a secondary particle. (Neutrons and x-rays are also produced as secondary particles, but they are not considered in this note.)*

The information provided by the gamma radiation could reveal important

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* Neutral beams are necessary because the charged particles that emerge from the accelerator would be bent by the magnetic field of the earth in their long path to the target. This would make it very difficult to position the beam on the target. Also, mutual repulsion of the charged particles would spread the beam.

information about the contents of the target. The *amount* of gamma radiation received at the detector would be proportional to the mass of the target. Furthermore, the spectrum of the gamma radiation would be characteristic of the elements in the target so that the *composition* of the target could also be estimated.

It has been proposed to use NPBs for discrimination in ballistic-missile defense (BMD) in the midcourse phase.[1] In this phase, the postboost vehicles of the ballistic missiles would already have deployed up to 10 warheads and perhaps, in addition, 10 or more decoys for each warhead. An important task of midcourse BMD would be to discriminate the warheads from the decoys in order to concentrate the attack on the former.

The targets used in our accelerator measurements were thin samples of aluminum, iron, titanium, and uranium. They were all 0.001 inches (0.025 millimeters) thick, with the exception of aluminum, which was 0.002 inches (0.05 millimeters) in thickness. The uranium was depleted of the uranium-235 isotope down to a level of about 350 parts per million (ppm—natural uranium is 7,110 ppm uranium-235). The beam-target interactions resulted in the production of prompt gamma rays, whose energy spectrum was subsequently measured using a lithium-drifted germanium detector. Proton currents of 10–100 picoamperes (1 picoampere = $10^{-12}$ amperes) were used and the detector was positioned at five angles relative to the incident proton beam: 50°, 70°, 90°, 120°, and 135°.

Proton beams from the Crocker Nuclear Laboratory cyclotron of 30, 50, and 67.5 MeV were used. By measuring the gamma-ray yield as a function of beam energy a better assessment of the production of gamma rays in a thick target can be made.

We obtained not only a characteristic gamma-ray "signature" for each element, but also details as to how many of those gamma rays would be measured by a detector. Because each element of the target emits gamma radiation at particular energies, a detector with good energy resolution (such as a germanium detector) can resolve the elements in the target and determine the amount of each.

Figure 1 shows a sketch of the experimental setup. The beam is focused by a quadrupole magnet on the target. It then passes through the target and is collected by another quadrupole magnet and focused into a Faraday cup, which measures the beam current. The gamma-ray detector, which can be

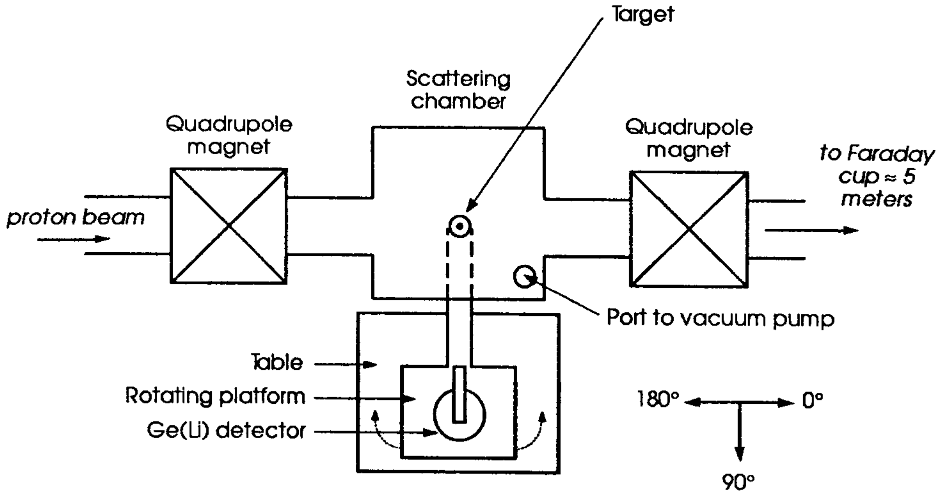


**Figure 1:** The experimental setup for studying the nuclear reaction ($p;x,\gamma$) at the Crocker Nuclear Laboratory

rotated to the angular positions stated above, is located on a platform adjacent to the target. To reduce the gamma ray background levels, it was arranged electronically to accept counts from the gamma-ray detector only during a cyclotron beam pulse (approximately 2 nanoseconds with 50 nanoseconds between pulses).

Table 1 gives selected signatory gamma energies for each of the four targets studied and their respective inclusive differential cross sections for each of the angles with a proton beam energy of 67.5 MeV. Similar results were obtained at 30 MeV for all four targets, and at 50 MeV, for all the targets except uranium.[2]

These data can be used to estimate the efficacy of discriminating warheads in midcourse by detecting gamma radiation induced by neutral particle beams. We use the notation of the American Physical Society study group on the science and technology of directed energy weapons whenever possible in order to facilitate comparison.[3]

The counting rate $\dot{N}_D$ (gamma-ray events per second) for detecting secondary gamma radiation from beam-target interactions is given by the following:

$$\dot{N}_D(E,\theta) = \dot{S}\, n_{tgt}\, \varepsilon_D(E)\, \Delta\Omega(\theta) \frac{d\sigma}{d\Omega}(E,\theta) \tag{1}$$

where

$\dot{S}$ is the number of $H^0$ atoms striking the target per second ( $= fI/e$)

$f$ is the efficiency of neutralization of the $H^-$ ions

$I$ is the current in amperes

**Table 1:** Differential production cross sections for selected characteristic gamma rays for each of the four targets in the ($p;x,\gamma$) experiment

| Target | $E$ *keV* | $\frac{d\sigma}{d\Omega}(E,\theta)$ *millibarns per steradian* $\theta$ = 50° | 70° | 90° | 120° | 135° | **Uncertainty*** *percent* |
|---|---|---|---|---|---|---|---|
| Aluminum-27 | 1,372.3 | 3.62 | 3.08 | 3.79 | 4.36 | 4.14 | 11 |
| | 1,810.8 | 3.25 | 2.49 | 2.63 | 2.26 | 2.39 | 14 |
| | 2,212.5 | 0.92 | 0.64 | 1.22 | 1.51 | — | 26 |
| Natural iron | 846.8 | 2.51 | 2.54 | 2.60 | 2.91 | 2.64 | 21 |
| | 931.4 | 3.07 | 2.67 | 2.50 | 2.26 | 2.80 | 21 |
| | 1,408.4 | 5.78 | 5.24 | 5.87 | 5.84 | 5.85 | 13 |
| Natural titanium | 889.2 | 4.62 | 4.42 | 5.19 | 5.36 | 3.58 | 23 |
| | 1,120.1 | 3.30 | 3.24 | 3.47 | 4.25 | 4.93 | 15 |
| | 1,312.1 | 1.82 | 1.91 | 1.63 | 2.00 | 2.31 | 21 |
| Uranium-238 | 280.0 | — | 2.13 | 2.83 | 5.76 | 12.5 | 54 |
| | 679.4 | 6.94 | 14.4 | 7.50 | 6.19 | 7.57 | 50 |
| | 930.8 | 3.46 | 11.5 | 14.5 | 11.2 | 5.37 | 45 |

The inclusive differential cross sections are listed as a function of the angle of detection $q$. The energy of the proton beam is 67.5 MeV

* These uncertainties are the average percentage errors of the differential cross section for each of the gamma-ray energies. They represent fitting errors due to to background subtractions, statistical errors, and other systematic errors in measurements. They should be taken as prudent upper limits to the uncertainties of these reported values (some individual measurements have substantially lower errors than these averages)

$e$ is the charge on an electron ( = $1.602 \cdot 10^{-19}$ coulombs)

$\varepsilon_D(E)$ is the efficiency of the gamma-ray detector for a gamma-ray energy $E$

$n_{tgt}$ is the number of nuclei per square centimeter of target traversed by the beam

$A_D$ is the area of the detector (in square meters)

$R_D$ is the distance from the target to the detector (in meters)

$\Delta\Omega(\theta) = A_D/R_D^2$ is the solid angle of the target as seen from the detector (in steradians)

$\theta$ is the angle of the detector as measured with respect to the direction of the $H^0$ beam

$\frac{d\sigma}{d\Omega}(E,\theta)$ is the $(p;x,\gamma)$ inclusive differential cross section for producing a gamma-ray energy $E$ at a detector angle $\theta$ (in $cm^2\ sr^{-1}$)

Assume that the target is uranium, $f = 0.5$, the detector area $A_D = 1.0$ square meter, and $\varepsilon_D(E) = 0.5$. Assume also that $n_{tgt} = 2 \cdot 10^{22}$ nuclei $cm^{-2}$, corresponding to 4 millimeters, the approximate range of 67.5 MeV–protons in uranium. We have also found that the differential cross sections for gamma ray production in uranium are approximately constant with respect to proton energy in the 30 to 67.5 MeV region (see below). This energy is lower than the 100-MeV design energy of the Los Alamos accelerator, which is being proposed for NPB applications.[4] However, the results of the $(p;x,\gamma)$ work indicate that this slight reduction in beam energy will not change the overall estimates significantly. The proposed characteristics for the Los Alamos accelerator are as follows:

| | |
|---|---|
| Beam energy | $= E_p = 100$ MeV |
| Beam current | $= I = 100$ milliamperes |

Beam diameter = $B_S$= 0.30 meters
Beam emittance* = $\eta$ = 1 millimeter·milliradian

With these assumptions and the Los Alamos accelerator characteristics (except the beam energy is taken to be 67.5 MeV), equation 1 for = 90° can be rewritten as:

$$\dot{N}_D(E,90°) = \frac{3.1 \cdot 10^{39}}{R_D^2} L \frac{d\sigma}{d\Omega}(E,90°) \tag{2}$$

Here $L$ is the loss of beam if the beam is larger than the target. $L = D_t^2/B_t^2$ where $D_t$ is the diameter of the target and $B_t$ is the diameter of the beam at the target.

A beam of accelerated particles will diverge upon leaving the accelerator due to its emittance. In the case of a neutralized beam of hydrogen atoms, there is an additional divergence due to the stripping away of one electron on the $H^-$ ions that emerge from the accelerator. These divergences add quadratically (since they are independent sources of error) and produce an effective beam diameter at the target ($B_t$) given by:

$$B_t^2 = B_S^2 + \alpha_e^2 R_t^2 + \alpha_S^2 R_t^2 \tag{3}$$

Here $B_S$ is the diameter of the beam at the accelerator exit (assumed to be 0.30 meters), $\alpha_e = \eta/B_S = (1 \cdot 10^{-6}$ m·rad)/(0.30 meters) = $3.3 \cdot 10^{-6}$ radians is the angular divergence due to the accelerator emittance, $\alpha_S$ is the angular divergence due to stripping, and $R_t$ is the distance from the accelerator to the target. The APS study gives a value for the beam divergence for hydrogen due to stripping as:

$$\alpha_S = \frac{20}{\sqrt{E_p}} \cdot 10^{-6} \text{ radians} \qquad \text{[APS equation 7.10]}$$

* Beam emittance measures the focusing property of a particle beam. For example, a beam with $\eta$ = 1 millimeter·milliradian, if focused to a 1-millimeter diameter spot, will have an angular divergence of 1 milliradian. If a smaller spot focus is made, the beam will have a larger angular divergence because $\eta$ is a constant characteristic of a given acceleration.

At $E_p$ = 67.5 MeV, this equation gives = $2.4 \cdot 10^{-6}$ radians. Therefore equation 3 becomes:

$$B_t^2 = 0.09 + 1.7 \cdot 10^{-11} R_t^2 \tag{4}$$

Again, $B_t$ and $R_t$ are in meters.

If the beam energy were 200 MeV, for example, $\alpha_S = 1.4 \cdot 10^{-6}$ radians. If the beam diameter is retained at 0.3 meters, then in equation 4 the second term becomes $1.3 \cdot 10^{-11} R_t^2$. This term is reduced only slightly because it is now dominated by the contribution from the source emittance, which by itself would give $1.1 \cdot 10^{-11} R_t^2$ for a 0.3-meter diameter beam with $\eta$ = 1 millimeter·milliradian.

In order to have a statistically meaningful measurement at the detector, it is necessary to have a sufficiently high count rate $\dot{N}_D$. We assume that 100 counts per second would be the minimum number necessary based on the results of the $(p;x,\gamma)$ experiment. The measurement uncertainties at such count rates would be comparable with the 10-percent approximate uncertainties in the measured differential cross sections. This in turn can be translated into similar uncertainties in determining the elemental composition of unknown targets. The approximate gamma-ray background in outer space (taken to be a few counts per second) is two orders of magnitude smaller. In this calculation, a time of 1 second will be assumed for the beam-on-target interval. Such a short time interval is necessary if the neutral particle beams are to sort out 10,000 warheads from possibly 100,000 decoys during the 20 minutes of the midcourse phase.

Consider, as a specific example, the detectability of the uranium in a warhead. For the case of the three characteristic gamma rays from uranium shown in table 1, the combined inclusive differential cross section $d\theta/d\Omega$ is 24.8 millibarns per steradian ($2.48 \cdot 10^{-26}$ cm$^2$ sr$^{-1}$) for 67.5-MeV protons with the detector at 90°. Such a value is appropriate for a detection system "tuned" so as to count only those gamma rays with the count energies that have been labeled "signatory" in table 1.

If the beam is larger than the target, the number of neutral atoms reaching the target is reduced by the factor $L$, and equations 2 and 4 become for $D_t$ = 0.5 meters:

$$\dot{N}_D = \frac{1.9 \cdot 10^{13}}{R_D^2}\left(\frac{1}{0.09 + 1.7 \cdot 10^{-11} R_t^2}\right) \tag{5}$$

Figure 2 shows a graph of $R_D$ versus $R_t$ from this expression, using $\dot{N}_D$ = 100 counts per second. For detection of gamma radiation, the values of $R_D$ and $R_t$ are much too small for practical application for midcourse discrimination; both quantities must be of the order of 1,500 kilometers or more in order to approach a "reasonable" number of accelerator-detector platforms. For NPB and detector ranges of 1,200 kilometers, Carter[5] estimates that 200 platforms would be needed, and even at 4,000 kilometers, 32 are required. Such large numbers of platforms are needed due to the "absentee factor" associated with orbiting platforms.

At 1,500-kilometer ranges for both $R_t$ and $R_D$ equation 5 gives $\dot{N}_D$ = 0.22 counts per second, or a factor of about 450 reduction in counting rate relative to that we assumed was necessary. The NPB intensity would have to be increased by this factor (to 45 amperes) in order to retain the detector counting rate at 100 counts per second. In addition, the actual counts may be considerably reduced due to absorption of the gamma rays in the uranium and the warhead's outer jacket.*

Another application of such NPB technologies might be in the monitoring of orbiting satellite payloads. In this case, the distances $R_t$ and $R_D$ could probably be reduced to the order of 100 kilometers or less and $L$ would be unity (the beam diameter at the target at these distances would be smaller than the diameter of the target). Equation 5 with the bracket placed equal to unity, $L$ = 1, gives $\dot{N}_D$ = 1,900 counts per second for $R_D$ = 100 kilometers and a beam current of 100 milliamperes. This estimate indicates that an accelerator beam of 1 milliampere (or less for smaller values of $R_D$) would be sufficient for satellite payload monitoring. Such a reduced current would have much less deleterious effects on electronics and other fragile components of orbiting satellites which might undergo such interrogation from a NPB.

In summary, it is clear from our estimates that, with the beam parameters given above, the proposed use of NPBs (in the context of gamma-ray

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* For a 3-millimeter steel jacket, the attenuation of the emitted gamma rays is about a factor of five.

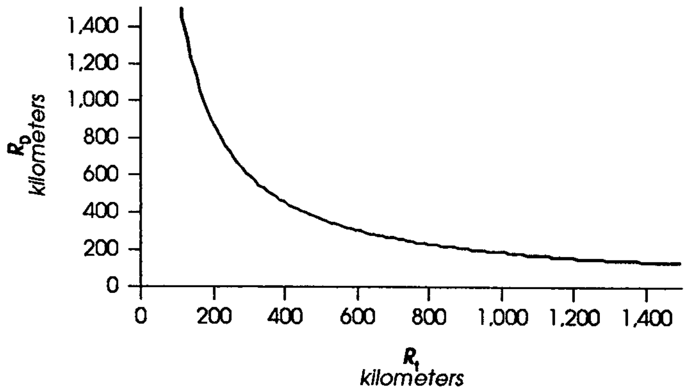


**Figure 2:** Distance from the target to the detector versus distance from the target to the accelerator ($R_D$ versus $R_t$) for threshold detectability in space of the characteristic gamma rays from the uranium-238 in a nuclear warhead from equation 5

**detection) is not a viable solution to the technological challenges of midcourse BMD schemes. The distances needed for successful operation are prohibitively small and thereby require excessive numbers of orbiting accelerator-detector platforms to accomplish even minimal BMD capabilities.**

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