Neutron multiplicity counting for warhead authentication: Bias reduction and quantification

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Abstract:

Neutron multiplicity counting is useful in warhead or warhead component authentication to determine if an item declared to be a warhead fulfils an attribute related to its fissile mass. The inspector will not know the configuration of the warhead or component, in particular the exact fissile material geometry and the configuration of potential material between the plutonium and detector. Assay bias for highly multiplicative samples has been studied only to a limited extent; corrections to the point model are based on empirical data valid for only a small range of geometries. We systematically study the bias and propose physics-based corrections for spherical shell geometries using MCNPX-PoliMi simulations. As a result, the bias compared to the point model equations can be significantly reduced, but an uncertainty remains which must be quantified.

Keywords: disarmament, verification, neutron multiplicity counting, point model

1. Disarmament Verification

As part of verified fissile warhead and warhead component inventory declarations and the verification of warhead dismantlement, three elements will most likely be key to a sound verification regime. First, warheads and warhead components must be uniquely identified so that warheads and components in stock are not counted twice. Second, warheads and components must be authenticated. Authentication in this context is the process during an on-site inspection by which it is assessed by measurements whether a specific item is a nuclear warhead (or component). Third, a robust Continuity of Knowledge could be defined as providing means to effectively demonstrate over a certain time or process, e.g. during warhead dismantlement, the unchanged identity of the treaty-accountable item and its integrity (i.e. that no undeclared changes to the item occurred).

Due to the classified nature of the items under investigation, direct measurements for authentication purposes will most likely not be possible as they would reveal information that is considered sensitive for nonproliferation, national security and possibly other reasons. The use of information barriers could overcome this problem. An information barrier takes classified measurements but converts the results to an unclassified output (such as a binary yes/no signal) while protecting the sensitive data from the inspector's view.

In the attribute approach, the inspecting and host parties agree on a set of attributes that the items would be checked against and on an analysis algorithm. This set should be defined in a way that it allows for an assessment whether a declared warhead (component) is genuine. One of the attributes that could be considered is related to its fissile mass. This attribute could perhaps be assessed by neutron multiplicity measurements using He-3 detectors.

A high reliability of attribute measurement techniques is required as inspectors cannot review and analyze detailed measurement results, if they are in doubt for whatever reasons. In contrast to other situations where radioactive samples are characterized, the knowledge that exists prior to the measurements, for example the sample's geometry, may be inadequate. Many measurement techniques require certain information on a sample to function accurately. Inspectors must understand how large deviations between real and measured values (bias) become as the properties of the item and intervening materials vary in plausible manners. Besides the configuration of the fissile material itself, bias may be the result of the potential presence of materials between warhead component and detector. In the case of fully assembled warheads, materials such as a conventional explosive surround the fissile component. Furthermore, most nuclear warheads and warhead components are stored in containers for safety reasons [1, p. 33].

In this paper, the major source of neutron multiplicity counting bias with relevance to warhead authentication is discussed which occurs for samples with high masses and neutron multiplication. Furthermore, it is investigated how this bias depends on the sample configuration in order to assess the reliability of neutron multiplicity counting when the configuration remains unknown.

2. Bias for highly multiplicative plutonium samples

Neutron multiplicity counting assesses the plutonium mass by counting the neutrons that are detected within a defined gate length after a neutron trigger. The measured quantities are the Singles, Doubles and Triples rates S, D and T. The theory behind neutron multiplicity counting that allows the deduction of the fissile mass, the neutron multiplication and the quantification of (α, n) reactions from S, D and T is based on a derivation by Böhnel [2]. It inter alia makes the assumption that the amount of induced fission started by the neutrons from a spontaneous fission is constant regardless of where an original spontaneous fission event occurred ("point model"). While this assumption is unproblematic for gram quantities of plutonium metal, it becomes a major source of bias with increasing sample size.

Indeed, leakage of neutrons from a spontaneous fission and secondary neutrons from induced fission depends on the position of the initial spontaneous fission event [3]. For spherical configurations, this dependence can be expressed by the function $M(r)$, where M is the multiplication, i.e. the total number of leaked neutrons per spontaneous fission neutron, and r is the position of the spontaneous fission event.

There has been some success in applying empirical correction factors that depend on the measured multiplication: Krick et al. [3] determined separate S, D and T corrections based on MCNPX simulations of plutonium cylinders to obtain the correct masses. These corrections remain, however, geometry-dependent [3].

Croft et al. [4] proposed another model coupled with the desired physical understanding: In the equations required to deduce the fissile mass, the multiplication $\langle M^n \rangle$ appears up to the fifth order $(\mathrm{n} = 5)$ [5]. According to the "point model", assuming constant multiplication at all spontaneous fission locations, $\langle M^n \rangle = \langle \mathrm{M} \rangle^{\mathrm{n}}$. Therefore, Croft et al. propose correction factors [4]

$$\mathrm{g_n} = \frac{\langle \mathrm{M^n} \rangle}{\langle \mathrm{M} \rangle^{\mathrm{n}}}, \qquad \mathrm{n} = 2 \dots 5$$

to correct for falsely using $\langle M \rangle^n$. The g_n are calculated from

$$\langle \mathrm{M^n} \rangle = \frac{1}{\mathrm{V}} \int \mathrm{M^n}(\vec{\mathrm{r}}) \mathrm{dV}$$

The corrected equations are then [4]

$$S = F \cdot \epsilon \cdot \langle M \rangle \cdot \nu_{sf1}(1+\alpha)$$

$$D = \frac{F \cdot \epsilon^2 \cdot f_d \cdot \langle M^2 \rangle}{2} [\nu_{sf2} \cdot g_2 + (g_3 \cdot \langle M \rangle - g_2) \frac{\nu_{sf1} \cdot \nu_{i2}}{\nu_{i1} - 1} (1+\alpha)]$$

$$T = \frac{F \cdot \epsilon^3 \cdot f_t \cdot \langle M^3 \rangle}{6} [\nu_{sf3} g_3 + (g_4 \cdot \langle M \rangle - g_3)(1+\alpha) \frac{\nu_{sf1} \cdot \nu_{i3}}{\nu_{i1} - 1} +$$

$$3(g_4 \cdot \langle M \rangle - g_3) \frac{\nu_{sf2} \cdot \nu_{i2}}{\nu_{i1} - 1} + 3(g_5 \cdot \langle M^2 \rangle - 2 g_4 \cdot \langle M \rangle + g_3)(1+\alpha) \frac{\nu_{sf1} \cdot \nu_{i2}^2}{(\nu_{i1} - 1)^2}]$$

where ν_{sfn} are the factorial moments of the spontaneous fission multiplicity distribution, ν_{in} are the factorial moments of the induced fission multiplicity distribution, F is the spontaneous fission rate from which the fissile mass m can be deduced if the isotopic composition is known, ϵ is the detection efficiency, α is the ratio of (α, n) to spontaneous fission reactions, f_d and f_t are the Doubles and Triples gate fractions. We have solved these equations for $\langle M \rangle$, α and m.

3. Simulations

It has been shown that this approach indeed removes the bias [6]. This requires, however, full knowledge of the sample configuration in order to obtain $M^n(\vec{r})$ and the g_n from Monte Carlo simulations. In the following, parameter studies are presented with the aim of showing how the g_n can be estimated when the sample configuration is not fully known.

MCNPX-PoliMi simulations [7] have been performed with plutonium metal samples (94% Pu-239 and 6% Pu-240, $\rho = 19.8 \, ^{\mathrm{g}}/_{\mathrm{cm}^3}$) in spherical geometries, defined by their outer radius $\mathrm{r_{out}}$ and in the case of hollow spheres their inner radius $\mathrm{r_{in}}$. A series of solid spheres and four series of hollow spheres ($\mathrm{r_{in}} = 1.0 \text{ cm}, 2.0 \text{ cm}, 3.5 \text{ cm}, \ 5.0 \text{ cm}$) were simulated with a variety of masses and accordingly $\mathrm{r_{out}}$. In the individual series, the thickness $\mathrm{d} = \mathrm{r_{out}} - \mathrm{r_{in}}$ was increased up to 2.9 cm.

<u>g_n estimate based on thickness</u>

The simulations show a strong dependence of the correction factors on the thickness d. Figure 1 shows $g_2(d)$ for the configurations with different $\mathrm{r_{in}}$. The slopes of g_3, g_4 and g_5 are similar, as can be seen from Figures 4, 5 and 6 in the Appendix. Most importantly, the figures show that the dependence of the g_n on r_{in} is rather limited; the curves of all hollow spheres are very similar.

Based on these results, the g_n can be approximated as a function of d if it is known whether the configuration is best resembled by a solid or hollow sphere, but without necessarily knowing r_{in} or r_{out}. When for example choosing our results for $r_{in} = 2.0 \, cm$ as reference curves to determine the g_n, the deviations of the plutonium mass obtained with the corrected analysis from the true values can be expected to be small for hollow spheres with different r_{in} but constant d.

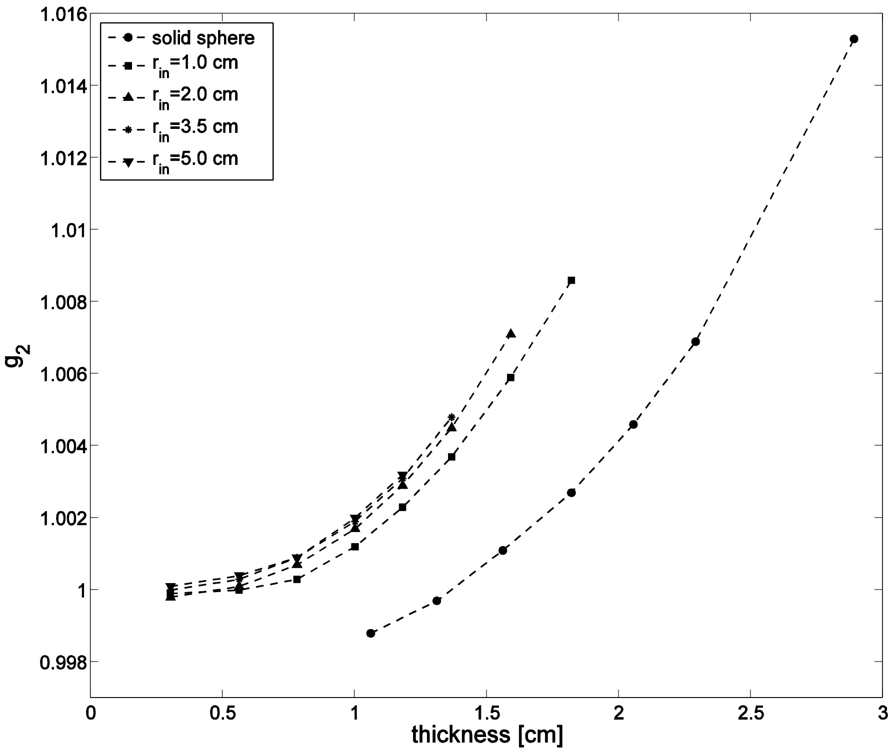

Figure 1: g_2 as a function of thickness

g_n estimate based on multiplication

If d is not available, an estimate of the g_n can also be obtained as a function of the average multiplication, a direct output of the analysed multiplicity counting results. From Figure 2 and also Figures 7, 8 and 9 in the Appendix, it can be seen that the slopes of $g_n(<M>)$ are steeper for smaller r_{in}. Depending on the available information on the sample configuration, we suggest to choose a reference curve and an empirical fit function. Double exponential functions are suited to sufficiently represent the data. Assuming a hollow sphere, a reasonable choice for a reference curve could for example be the $r_{in} = 2.0\ cm$ data. In general, the magnitudes of the differences between the curves of the different r_{in} are larger for $g_n(<M>)$ than for $g_n(d)$. As a result, the possible deviations of the g_n estimated from $g_n(<M>)$ are generally larger compared to $g_n(d)$.

g_n estimate based on fissile mass

It has been proposed to estimate the g_n as a function of fissile mass for solid sphere and cylinder configurations [4]. Figure 3 shows g_2 of the solid and hollow sphere configurations. The results for g_3, g_4 and g_5 are shown in Figures 10, 11 and 12 in the Appendix. Determining the g_n from a reference function of the fissile mass introduces large uncertainties, as their values strongly depend on the actual configuration. Thus, a reliable reference function cannot be given without additional information such as the radius or the multiplication.

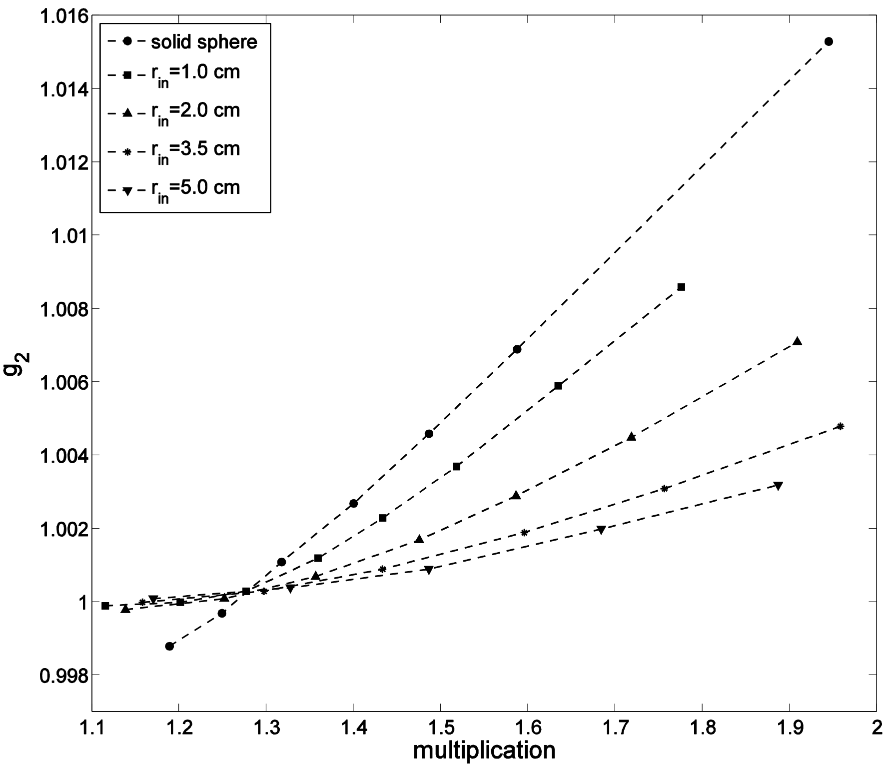

Figure 2: g_2 as a function of multiplication

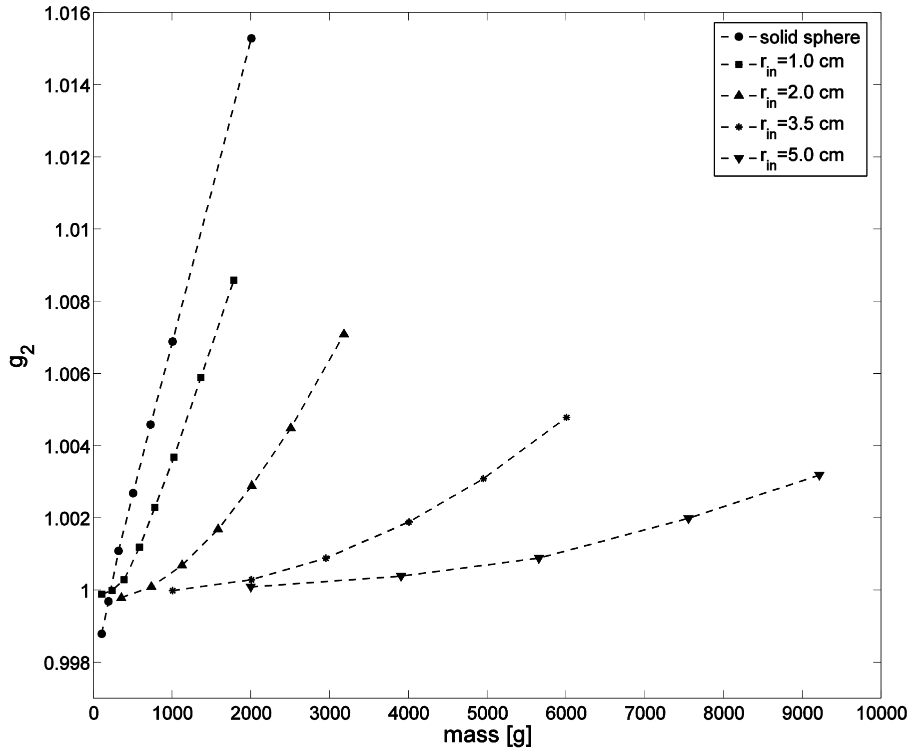

Figure 3: g_2 as a function of fissile mass

Influence of isotopic composition

Results of simulations with different plutonium isotopic compositions are shown in Table 1. The g_n increase slightly with Pu-239 content. Compared to the influence of geometries, the effect of the isotopic composition is small. Knowledge of the isotopic composition is helpful to estimate the g_n, but g_n estimates without considering the isotopic composition can remain fairly accurate.

Pu-239	Pu-240	g_2	g_3	g_4	g_5
0.70	0.30	1.0040	1.0118	1.0233	1.0383
0.85	0.15	1.0045	1.0133	1.0263	1.0433
0.97	0.03	1.0049	1.0146	1.0288	1.0474

Table 1: g_2 of a hollow sphere configuration (inner radius 3.5 cm, outer radius 4.9 cm) and different isotopic compositions

	Reflected solid sphere $r_{out} = 2.3\ cm$	Reflected hollow sphere $r_{in} = 3.5\ cn, r_{out} = 4.9\ cm$
g_2	1.0059	1.0033
g_3	1.0187	1.0098
g_4	1.0385	1.0193
g_5	1.0656	1.0319

Table 2: g_n for reflected configurations

Influence of neutron reflection

In order to study the influence of neutron reflection, simulations have been performed for two plutonium configurations (a solid sphere, $r_{out} = 2.3\ cm$ and a hollow sphere, $r_{in} = 3.5\ cn, r_{out} = 4.9\ cm$) surrounded by a 3 cm thick layer of polyethylene ($\rho = 0.955\ {}^{g}/_{cm^3}$). The results for the g_n are shown in Table 2. Compared to the unreflected configurations, they are somewhat smaller. Accordingly, information of reflection is helpful to determine the g_n with high accuracy.

4. Conclusion

Without detailed knowledge of the sample configuration, the g_n must be estimated. For hollow spheres, they can be approximated with high accuracy when the thickness d is known. A less accurate estimate is obtained when only the multiplication is known. Reflection decreases the g_n. As the available information on the sample configuration will be limited in the case of warhead authentication, uncertainties in the mass assessments remain due to the uncertainties of the g_n. The more information is available, the more reliable will the assessment be. In any case, according to which information is given, the remaining uncertainties should be quantified to understand the reliability of the technique.

5. Acknowledgements

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6. References

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Appendix

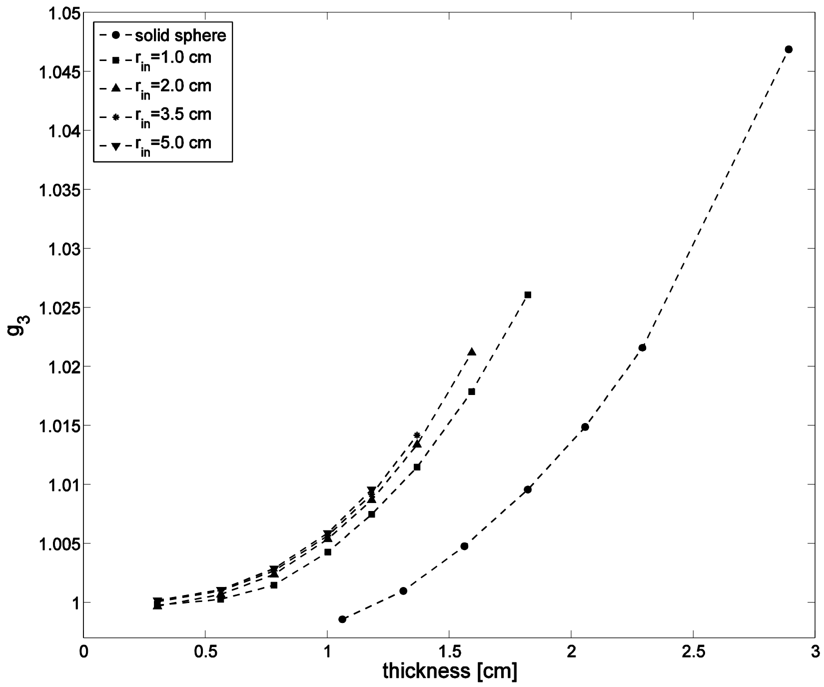

Figure 4: g_3 as a function of thickness

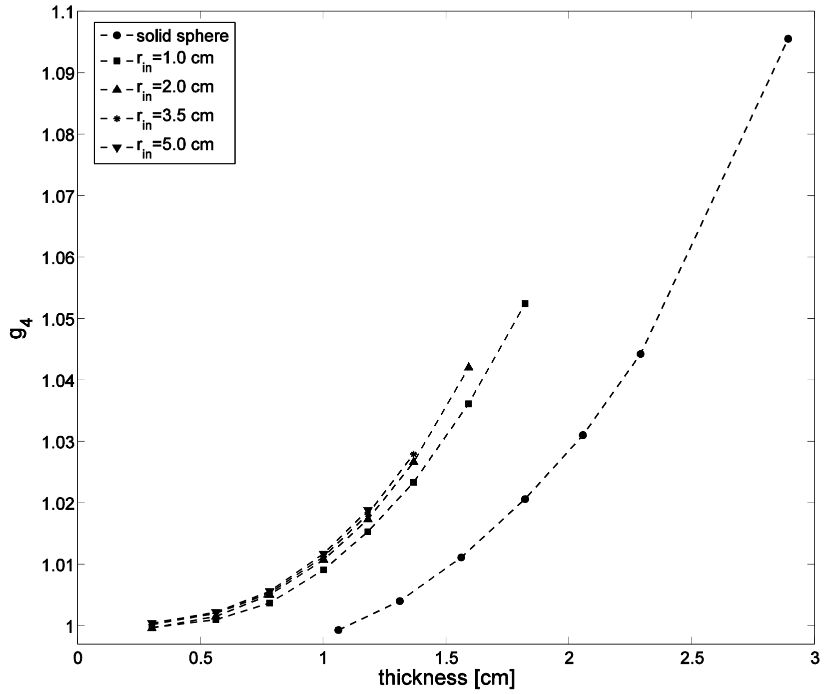

Figure 5: g_4 as a function of thickness

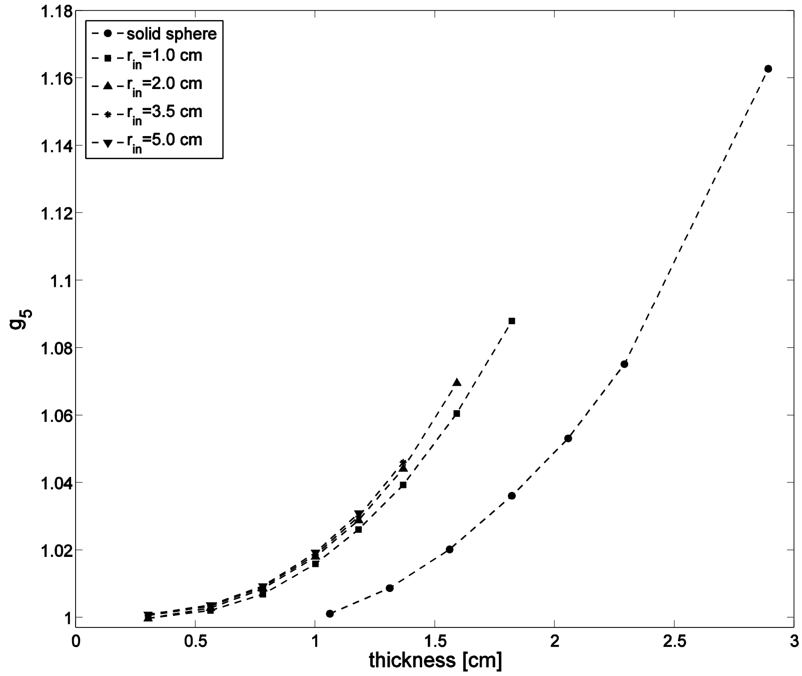

Figure 6: g_5 as a function of thickness

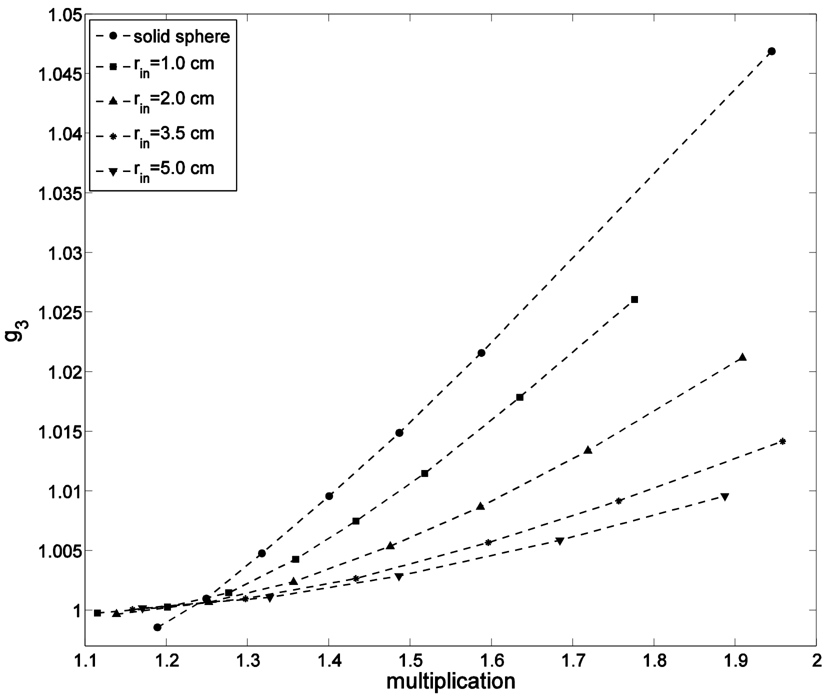

Figure 7: g_3 as a function of multiplication

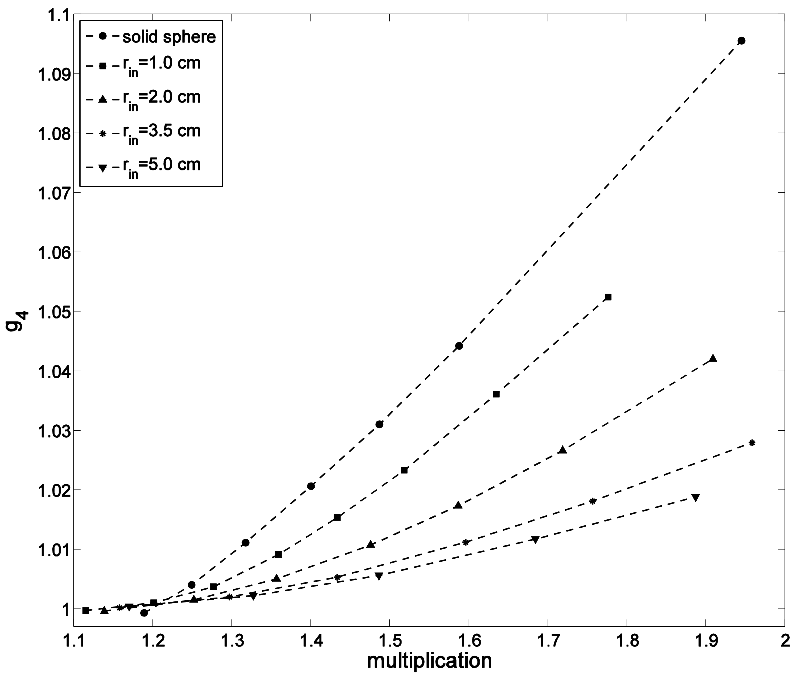

Figure 8: g_4 as a function of multiplication

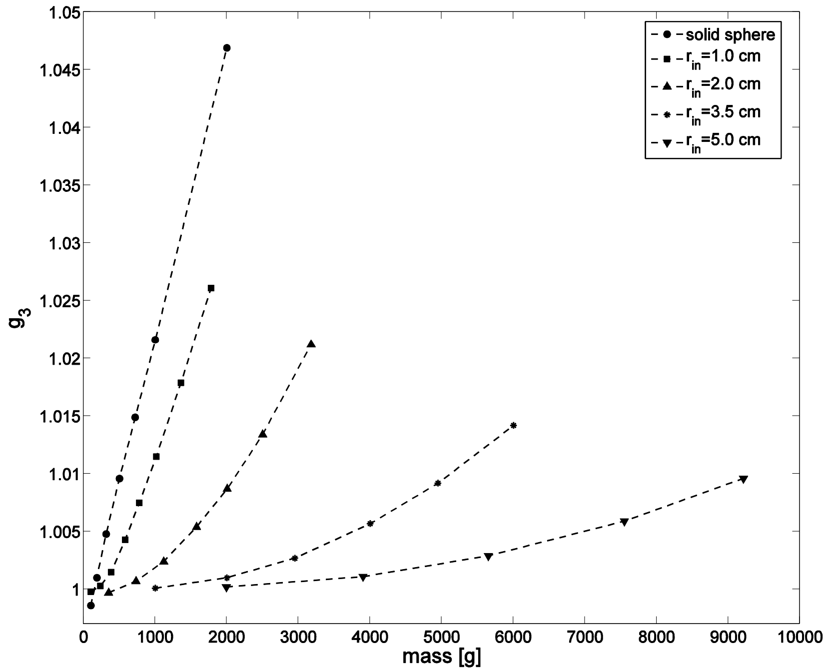

Figure 9: g_5 as a function of multiplication

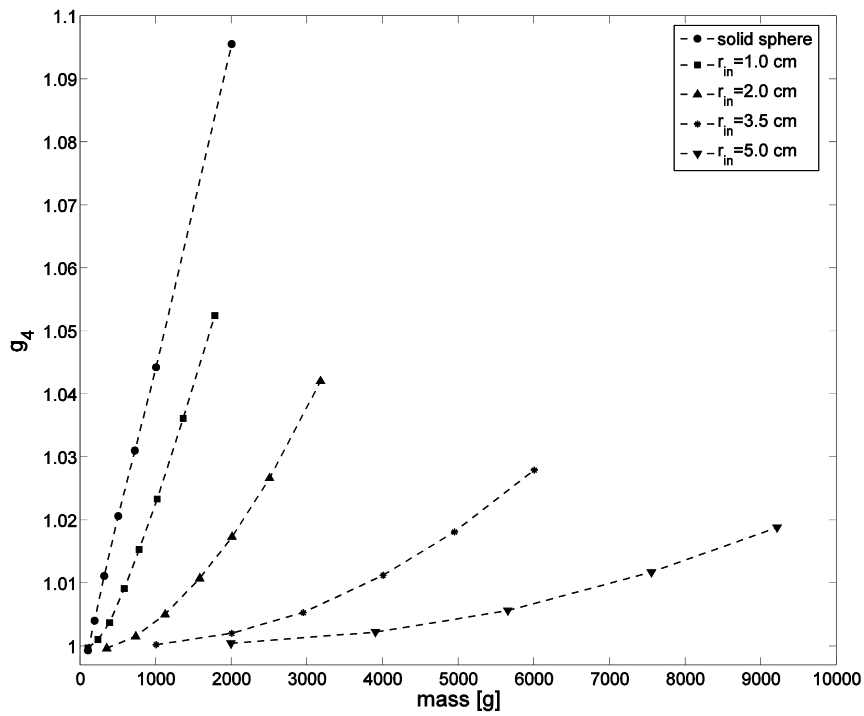

Figure 10: g_3 as a function of fissile mass

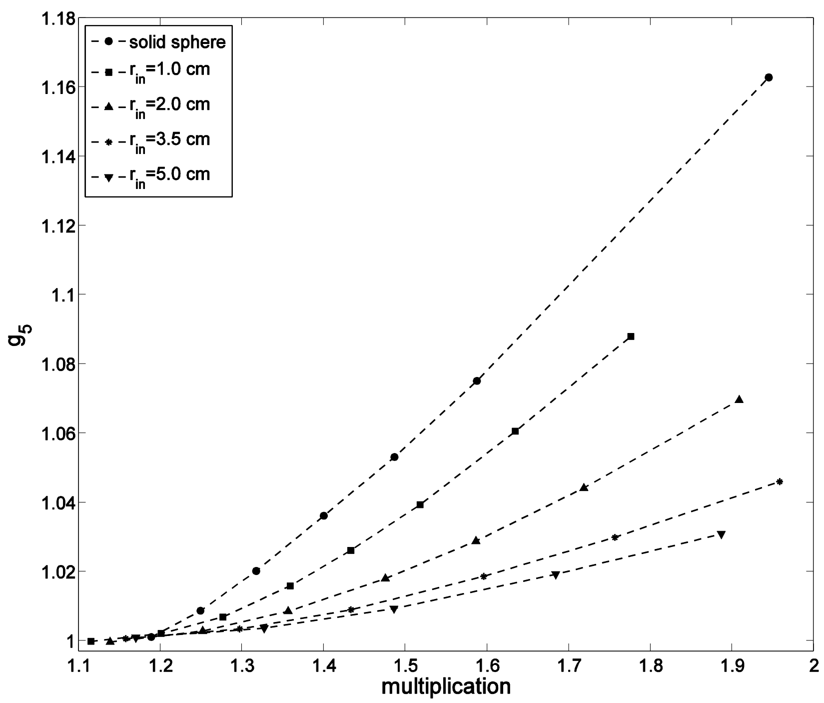

Figure 11: g_4 as a function of fissile mass

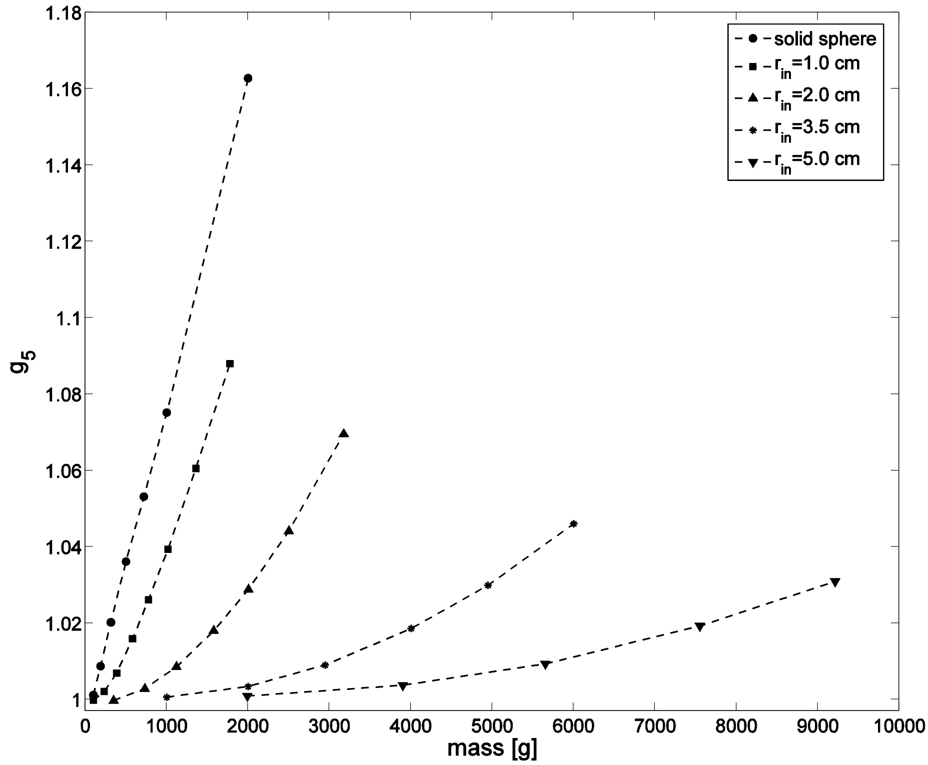

Figure 12: g_5 as a function of fissile mass