Gamma-Ray Measurements of a Soviet Cruise-Missile Warhead

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A portable germanium detector was used to detect gamma-ray emissions from a nuclear warhead aboard the Soviet cruiser *Slava*. Measurements taken on the missile launch tube indicated the presence of uranium-235 and plutonium-239—the essential ingredients of nuclear weapons. With the use of this equipment, these isotopes probably could have been identified at a distance of 4 meters from the warhead. Such inspections do not reveal detailed information about the design of the warhead.

SEA-LAUNCHED CRUISE MISSILES (SLCMs) POSE SERIOUS problems for nuclear arms control and for the security of the United States, the Soviet Union, and other nations. When armed with nuclear warheads, long-range SLCMs could attack strategic targets with little warning. SLCMs could be deployed on virtually any kind of ship, and it will be difficult to verify limits on SLCMs by means of traditional methods. SLCMs are small; nuclear and conventional versions are often identical in appearance; and their manufacture and testing are difficult to monitor.

Until September 1989, SLCMs were a major obstacle in the Strategic Arms Reduction Talks (START) (*1*). At that time, U.S. and Soviet officials met in Jackson Hole, Wyoming, and agreed to set the SLCM issue aside and proceed with the rest of the START agenda. In the long run, however, the Soviet Union—and many U.S. analysts—believe that the deployment of nuclear SLCMs must be restricted.

Proposals to limit SLCMs vary considerably in scope: one could limit or ban nuclear SLCMs only, combine limits on nuclear SLCMs with limits on conventional SLCMs, or simply limit or ban the total number of SLCMs without regard to warhead type (*2*). In cases where nuclear SLCMs are banned or limited, it would be useful to be able to detect or count nuclear warheads.

All nuclear warheads contain materials that are radioactive. It has therefore been suggested that gamma-ray and neutron detectors could be used to inspect a ship for the presence of nuclear weapons without requiring physical access to the weapon (*3*). Gamma rays are emitted at energies that are characteristic of the structure of the emitting nucleus. Therefore, a high-resolution gamma-ray detector can allow one to almost always unambiguously identify the nucleus that emitted the radiation.

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Measurements

To explore the utility of various radiation detectors for verification purposes, a series of simple experiments was carried out on 5 July 1989 on the Black Sea near Yalta under the auspices of the Natural Resources Defense Council (NRDC) and the Academy of Sciences of the U.S.S.R. The Soviet Navy provided the cruiser *Slava* (Fig. 1) (*4*). We were informed that the *Slava* was armed with a single nuclear-armed SS-N-12 SLCM in the outside, forward launcher on the starboard side, and that no other nuclear weapons were on board during the experiment. Teams of scientists from the NRDC and the U.S.S.R. used seven different types of detectors. The characteristics of these instruments are summarized in Table 1. Instruments 1 to 4 were portable devices; all except number 7 detected gamma rays.

In this article we discuss measurements that were made with detector number 1, a coaxial high-purity germanium detector. The 151-cm^3 sensitive volume was cylindrical: 5.9 cm in diameter and 5.9 cm long (*5*). It had an energy resolution of about 2 keV (full width at half-maximum) at an energy of 1000 keV. The detector pulses were analyzed with a portable multichannel analyzer with 4096 channels (*6*). Only those gamma rays with energies between 30 and 2670 keV were recorded.

We made the following measurements on the *Slava*: three measurements, totaling about 24 min, on the launch tube directly above the warhead (*7*); one 10-min measurement on the adjacent empty launch tube; and two background measurements lasting 60 and 10 min on the deck of the ship about 27 and 32 m in front of the launch tube. The total count rates in these four locations were 393.2 ± 0.5 counts per second (cps), 36.3 ± 0.3 cps, 11.23 ± 0.06 cps, and 11.14 ± 0.14 cps, respectively (errors are from counting statistics only).

The three measurements on the launch tube were combined to form a single 24-min measurement (*8*); the combined spectrum is shown in Fig. 2. The spectra were analyzed with three different peak-finding and peak-fitting programs to determine the location and intensity of the peaks. The results of the three programs were in excellent agreement; for consistency we will only use those given by the HYPERMET program, which gave the most complete results (*9*).

The energy calibration of the detector proceeded in two steps. First, a ^{60}Co source, which produces strong gamma rays at 1173 and 1332 keV, was used to give a linear relation between channel number and gamma-ray energy. This linear calibration was used to identify 16 prominent gamma-ray emissions in the spectrum shown in Fig. 2; the channel numbers and gamma-ray energies of these peaks were then used in a quadratic least-squares fit (*10*).

Table 2 lists the peaks whose statistical significance exceeded 3 SD above background (*11*). The identity of the parent radionuclide was identified in every case but one (*12*). Many of the lines were due to ^{235}U or ^{239}Pu; the presence of either of these materials suggests the presence of a nuclear warhead. In addition, we identified gamma rays emitted by ^{234m}Pa (a decay product of ^{238}U), ^{212}Bi, and ^{208}Tl (decay products of ^{232}U) (*13*), and ^{241}Am (a decay product of ^{241}Pu). A list of the gamma rays that can be attributed to the presence of uranium and plutonium is given in Table 3 (*14*).

The presence of ^{232}U is noteworthy because it is not a naturally occurring isotope of uranium; it is, however, produced in nuclear reactors (*15*). The U.S.S.R. must therefore have used uranium from reprocessed reactor fuel as the feedstock for the uranium enrichment process; ^{232}U would then be enriched along with ^{235}U. However, ^{232}U would not be present in highly enriched uranium that is produced entirely from virgin natural uranium.

The remaining peaks are due to background radiation, neutron reactions, and pair production. For example, the broad peak centered at 478 keV is probably due either to a (n, α) reaction with ^{10}B or to inelastic scattering with ^{7}Li (*16*). Other neutron-induced gamma rays were emitted at 846.76 keV from (n, n′γ) reactions with ^{56}Fe in steel and at 2223.25 keV from (n, γ) reactions with hydrogen in the fuel of the missile or the high explosive of the warhead. By comparing the spectrum with that taken on the adjacent empty launch tube, we can attribute several peaks to natural background radiation—at 609.31 keV (^{214}Bi) and at 1460.83 keV (^{40}K)—and radioactive fallout—at 604.71 keV (^{134}Cs) and at 661.66 keV (^{137}Cs). The peaks at 511, 1592, and 2103 keV are due to pair production (*17*).

Maximum Detection Distance

For a radioactive source to be identified, its signal at the detector must exceed statistical fluctuations in the background. To minimize the probability of false alarms, a signal is not recorded until an increase of 3 to 5 SD above the mean background occurs (*18*). We examine two cases: (i) where the signal represents the total count rate integrated over the entire recorded energy spectrum, and (ii) where the signal represents the count rate of discrete gamma-ray emissions.

The simplest way to search for radioactive material is to record the total count rate. One first establishes a value for background count rate for the survey area and then looks for a count rate that is significantly greater. In our case, however, an analysis of this type suffers from a lack of background measurements taken at many different locations.

Table 1. Detectors used during the experiment.

1. High-purity germanium detector, 27 cm^2 (U.S.)
2. Lithium-drifted germanium detector, 14 cm^2 (U.S.S.R.)
3. Sodium iodide detector, 100 cm^2 (U.S.)
4. Sodium iodide detector, ≈10 cm^2 (U.S.S.R.)
5. Ship-based sodium iodide detector, 2500 cm^2 (U.S.S.R.)
6. Truck-based sodium iodide gamma-ray telescope, 440 cm^2 (U.S.S.R.)
7. Helicopter-based ^{3}He neutron detector, 2.5 m^2 (U.S.S.R.)

Let C_i and B_i equal the total count rate and the background count rate at point i, r_i equal the distance between the warhead and the detector at this point, and F_i equal the relative shielding factor along this path. If we assume that the signal decreases as the inverse square of the distance (*19*)

$$\frac{(C_i - B_i)r_i^2}{F_i} = \text{constant} \qquad (1)$$

where $i = 1$ and 2 refer to the measurements made on the loaded and empty launch tubes, and $i = 3$ and 4 refer to those made on the deck. From photographs (for example, Fig. 3) and a measurement of the launch tube diameter, we estimate that $r_1 = 0.73 \pm 0.03$ m, $r_2 = 2.94 \pm 0.14$ m, $r_3 = 27 \pm 2$ m, and $r_4 = 32 \pm 2$ m.

As can be seen from Eq. 1, each measurement made along a different path brings with it two new variables: B and F. Only measurements 3 and 4 were made along the same path (and therefore have about the same value of F). If we assume that B is equal at these two points, then the background is given by

$$B_3 = B_4 = \frac{C_4 r_4^2 - C_3 r_3^2}{r_4^2 - r_3^2} = 10.9 \pm 0.5 \text{ cps} \qquad (2)$$

In other words, the count rate on the deck is due almost entirely to background radiation.

Most of the terrestrial gamma-ray background flux is due to

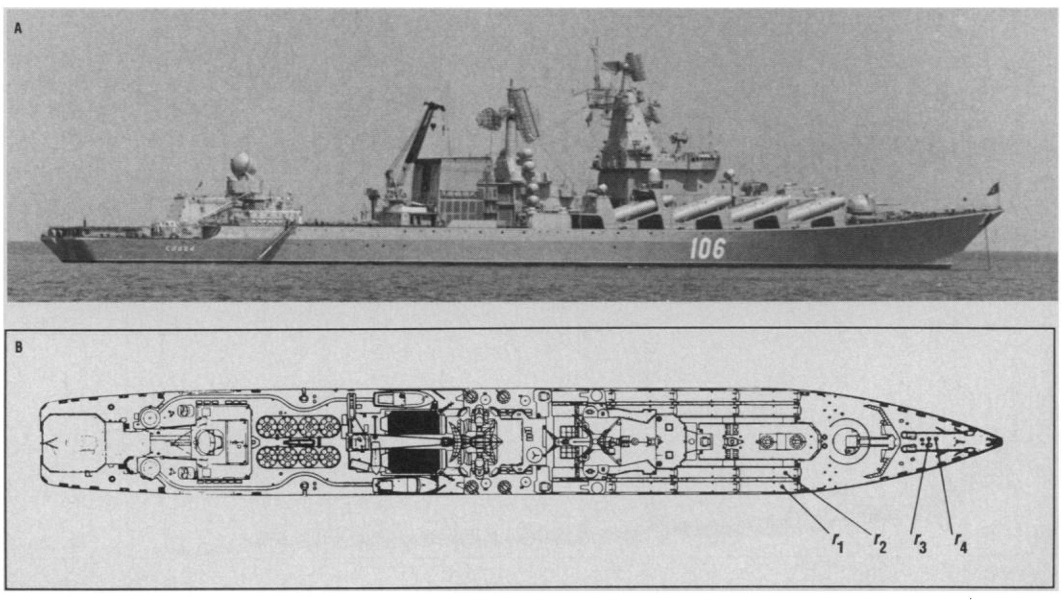

Fig. 1. (**A**) The Soviet cruiser *Slava*. [Photo courtesy of Congressman Bob Carr (D–MI)] (**B**) Diagram showing locations where measurements were made. [Reprinted with permission from (*28*), copyright 1986, The Naval Institute Press]

radionuclides in soil and rock: ^{40}K and decay products of ^{232}Th and ^{238}U (*20*). It is reasonable to assume that these radionuclides would also account for most of the gamma-ray flux above a 10,000-ton ship, since steel would be contaminated with K, Th, and U impurities present in iron ore. Because emissions from these radionuclides were 2.0 ± 0.2 times more intense in the launch tube spectra than in the deck spectra, we will assume that the total background count rate on the launch tubes is twice as great as that on the deck: $B_1 = B_2 = 22 \pm 2$ cps (*21*).

The maximum distance in direction i at which the warhead could have been detected is given by

$$r_{\max} = r_i \left[\frac{C_i - B_i}{C_{\min} - B_i} \right]^{1/2} \tag{3}$$

where $C_{\min}$ is the minimum count rate that would indicate the presence of a warhead. If the background were perfectly uniform, $C_{\min}$ would be determined by counting statistics; for a counting time of 10 min and a significance level of 3 SD, $C_{\min}$ could be as little as 4 to 5% above B_i, leading to $r_{\max}$ of 13 to 20 m (*22*).

The background was not uniform, however. Our analysis suggests that the background above the ship varied by about a factor of 2 over a distance of 30 m. If, as would seem prudent in view of this variability, $C_{\min}$ must be 30 to 100% above B_i, then $r_{\max}$ would only be 2 to 5 m, and $r_{\max}$ could not be improved by increasing the detector area or counting time.

The preceding discussion made no use of the high energy resolution of germanium detectors. Detecting the characteristic emissions of ^{235}U or ^{239}Pu represents far more convincing evidence of the presence of a nuclear warhead than an increase in the total count rate, and avoids confusing warheads with other radioactive sources (for example, depleted-uranium bullets) that may be on a ship.

Because only minute concentrations of ^{235}U and ^{239}Pu are found in common materials, emissions from these radionuclides can be attributed entirely to the warhead (that is, $B = 0$). The same assumption does not hold for emissions from ^{208}Tl, however, because ^{208}Tl is a decay product of both ^{232}U in the warhead and ^{232}Th impurities in the steel. Using the measured intensity of the 911-keV line from ^{228}Ac, which is a decay product of ^{232}Th but not of ^{232}U, we estimated that $79 \pm 17\%$ of the ^{208}Tl decay counts detected on the deck are due to background (*23*).

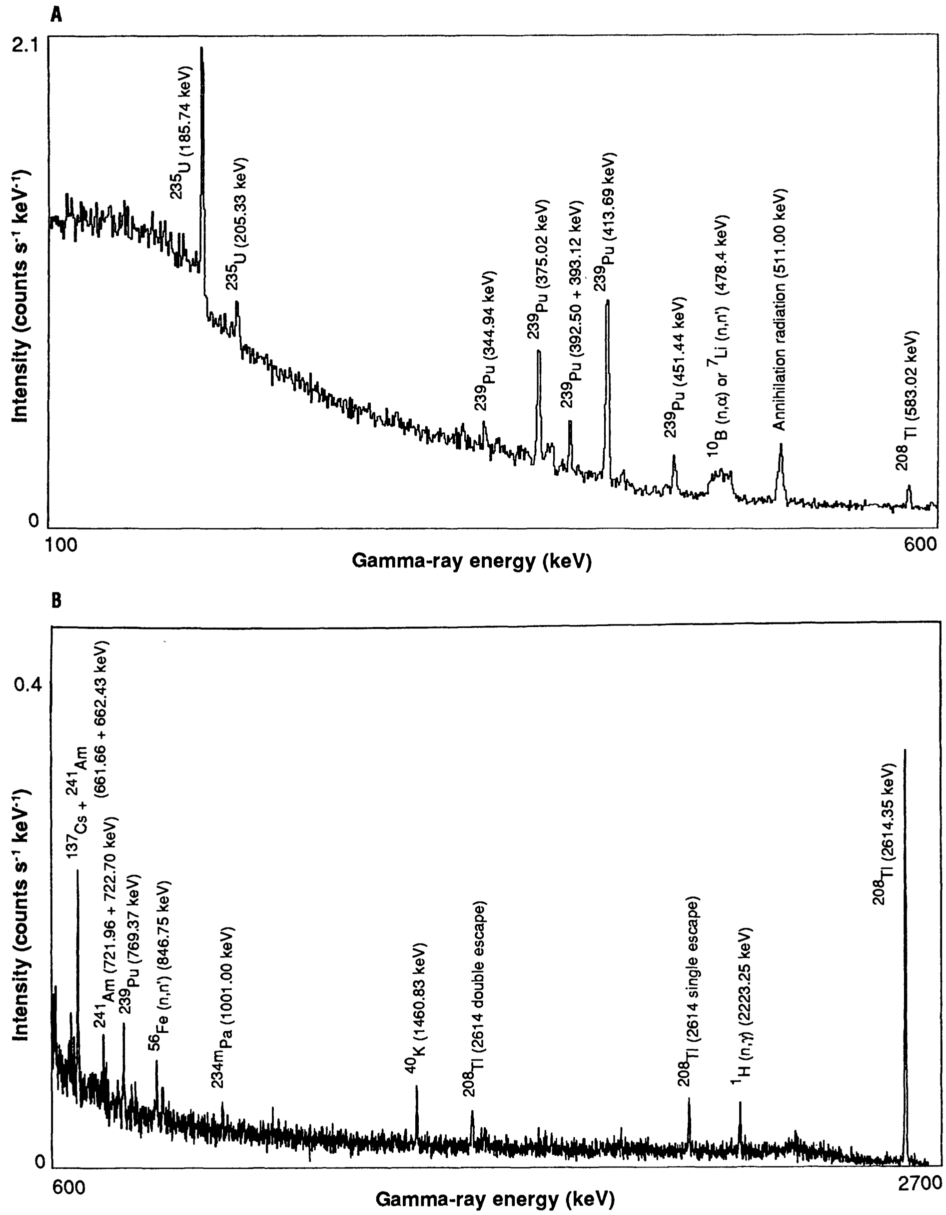

Fig. 2. (**A**) Gamma-ray spectrum from 100 to 600 keV; (**B**) gamma-ray spectrum from 600 to 2700 keV. [Adapted from (*29*)]

Applying Eq. 3 to each line, we find that the most detectable emissions are the 186-keV line from ^{235}U, the 414-keV or the 769-keV line from ^{239}Pu, and the 2614-keV line from the decay of ^{232}U (*24*). In direction 1 (above the warhead), r_{max} = 4 m for ^{235}U and ^{239}Pu, if we assume a counting time of 10 min and a significance level of 3 SD; for ^{232}U, r_{max} = 5 m. In direction 2 (to the side of the launch tube), r_{max} = 1.5 m for ^{235}U, 3 m for ^{239}Pu, and 4 m for ^{232}U. In direction 3 (in front of the launch tube), r_{max} = 6 m for ^{235}U, 12 m for ^{239}Pu, and 6 m for ^{232}U; the lid of the launch tube apparently provides less shielding than its sides (*25*). It is apparent that one must be fairly close to the launch tube to be certain of detecting fissile materials.

Warhead Concealment

Even if nuclear weapons can be detected as they are normally deployed, they could be concealed by placing shielding around the weapon or by moving the weapon to a part of the ship that is not open to inspection. It may even be possible to produce special nuclear weapons that emit very little radiation (*3*).

For the weapon in our experiment, the most stringent requirement for gamma-ray shielding is set by the highly penetrating 2614-keV line. A 100-fold reduction in the intensity of this line would have been required to make it undetectable outside the launch tube; a layer of tungsten at least 6 cm thick placed between the missile and the launch tube would have been sufficient. Adding this much shielding is feasible in principle for the launch tubes we examined (which had a 12-cm space between the top of the missile and the inside of the launch tube), but the existence of such shielding could be detected by visual inspection or with a few simple gamma-ray transmission measurements.

Concealing a cruise missile in another part of the ship appears to be rather difficult—at least for the United States (*2*). Little is known about Soviet equipment; however, in the case of the *Slava*, it did not appear possible to remove the missiles from the launch tubes while at sea—at least not without the help of a crane from a neighboring ship. In theory it would be possible to remove the warhead from the missile, conceal it in a shielded box during an inspection, and reinstall it afterward. It is not considered credible, however, to install a U.S. SLCM warhead at sea without seriously compromising the reliability of the missile.

Table 2. The observed energy, expected energy, and suspected origin of the peaks in Fig. 2 whose significance exceeded 3 SD (*11*).

Observed energy (keV)	Expected energy (keV)	Suspected origin
185.7 ± 0.2*	185.74	^{235}U
205.3 ± 0.3*	205.33	^{235}U
332.4 ± 0.3*	332.81	^{239}Pu
344.8 ± 0.3*	344.94	^{239}Pu
375.1 ± 0.3*	375.02	^{239}Pu
380.3 ± 0.9	380.17	^{239}Pu
382.6 ± 0.9	382.68	^{239}Pu
392.9 ± 0.9	392.99†	^{239}Pu
413.7 ± 0.2*	413.69	^{239}Pu
422.6 ± 0.3	422.57	^{239}Pu
451.5 ± 0.2*	451.44	^{239}Pu
478.0 ± 0.6	478.4	^{10}B (n, αγ) or ^{7}Li (n, n′γ)
511.0 ± 0.2*	511.00‡	Annihilation radiation
583.4 ± 0.2*	583.02	^{208}Tl (from ^{232}U)
604.5 ± 0.3	604.71	^{134}Cs (background)
609.4 ± 0.3	609.31	^{214}Bi (background)
639.9 ± 0.5	640.15	^{239}Pu
646.1 ± 0.3*	645.98	^{239}Pu
652.5 ± 0.5	652.18	^{239}Pu
661.7 ± 0.9	661.84§	^{137}Cs and ^{241}Am
721.8 ± 0.3	722.47‖	^{241}Am (from ^{241}Pu)
727.7 ± 0.3	727.25	^{212}Bi (from ^{232}U)
769.0 ± 0.3*	769.37	^{239}Pu
846.4 ± 0.3	846.75	^{56}Fe (n, n′γ)
860.2 ± 0.3*	860.30	^{208}Tl (from ^{232}U)
1000.8 ± 0.3*	1001.00	^{234m}Pa (from ^{238}U)
1460.6 ± 0.2*	1460.83	^{40}K (background)
1591.7 ± 0.3	1592.35	^{208}Tl double escape
1942.7 ± 0.5		?
2103.1 ± 0.2*	2103.35	^{208}Tl single escape
2223.2 ± 0.3	2223.25	^{1}H (n, γ)
2614.4 ± 0.2*	2614.35	^{208}Tl (from ^{232}T)

*Lines used in the least-squares energy calibration. †Weighted average of two lines from ^{239}Pu: 392.50 keV (0.000116%) and 393.12 keV (0.000444%). ‡Combined with a weaker line from ^{208}Tl at 510.606 keV. §Weighted average of ^{137}Cs line at 661.660 keV and ^{241}Am line from decay of ^{241}Pu at 662.426 keV. ‖Weighted average of two lines from ^{241}Am: 721.962 keV (0.000060%) and 722.70 keV (0.00013%).

What Can Be Learned About Warhead Design?

It is sometimes said that measurements of gamma-ray spectra might reveal sensitive details about the design of nuclear warheads. To investigate this possibility we constructed various models of the warhead on the *Slava*, with the thicknesses of the various components adjusted to give the best possible agreement with our measurements.

The observed intensity of a particular gamma-ray emission, *C*, is equal to the product of the decay rate per gram of the parent isotope *S*, the mass of the parent isotope *M*, the self-shielding factor *G* (that is, the fraction of gamma rays that exit the source unscattered), the external shielding factor *F* (the fraction of gamma rays exiting the

Table 3. The observed intensity, branching ratio, and decay rate of gamma-ray emissions observed in Fig. 2 that are due to isotopes of uranium and plutonium or their daughters (*14*).

Parent radionuclide	Expected energy (keV)	Observed intensity (counts/s)	Branching ratio (%per decay)	Decay rate $(g \times s)^{-1}$
^{232}U*	583.02	0.190 ± 0.018	86.	2.31×10^{11}
	727.72	0.058 ± 0.018	6.65	4.97×10^{10}
	860.30	0.071 ± 0.013	12.0	3.22×10^{10}
	1620.66	0.030 ± 0.012	1.51	1.13×10^{10}
	2614.35	1.369 ± 0.031	99.79	2.68×10^{11}
^{235}U	143.79	0.118 ± 0.051	10.5	8,400
	163.38	0.103 ± 0.038	4.7	3,800
	185.74	1.870 ± 0.074	53.	42,000
	205.33	0.361 ± 0.062	4.7	3,800
^{238}U*	1001.00	0.082 ± 0.014	0.65	81
^{239}Pu	332.81	0.137 ± 0.046	0.000505	11,600
	344.94	0.191 ± 0.061	0.00057	13,100
	375.02	0.862 ± 0.160	0.00158	36,300
	380.17	0.131 ± 0.071	0.000307	7,040
	382.68	0.160 ± 0.073	0.00026	6,000
	392.99	0.373 ± 0.090	0.00056	12,800
	413.69	1.582 ± 0.064	0.00151	34,600
	422.57	0.139 ± 0.027	0.000119	2,730
	451.44	0.318 ± 0.036	0.000192	4,410
	640.15	0.083 ± 0.025	0.0000079	181
	645.98	0.113 ± 0.025	0.0000145	333
	652.18	0.075 ± 0.024	0.0000064	147
	756.42	0.051 ± 0.018	0.0000034	77
	769.37	0.158 ± 0.020	0.0000110	252
^{241}Pu*	662.43	0.116 ± 0.043†	0.00036	174,000
	722.47	0.131 ± 0.026	0.00013	92,000

*The presence of this isotope is inferred from the observed daughter activities. †After subtracting the background from the decay of ^{137}Cs at 661.660 keV measured on the adjacent empty launcher.

source in the direction of the detector that arrive unscattered), the efficiency of the detector ϵ (the fraction of unscattered gamma rays that are fully absorbed in the detector), and the solid angle subtended by the detector Ω:

$$C = SMGF\epsilon(\Omega/4\pi) \tag{4}$$

Decay rate. The rate at which a particular gamma ray is emitted, S, is equal to the branching ratio (gammas per decay) multiplied by the decay rate of the emitting radionuclide (decay counts per second). The decay rate of the jth daughter, Q_j, is given by

$$Q_j(t) = \frac{1.91 \times 10^{16}}{W} \prod_{i=0}^{j} \lambda_i \sum_{h=0}^{j} \left[\frac{\exp(-\lambda_h t)}{\prod_{\substack{k=0 \\ k \neq h}}^{j} (\lambda_k - \lambda_h)} \right] \tag{5}$$

where 1.9×10^{16} is Avogadro's number (6.02×10^{23} atoms per mole) divided by the number of seconds per year (3.16×10^7), W is the atomic weight of the parent (grams per mole), t is the age of the material (years), and λ_i is the decay constant of the ith daughter (years^{-1}). (Q_0 is the activity of the parent, Q_1 is the activity of the first daughter, and so on.)

Self-shielding. If the radioactive material is in the shape of a sphere or an empty spherical shell, then the self-shielding factor far from the sphere can be approximated by

$$G \approx \frac{1}{\beta\mu r}(1 - e^{-\beta\mu r}) \tag{6}$$

where μ is the linear attenuation coefficient and r is the thickness of the shell; β, which depends on the radius ratio of the shell, ranges from 4/3 for solid spheres to 4 for thin shells (*3*).

External shielding. The external shielding factor F provided by a series of flat parallel absorbers is given by

$$F = \Pi_i e^{-\mu_i x_i} \tag{7}$$

where μ_i is the linear attenuation coefficient and x_i is the thickness of the ith absorber along the path between the source and the detector. The equation for a series of spherical shells in which the thickness is not much smaller than the radius is much more complicated (*3*).

Efficiency. The detector was calibrated in the laboratory by using 17 gamma-ray emissions from six radioactive sources of known strength (^{57}Co, ^{88}Y, ^{133}Ba, ^{137}Cs, ^{228}Th, and ^{241}Am). The sources were placed in approximately the same position relative to the detector as was the warhead in the measurement on the loaded launch tube. The efficiency of the detector for the ith line is given by

$$\epsilon_i = \left[\frac{C_i - B_i}{Qf_i(\Omega/4\pi)} \right] \tag{8}$$

where C_i is the total count rate and B_i is the background count rate (counts per second), Q is the activity of the source (decays per second), f is the branching ratio (gammas per decay), and Ω is the solid angle. Figure 4 shows the results.

Solid angle. Accurate evaluation of the solid angle Ω requires knowledge of the shape and size of the source—information not provided by the Soviets. We estimated that the distance from the center of the missile to the center of the detector was 73 ± 3 cm. Since the detector was mounted horizontally on the launcher, $(\Omega/4\pi) = (5.9/73)^2/4\pi = 0.00052 \pm 0.00004$, where 5.9 is the length and diameter of the detector crystal in centimeters.

Analysis of the data. We began our analysis with ^{239}Pu, for which we observed gamma-ray emissions at 14 different energies from 333 to 769 keV. The plutonium was assumed to be in the form of an empty spherical shell in the center of the weapon, surrounded by low-, medium-, and high-Z materials. High-explosive was chosen to represent low-Z materials (the relative attenuation caused by other common low-Z materials—beryllium, boron, and aluminum—is very similar). Medium-Z materials, such as the steel launch tube,

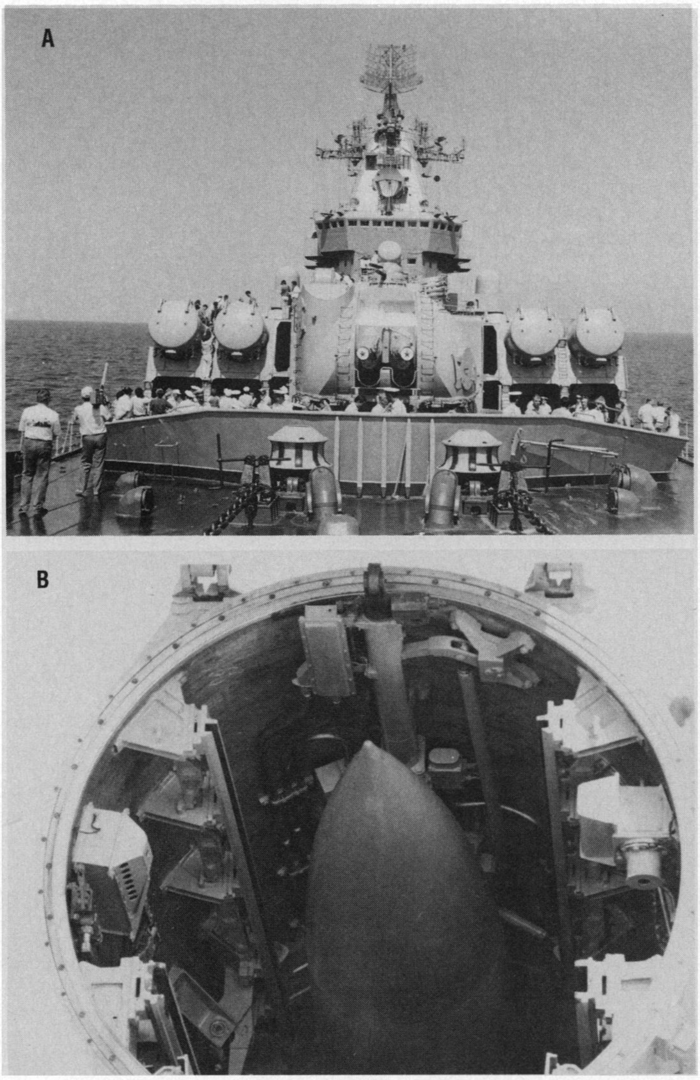

Fig. 3. (**A**) View from the deck of the *Slava* showing four of the cruise missile launch tubes. (**B**) View into an opened launch tube. (**C**) Gamma-ray detector in position for measurement on a launch tube. [Photos courtesy of Congressman Bob Carr (D–MI)]

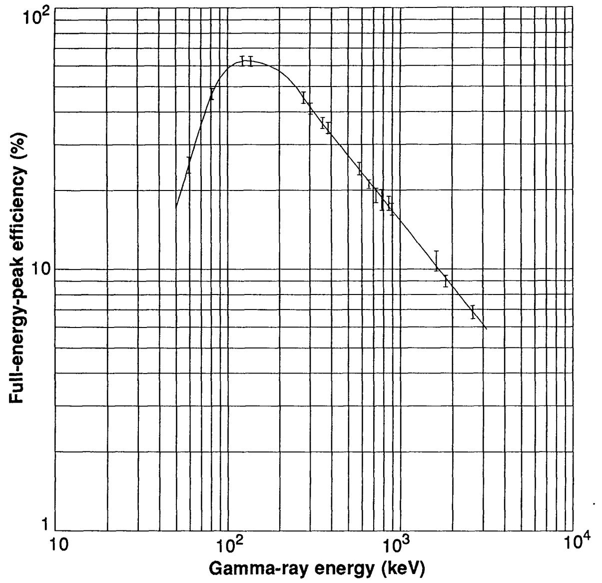

Fig. 4. Full energy peak efficiency of the detector as a function of gamma-ray energy. The error in the efficiency is the combined errors of the count rate, the background rate, the activity of the source, and the branching ratio to 1 SD.

were represented by iron. Uranium represented high-Z materials. The variables in the least-squares fit were the thicknesses of these three materials and the mass and the outside radius of the plutonium shell. The concentration of ^{239}Pu was taken to be 96%.

The fact that the low-energy gamma rays from ^{235}U were seen implies that there is very little high-Z material outside the uranium (the mean-free-path of 186-keV gamma rays is 0.36 mm in uranium). Our initial assumption was a shell of ^{235}U surrounding a shell of ^{239}Pu (as in a composite-core fission weapon), but we found it impossible to obtain a good fit to either the plutonium or the uranium data with this model.

If, on the other hand, we assumed that the ^{239}Pu was immediately surrounded by low-Z material, it was surprisingly easy to obtain acceptable fits ($\chi^2 \lesssim 1$ per degree of freedom) with many combinations of these variables. The combinations that resulted in acceptable fits included plutonium radii of 5.4 to 8.0 cm, plutonium masses of 3 to 6 kg, high-explosive thicknesses of 3 to 10 cm, iron thicknesses of 6 to 8 cm, and uranium thicknesses of 0.1 to 0.4 cm. In general, changes in the value of one variable could be offset by a combination of changes in other variables. While these values may seem reasonable, it is apparent that this type of analysis cannot uncover sensitive design details.

Using the values given by the above analysis and the count rates of the two ^{241}Am gamma rays, we estimated the percentage of ^{241}Pu to be $0.20 \pm 0.10\%$, which corresponds to a ^{239}Pu concentration of $96 \pm 1\%$ and a ^{240}Pu concentration of $4 \pm 1\%$ (*26*). For comparison, U.S. weapons-grade plutonium typically contains 6% ^{240}Pu; supergrade plutonium (used in some U.S. warheads) contains 3% ^{240}Pu (*27*).

The analysis of the uranium data is necessarily much less precise because we have only ten lines from all three isotopes and two additional variables: the concentrations of ^{232}U and ^{238}U. Moreover, the four ^{235}U lines, which cover a narrow range of low energies (144 to 205 keV), are statistically decoupled from the five ^{232}U lines at much higher energies. The intensity of the single ^{238}U line can only be used to estimate the concentration of that isotope. The data are roughly consistent with a 7- to 15-kg uranium shell with a radius of about 10 to 15 cm not surrounded by a thick layer of low-Z materials. The data are also consistent with a ^{232}U concentration of 0.1 to 0.2 ppb and a ^{238}U concentration of 4 to 6% [U.S. weapons-grade uranium is 5.5% ^{238}U (*27*)].

Thus, we do not believe that such measurements are capable of revealing sensitive information about the design of the warhead. But even if sensitive details could be revealed, there are ways to protect such information. In general, there seem to be three types of concerns: (i) that the inspecting nation could learn new weapon design techniques; (ii) that something could be learned about the general technical sophistication of the other nation; and (iii) that the information revealed might aid possible proliferators. The latter problem could be solved simply by keeping the data confidential. The other two concerns could be ameliorated by designing special detection equipment that would only collect data in narrow energy bands of interest (for example, around 186, 414, 769, and 2614 keV).

Conclusions

The measurements we made with the germanium detector on the *Slava* provided valuable information for building a verification regime for SLCMs. At close range it is possible to detect the fissionable materials in at least one type of warhead, even when it is shielded by a thick launch tube. The ability to clearly identify either ^{235}U or ^{239}Pu would provide prima facie evidence that a nuclear warhead was contained in a launcher.

Detecting line emissions from ^{235}U and ^{239}Pu is a more certain and, in the absence of extensive background measurements, a more efficient method of searching for nuclear warheads than looking for an increase in the total count rate. The most intense lines from ^{235}U and ^{239}Pu could have been detected through the launch tube at a distance of 4 to 5 m.

The warhead could have been concealed by placing a thick layer of tungsten inside the launch tube, but such shielding could be revealed by simple gamma-ray transmission measurements. Alternatively, the warhead could be removed to a shielded box, although this is not possible for current U.S. SLCMs. Moving the entire SLCM below decks did not appear possible on the *Slava*.

Our analysis indicates that passive radiation detectors, even those with high energy resolution, cannot be used to reveal sensitive weapon design information, at least if such measurements are constrained to a few locations and counting times of less than 1 hour. There simply is too little information in the spectra to constrain the many possible variables in a realistic warhead design.

Finally, it should be emphasized that passive radiation detection is only one tool of many that may be useful in future arms control agreements. Some types of agreements—such as a ban on nuclear weapons on certain naval vessels, or one in which a particular missile must be identified as conventional or nuclear—might be facilitated by such techniques, whereas other types of agreements might not benefit at all.

REFERENCES AND NOTES

1. S. M. Keeny, C. Floweree, S. Resor, G. C. Smith, *Arms Control Today* **19**, 9 (August 1989).
2. G. N. Lewis, S. K. Ride, J. S. Townsend, *Science* **246**, 765 (1989).
3. A detailed discussion of warhead detection techniques is given by S. Fetter *et al.*, *Sci. Glob. Secur.* **1**, 225 (1990).
4. The *Slava*, which became operational in 1982, is about 200 m long and has a crew of about 600. The turbine-powered ship can launch up to 16 SS-N-12 SLCMs, 64 SA-N-6 surface-to-air missiles, and has ten 21-inch torpedo tubes.
5. A portable Dewar filled with liquid nitrogen keeps the detector (Princeton Gamma-Tech, model IGC3520) at operating temperatures for up to 2 days.
6. The portable Davidson model 2056-B 4096-channel analyzer also provided power for the detector and amplifier.
7. The Soviets suggested that we place the detector about 3.4 m from the front end of the launch tube to maximize the count rate. We verified this by making measure-

ments along the tube with a small hand-held detector.
8. Because of a small increase in amplifier gain between the first and third measurements, combining the raw data increased the peak width. This had a negligible effect on the energy calibration and the estimates of the areas under peaks, however.
9. G. W. Phillips and K. W. Marlow, "Program HYPERMET for automatic analysis of gamma-ray spectra from germanium detectors" (NRL 3198, Naval Research Laboratory, Washington, DC, 1976). The other two programs were MINIGAM II (sold by EG&G Ortec, Oak Ridge, TN) and PEAKFIT (written by S. Fetter).
10. The least-squares fit was given by $E_\gamma = 1.02 + 0.65103\ n + 4.25 \times 10^{-7}\ n^2$, where n is the channel number and E_γ is the gamma-ray energy in kiloelectron volts.
11. The error in the observed energy is the combined error of the peak fit and the energy calibration to 1 SD. Expected energies are from E. Browne and R. B. Firestone [*Table of Radioactive Isotopes* (Wiley, New York, 1986)] and F. E. Senftle, H. D. Moore, and D. B. Leep [*Nucl. Instrum. Meth.* **93**, 425 (1971)].
12. We could not identify the gamma-ray emission at 1942.7 keV, which was just significant at the 3 SD level in the combined spectrum.
13. ^{212}Bi and ^{208}Tl are also decay products of naturally occurring ^{232}Th, but if ^{232}Th was the parent we also would have observed intense gamma rays at 911.16, 968.97, and 1588.23 keV from the decay of ^{228}Ac.
14. The error in the observed intensity is the error in the curve fit to 1 SD. The branching ratios are from E. Browne and R. B. Firestone [*Table of Radioactive Isotopes* (Wiley, New York, 1986)]. For gamma rays emitted by a radioactive daughter, the decay rate depends on the age of the material; the decay rates given here are for a decay time of 10 years (that is, 10 years after starting with 1 g of the pure parent isotope). For a decay time of 5 years, the production rate from ^{208}Tl is 10% smaller; that from ^{241}Am is 1.8 times smaller. For a decay time of 20 years, the production rate from ^{208}Tl is 10% smaller; that from ^{241}Am is 1.6 times greater.
15. ^{232}U is produced in nuclear reactors in the following way:

$$^{235}\mathrm{U} \xrightarrow[7 \times 10^8 \text{ years}]{\alpha} {}^{231}\mathrm{Th} \xrightarrow[1\,1 \text{ day}]{\beta} {}^{231}\mathrm{Pa}\ (n, \gamma)\ {}^{232}\mathrm{Pa} \xrightarrow[1.3 \text{ day}]{\beta} {}^{232}\mathrm{U}$$

About 1 ppb of ^{231}Pa, which has a half-life of 33,000 years and a thermal neutron-capture cross section of 260 barns, is produced every year by the decay of ^{235}U.
16. The excited ^{7}Li nucleus created by either reaction would be moving at high speed when it emits the gamma ray, leading to a Doppler-broadened line with a maximum width of about 16 keV, just as we observed. ^{10}B could be in the missile fuel or possibly in the warhead; ^{7}Li could be in the thermonuclear fuel.
17. If a gamma ray has an energy greater than 1022 keV, it may create electron-positron pairs in the detector. After coming to rest, the positron interacts with an electron and both are annihilated, leading to the emission of two 511-keV gamma rays. If both of these gamma rays escape from the detector, a "double escape peak" is registered at 1022 keV below the energy of the original gamma ray; if only one escapes, a "single escape peak" is recorded. Thus, the strong 2614-keV gamma ray leads to single and double escape peaks at 2103 and 1592 keV. The peak at 511 keV arises from pair production in materials outside of the detector.
18. The probability of 3 SD occurring at random is 0.13%; for 4 SD, it is 0.0032% (one chance in 30,000); for 5 SD, it is 0.000029% (one chance in three million).
19. The mean-free-path of even low-energy gamma rays in air is large compared to the distances under consideration (for example, 65 m at 186 keV). Moreover, the finite size of source does not cause significant errors even at short distances: r^{-2} scaling underestimates the solid angle by less than 4% for a source-to-detector distance of 73 cm and a source radius of 10 cm.
20. These three sources, in roughly equal amounts, typically account for more than 90% of the background gamma-ray flux; cosmic rays, cosmogenic radionuclides (for example, ^{14}C in the atmosphere), fallout, airborne radon, and other primordial radionuclides account for less than 10% [National Council on Radiological Protection (NCRP), "Exposure of the population in the United States and Canada from natural background radiation" (NCRP Report 94, NCRP, Bethesda, MD, 1987)].
21. We observed five lines from ^{214}Bi and ^{214}Pb (daughters of ^{238}U), one line from ^{228}Ac (a daughter of ^{232}Th), and one line from ^{40}K. The ratio of the intensity of these lines on the launch tubes to their intensity on the deck was 1.8 ± 0.2, 2.8 ± 1.2, and 2.5 ± 0.3, respectively. If the three sources contribute roughly equal amounts to the background flux, the average ratio is 2.0 ± 0.2. However, the presence of humans nearby, each of whom contains more than 100 g of K, makes the ^{40}K ratio of doubtful utility.
22. Let c and b be the total number of counts and the total number of background counts recorded in a given time t. Then $s = c - b$, $\sigma_s^2 = \sigma_c^2 + \sigma_b^2$, and $s = m\sigma_s$ for a signal significant at the $m\sigma$ level. Solving for s, we have $s = \frac{1}{2}m^2[1 + (1 + 8b/m^2)^{1/2}]$. If $b = Bt = (10.9 \text{ cps})\ (600 \text{ s}) = 6540$ counts and $m = 3$, then $s = 348$ counts, which is 0.58 cps or 5.3% of the background rate. Similarly, if $B = 22$ cps, s would be 0.82 cps or 3.7% of B.
23. By comparing the intensity of the 911-keV ^{228}Ac line to the intensity of the 583- and 2614-keV ^{208}Tl lines as measured on the deck, we estimate, after correcting for differences in detector efficiency and self-absorption by the steel, that 79 ± 17% of the ^{208}Tl counts on the deck arise from the decay of ^{232}Th. The 2614-keV background count rate was therefore 0.0058 ± 0.0017 cps on the deck; since the ratio of 911-keV count rate on the launch tube to that on the deck was 2.8 ± 1.2, the background count rate on the launch tube was 0.016 ± 0.008 cps.
24. In this case, Eq. 3 must include in B_i the background generated by the warhead itself due to Compton-scattered gamma rays. HYPERMET produces estimates of s and σ_s, which can be used to estimate this source of "background." Since $\sigma_s^2 = \sigma_c^2 + \sigma_b^2 = c + b = s + 2b$, $b = (\sigma_s^2 - s)/2$. Therefore, the Compton-scattered component of the background at r_{max} is given approximately by $\frac{1}{2}(\sigma_s^2 - s)\ (r_i/r_{max})^2$.
25. If we adjust the thickness of steel in the launch tube lid so that the 186- and 2614-keV lines have the correct intensity at point 3, then we would predict the 769-keV line to be much lower in intensity (and the 414-keV line to be greater in intensity) than we observed at this point. The results are, however, roughly consistent with a model in which the plutonium is shielded by heavy metal in direction 3 but that the uranium is not (as might be the case in a thermonuclear weapon with the secondary facing forward).
26. These concentrations are for a Pickering-type Canadian deuterium-uranium reactor. The concentrations of ^{239}Pu and ^{240}Pu for a given ^{241}Pu concentration are very similar in a graphite production reactor.
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