J Radioanal Nucl Chem (2013) 298:2075–2083
DOI 10.1007/s10967-013-2678-5

Reinforced evidence of a low-yield nuclear test in North Korea on 11 May 2010

Lars-Erik De Geer

Received: 16 July 2013 / Published online: 27 August 2013

Abstract In May 2010 unique aerosol-bound and noble gas (xenon) radionuclide signatures were observed at four East Asian surveillance stations designed to detect evidence of nuclear testing. An article published in early 2012 provided an analysis that suggested the findings were due to a low-yield underground nuclear test in North Korea on 11 May 2010. As the aerosol and noble gas datings, however, only agreed on the fringes of their uncertainties an official North Korean telegram that on 12 May 2010 reported about a nuclear fusion experiment 1 month earlier inspired a solution. Assuming that included a low-yield nuclear explosion and that it had left xenon isotopes in the same cavity, the xenon dating could be "moved" to overlap with the aerosol dating. The article stirred a serious controversy where representatives of the U.S. government and the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) refused to comment on it. In this paper the xenon dating agrees with the aerosol one without resorting to a previous explosion. It shows instead that fractionation during lava cooling is the explanation and how that plays a paramount role in how xenon signatures from underground nuclear explosions should be interpreted. It also presents new observations that effectively imply that no nuclear reactor or any other nuclear installation could have caused the May 2010 signals. All in all these are the most interesting and rich ones ever encountered by the Organization and they truly demonstrate that the verification system can deliver much better sensitivity than it was originally designed for.

Keywords CTBT · North Korea · Underground nuclear testing · Xenon leaks

Introduction

The unique data collected between 13 and 22 May 2010 in East Asia, which is the basis for the present article, was summarized in Table 1 of Ref. [1]. It covered detections of ^{140}Ba/^{140}La by a CTBTO aerosol sampler at Okinawa in Japan and of ^{140}La by a CTBTO sampler at Ussuriysk in the Russian Federation. It further included observations of ^{133}Xe and ^{135}Xe at the Geojin national noble gas station in the northeast corner of South Korea as well as ^{133}Xe detected at Takasaki in Japan. The Takasaki observations were individually not unique for the station but the long sequence of five to six detections during 3.5 days was, and that indicates a non-local source. Some local contamination can, however, not be excluded, which is actually demonstrated by the small ^{135}Xe signal on 18 May that with an activity ratio to ^{133}Xe greater than four is about 5,000 times too high when compared to the Geojin ratio. These observations, amended by the new ^{141}Ce data discussed below, are given in Online Resource 1. That also includes the display of the relevant decay chains given in the previous paper [2, 3].

The most important new element in the present analysis is that the radioactive iodine precursors tellurium and antimony produced in an underground nuclear explosion can be trapped when the melted rock cools down and solidifies. If this occurs within the first hour the very different half-lives

The author retired in 2012 from Swedish Defence Research Agency (FOI) and in 2006 from the Comprehensive Nuclear-Test-Ban Treaty Organization.

Electronic supplementary material The online version of this article (doi:10.1007/s10967-013-2678-5) contains supplementary material, which is available to authorized users.

L.-E. De Geer (✉)
Flädervägen 51, 194 64 Upplands Väsby, Sweden
e-mail: ledg1945@gmail.com

of these isotopes in the range of 20 s to 1 h will cause a substantial change of the subsequent ^{133}Xe to ^{135}Xe ratio in the residual cavity gas. This will have a profound impact on the process of dating the explosion via the radioxenon signature. It is shown below that the explosion time estimate in the May 2010 case will move 6–30 h backwards, including overlap with the aerosol dating, if trapping is assumed to have occurred within the first half hour.

The second new observation is that ^{141}Ce, which is a fourth generation daughter of the very short-lived ($T_{1/2} = 1.73$ s) noble gas isotope ^{141}Xe, has now indeed been observed in gamma spectra from samples sent to the Provisional Technical Secretariat (PTS) of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) radionuclide laboratories. Detecting ^{141}Ce means that the source unambiguously must have been a nuclear explosion as there is no other way to get enough ^{141}Xe out of a fission fuel matrix in time. The detection of ^{141}Ce, ^{140}Ba and to a lesser extent ^{137}Cs, which are all daughter activities of very short-lived noble gas isotopes, thus rejects all other realistic explanations of the East Asia detections of May 2010.

The scenario that is here shown to be fully supported by the observations is that a low-yield (ton to tens of tons TNT equivalent) nuclear test was carried out underground in North Korea on 11 May 2010. There was a prompt venting of noble gases dominated by very short-lived xenon isotopes with high independent fission yields ($^{137, 140, 141}$Xe). These radionuclides transformed in respective decay chains to caesium, barium and lanthanum isotopes that were within minutes adsorbed on natural aerosol particles. Hours and days later they occurred as ^{137}Cs, ^{140}Ba and ^{140}La as well as ^{141}Ce that were detected on filters exposed at Okinawa and at Ussuriysk (^{140}La). Probably due to a filtered purge one to one and a half days after the test, there was a release of longer-lived xenon isotopes ($^{131m, 133m, 133, 135}$Xe) that by then had been formed through decay of high yield precursors.[1]

The analyses are covered below in the order of the prompt venting (based on aerosol samples), the delayed emission (based on radioxenon samples), extended atmospheric transport modelling, the possible yield of the test given that there was no seismic detection and finally a summary and discussion.

The prompt release

Excluding non-nuclear explosion sources

In the previous article [1], possible indicators other than ^{140}Ba/^{140}La of short-lived xenon releases in the Okinawa samples were discussed and traces of ^{137}Cs were found in re-measurements of samples sent to CTBTO-certified laboratories. No laboratory reported any detection of other noble-gas-progeny nuclides like the most prominent one, ^{141}Ce, which would stem from the 1.73-s half-life ^{141}Xe. Later, however, careful checks of the relevant laboratory spectra revealed that there had actually been at least two detections of ^{141}Ce (samples collected on 15 and 20 May 2010) among the eight Okinawa samples shown to have contained high ^{140}Ba levels. The relevant part of the spectrum from the 20 May sample is shown in Fig. 1.

This opens the possibility to estimate the source-to-atmosphere transport time from the measured ^{140}Ba/^{141}Ce-ratios. The 15 May 2010 sample showed 81.9 ± 3.6 and 0.50 ± 0.23 μBq/m^3 of ^{140}Ba and ^{141}Ce respectively. That gives a ^{140}Ba/^{141}Ce-atom-ratio corrected 4 days back to the release time of 73 ± 34 when this ratio actually refers to ^{140}Xe/^{141}Xe. The 20 May sample showed 43.8 ± 2.8 and 0.28 ± 0.09 μBq/m^3 of ^{140}Ba and ^{141}Ce respectively, which similarly yields a release time ^{140}Xe/^{141}Xe-atom-ratio of 83 ± 27. The average ^{140}Xe/^{141}Xe-atom-ratio is 79 ± 21. The transport time was then estimated as 7.8 ± 0.9 s if the fuel was plutonium and 9.4 ± 0.9 s if it was uranium (see Online Resource 2 for the Mathematica code *Xebate* that was written to do most calculations for this paper).

Virtually no source other than a nuclear explosion with its instantaneous vaporization of the fuel would be capable to inject large amounts of these short-lived noble gas radionuclides into the atmosphere without any alongside traces of aerosol-borne fission products (many of which are produced at several times higher rates than ^{140,141}Xe). As the Takasaki station, which runs both aerosol and radioxenon samplers, found radioxenon but no fresh anthropogenic aerosol activities, like e.g. $^{131, 133}$I or ^{132}Te, in the

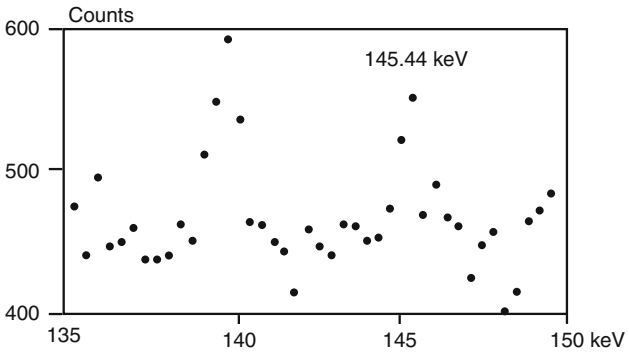

Fig. 1 The 145.4 keV ^{141}Ce peak in the spectrum of the full Okinawa 20 May 2010 sample. It was measured by a CTBT certified laboratory for 7 days between 4 and 11 June 2010. The peak area is 190 ± 60 counts. The peak at around 140 keV is due to cosmic neutron interactions in the detector. There is no such explanation of the 145 keV peak and there is no other reasonable explanation of it like the decay of another nuclide

[1] In this paper these longer-lived neutron-rich xenon isotopes are referred to as *radioxenon*. Another convention used is that all time notations are UTC, including concepts like morning, evening and night.

relevant period, the explosive character of this event is strongly implied.

Another reason for excluding other scenarios was the strength of the event where the meteorological analyses pointed at a prompt venting of some 400 PBq ^{140}Xe [4], which corresponds to several tons of TNT equivalent. That is around 10^{21} fissions, which greatly exceeds any known criticality accident in the past, set aside the 1986 Chernobyl disaster [5]. But even then, the nuclear transient that has been discussed did not involve much more than that [6]. Regardless of the explosion constraint, nuclear installations in the area have been carefully checked for announced emissions and meteorological connectivities to the detection scenario without finding any alternative source [7].

Dating the explosion from the ^{140}La/^{140}Ba-ratio

Whenever a radionuclide signature is detected that is suspected to come from a nuclear explosion one tries to find pertinent radionuclide ratios to estimate the explosion time, which can then be compared with other potentially corroborative information, most often seismic signals. During the 35-years long period of atmospheric testing the ^{95}Nb to ^{95}Zr-ratio was an excellent such clock for ages up to several months and even a year [8]. With shorter half-lives involved, the ^{140}La/^{140}Ba-ratio can in the same way be used to estimate the age during the first week or so. ^{140}Xe is released within seconds to the atmosphere where it with a half-life of 13.6 s decays to ^{140}Cs that in turn with a half-life of about a minute decays to ^{140}Ba. In such a situation free caesium and barium atoms attach to the natural aerosol within minutes and the local aerosol will soon be loaded with an initial amount of ^{140}Ba atoms. The *clock* starts and works well for a good week before the ^{140}La/^{140}Ba-ratio reaches its equilibrium. A prerequisite for this is of course that there is no chemical/physical process, apart from decay, that changes the ratio during this week (see Online Resource 3 for a discussion that concludes that this with very high probability is true [8–10]).

In the previous article a simple ^{140}La/^{140}Ba-dating was made from the analysis of the 487 (^{140}La) and 537(^{140}Ba) keV peaks in the first and strongest detection at Okinawa. In a new analysis all eight positive samples from that station were utilized and in addition some timing information carried by the preliminary spectra that are routinely delivered to the International Data Centre (IDC) every 2 h was used. A careful peak analysis is then essential and it was done in Excel for all samples, where the two strongest samples (15 and 19 May 2010) were subdivided into four 6-h spectra each. The 487 keV peaks were corrected for small contributions from the radon daughters ^{214}Pb and ^{208}Tl and the 537 peak was similarly corrected for a 6 counts per day contribution [11] due to cosmic neutrons exciting the second level of ^{206}Pb in the lead shield (Online Resource 4).

Figure 2 shows a growing trend in the 15 May sample and ratios indicating equilibrium in the sample collected 4 days later.

To estimate the explosion time the 14 data points were fitted to the theoretical area-ratio function [1]:

$$\frac{A_{487}}{A_{537}} = \frac{\lambda_{\mathrm{La}}}{\lambda_{\mathrm{La}} - \lambda_{\mathrm{Ba}}} \cdot \frac{B_{487}}{B_{537}} \cdot \frac{\varepsilon_{487}}{\varepsilon_{537}} \cdot \frac{\mathrm{ccf}_{537}}{\mathrm{ccf}_{487}} \cdot \left[1 - \frac{\lambda_{\mathrm{Ba}}}{\lambda_{\mathrm{La}}} e^{-(\lambda_{\mathrm{La}} - \lambda_{\mathrm{Ba}})t} \cdot \frac{1 - e^{-\lambda_{\mathrm{La}} t_C}}{1 - e^{-\lambda_{\mathrm{Ba}} t_C}}\right]$$

Here the relevant decay constants, branching-ratios, detector efficiencies and coincidence correction factors are easily recognised. The counting time, t_C, is 1 or 0.25 days and t marks the time after fission, which can also be expressed as $t = \tau + T$, where T is the time we want to estimate between fission and start of acquisition of the first spectrum, 00:23 on 17 May 2010, and τ runs from that point forward. The area-ratio is a ratio of two normally distributed variables, but is strictly not a normal variable itself. Its probability density function (pdf) can, however, quite easily be calculated on a computer [12]. The fitting can then be done just by calculating the joint probability density function as the product of the pdf of each data point as a function of T. The thicker pdf in Fig. 3a gives the results with a maximum-likelihood/best-fit for an explosion at 17:10 on 11 May 2010 with a full width at half maximum (FWHM) of 2.6 days. Uncertainties in the knowledge of the nuclear and detector constants were taken into account by repeating the analysis 150 times with these parameters drawn from their assumed normal distributions, with values and variances for the λ:*s* and *B*:*s* taken from ENSDF [2], the efficiency-ratio considered sharp due to the proximity of the two energies and with $\mathrm{ccf}_{487} = 1.234 \pm 2\ \%$ and $\mathrm{ccf}_{537} = 1 \pm 0\ \%$. The calculation of ccf_{487} was previously described in detail [1] and the uncertainty estimate is based on a comparison with independent Finnish estimates [11] and experience of VGSL[2] at CTBTO and FOI (Swedish Defence Research Agency). Disregarding the parameter variances the thinner pdf in Fig. 3a results, with a maximum likelihood about 1 h later and a FWHM half a day less.

A Finnish group has recently published an analysis based on all 96 2-h slices minus 12 that had less than ten counts in at least one peak [11]. Their time-zero estimate before considering the parameter uncertainties is 16:00 on 12 May. The spectra were analysed with an advanced

[2] VGSL is an acronym for Virtual Gamma Spectroscopy Laboratory, a software written at the IDC that among other things calculates coincidence correction factors by simulating the measurement process in the computer. Its engine is the well-known Monte Carlo program MCNP.

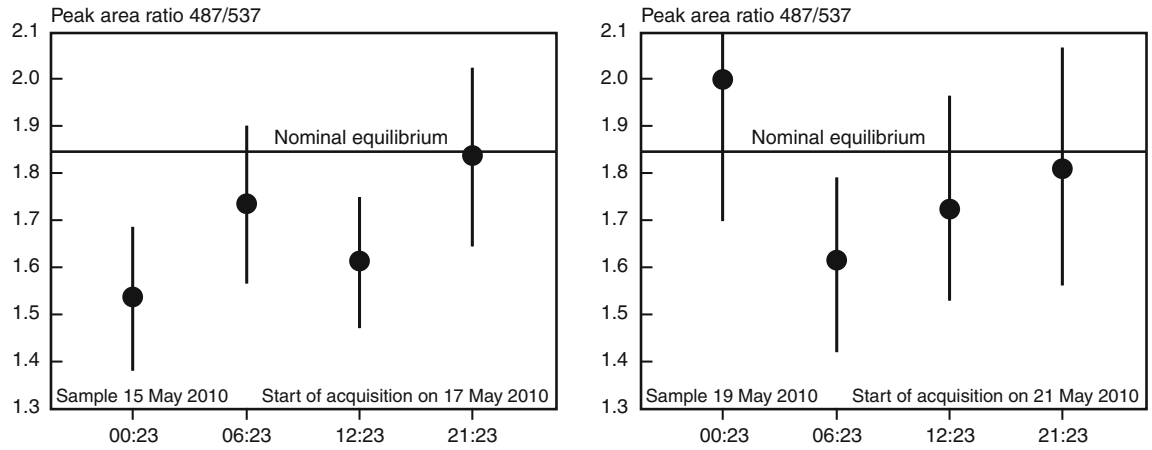

Fig. 2 The $487_{corr}/537_{corr}$-activity-ratio during the 24-h acquisition of the 15 May (*left*) and the 19 May (*right*) samples. The four points represent the area ratios in spectra collected during the first to the fourth 6-h periods on respective days

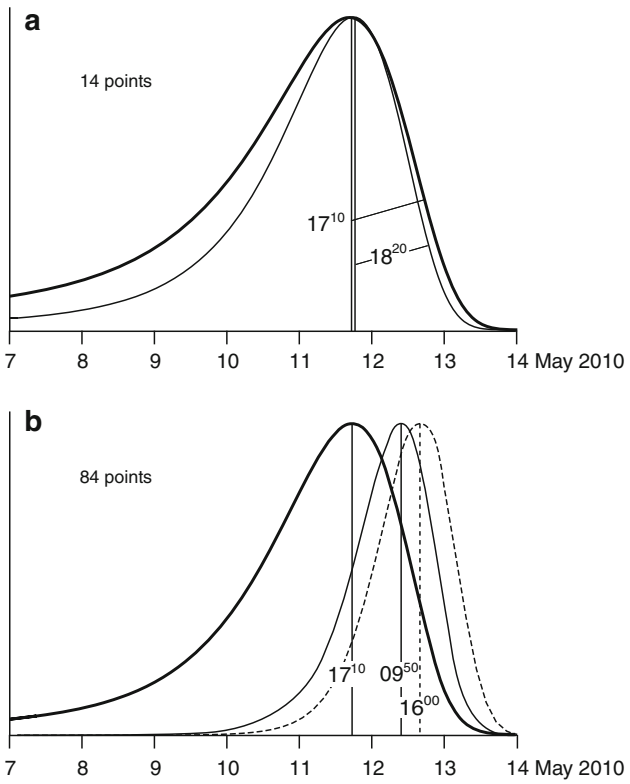

Fig. 3 Joint probability density functions for the 14- and 84-point analyses. The *thin curves* refer to the case when the nuclear constants are considered well known and the *thick ones* to the average when the constants are drawn from their assumed normal distributions and the calculation is repeated 150 times. The *dashed curve* in the 84-point fit corresponds to a calculation assuming Gaussian ratios and well-known parameters. The hours given are the maximum likelihood values, or the best fits, estimating the explosion time in the five cases

software, AMufi, and these results were kindly shared. Applying the technique above for these 84-point data yielded the results depicted in Fig. 3b. The Finnish group considered the area-ratios Gaussian, which actually has an impact, as several peak-area variation coefficients are high (this is not so for the 14-point analysis so the Gaussian and correct assumptions give there virtually the same pdf:s). With correct treatment the 84-point estimate moves 6 h back with an unchanged FWHM. Adding then parameter variances the time-zero estimate moves 17 h further back to 17:10 on 11 May, which is the same as the 14-point estimate. The FWHM increases significantly by 23 h, which, however, is 8.3 h shorter than the corresponding 14-point FWHM. The Mathematica routine to calculate the 14- and 84-point pdf:s is given in Online Resource 5.

The delayed release

Tellurium trapping

The second release was probably a filtered purge done to cleanse the tunnel system before entering. The detection/dispersion analysis has indicated an emission of about 100 TBq ^{133}Xe [4], which is within the range reported from underground nuclear testing at the Nevada Test Site in the United States [13].

Previously published radioxenon analyses have disregarded pre-release fractionation, and then the Geojin data implies a time-zero between 07:00 and 09:30 on 12 May 2010. Residual elements with high condensation temperatures do, however, mix with the liquid lava in the cooling cavity. This melt flows downwards within a few seconds and forms a puddle at the bottom. After several seconds it begins to solidify at around 1,000 °C into a glassy material, and this continues for a few minutes to a few hours depending on the type of rock and the mass melted [14, 15]. Most fission and activation nuclides are refractive and will then be effectively trapped, and this will also be true for a reasonable time for their subsequent decay products

even when they are volatiles or gases. Antimony and tellurium isotopes are precursors to volatile iodine and gaseous xenon in the mass 133 and 135 decay chains and at 100 kPa they condense at respectively 1,587 and 988 °C. The latter temperature is low compared to the lava solidification temperature so it is at first difficult to conclude that tellurium is trapped. Below it is argued, however, that the May 2010 test was decoupled and that implies that less rock melts and most energy goes into heating and pressurising the air in the cave up to residual pressures of ten or several tens of MPa [16]. During this high pressure phase the condensation temperature of tellurium is considerably higher (1,500 and 2,000 °C at respectively 2 and 10 MPa [17]), which implies that also tellurium behaves as a refractive element in this environment. Within a minute or so most of mass 135 has passed tellurium into iodine, while in mass 133 that takes a few hours. For a low-yield decoupled explosion the lava will certainly cool from the tellurium condensation temperature down to solidification in this time span and trapping will then have a significant impact on the ^{135}Xe/^{133}Xe-ratio in the residual cavity gas.

These processes are very complex and hard to predict in detail, but there are indications in the literature that Sb/Te trapping does occur in nuclear test cavities. Official U.S. documents [18, 19] confirm that the iodine precursors "*tellurium and antimony … formed under these conditions* [contained underground nuclear explosions] *do not readily release their xenon decay products*." In an example it is assumed that "*gases and particles are separated at 5 min*" and it is also noted that "*separation can certainly occur earlier*" and that after separation "*tellurium and lower Z precursors will not release xenon*."

The effects of cutting the decay chains between tellurium and iodine at the time of lava re-solidification[3] were studied in *Xebate*. By comparing theory and measurements at release time there is no need to add a cut also between iodine and xenon in the code, which otherwise should be considered as the purge most probably was filtered to supress, inter alia, iodine emissions. But then the measured values have to be corrected back to the release. The IDC refers radionuclide data to the time of sampling under the assumption that the nuclide concentration was constant during that time (12 h for the SAUNA system). This is done by multiplying the spectrum-average concentration [1] by a factor calculated by relevant integrations. This correction is undone simply by dividing with the same factor, and from there it is easy to make the decay corrections back to the release time or any other fixed time after the test. For ^{133}Xe it is generally a little bit more complicated as the corrected value depends on both the ^{133}Xe and the ^{133m}Xe spectrum averages. These corrections are built into the *Xebate* program. In this way the reported concentrations of ^{133m}Xe, ^{133}Xe, and ^{135}Xe of <0.2, 2.45, and 10.01 mBq/m^3 in the noble gas sample collected on 13 May 2010 are corrected to be 0–0.24, 2.63–2.60, and 27.8 mBq/m^3, respectively, at the time of release, which according to the meteorological analysis below occurred around 26 h before start of acquisition (the exact time of release is not a very sensitive parameter for the current analysis).

The analysis results are illustrated in Fig. 4, where the time of fission deduced from the ^{135}Xe/^{133}Xe activity-ratio range is plotted as a function of the time until solidification. Results are given for both plutonium and uranium fuel at 0 and 100 % trapping. Intermediate trapping efficiencies give regular bands between these extremes. It is clear that the explosion "moves backward" in time when the lava solidification point "moves closer" to time-zero. If solidification occurred 11 [Pu]/16[U] minutes after the explosion the radioxenon-dating fully agrees with the central ^{140}La/^{140}Ba estimate of 17:10 on 11 May 2010. This is not claimed to be the true time as the uncertainties are large, but it shows that there is nothing in the data that prevents the two dating methods to agree very well for a time-zero during 11 May 2010. The trapping could of course be less than total but still there can be consistency at earlier solidification, especially for uranium.

Plutonium is a less credible fuel if the nuclear fusion success announced on 12 May in an official telegram [20] is identified with the 11 May event. A reporter at Reuters read the message around midnight 11/12 May (Fredrik Dahl, Reuters, June 2012), and with a reasonable 6–12 h period before issuing the telegram, uranium almost is, or actually is, the only fuel option.

The trapping analysis depends on the accuracy of the fission yields of the mass 133 and 135 chain members. To check the sensitivity for this, the analysis was repeated with all recent yield evaluations available via the JANIS tool [3] plus the England and Rider [21] evaluation from 1994. This does not change the conclusions as can be seen in Online Resource 2.

Figure 4 only displays the results based on the ^{135}Xe/^{133}Xe-ratio, as there is only an estimated 0.2 mBq/m^3 upper limit for the ^{133m}Xe-value. Using that limit the ^{135}Xe/^{133m}Xe-ratio gives lines that for both fuels fall above the corresponding ^{135}Xe/^{133}Xe full trapping domains in the figure. Decreasing the ^{133m}Xe-concentration artificially below the limit pushes the lines towards these domains and for certain values the lines coalesce with respective centre lines of the ^{135}Xe/^{133}Xe-domains. These ^{133m}Xe-concentrations are estimates of the real but undetected ones. For uranium this happens at 0.135 ± 0.005 and for plutonium at 0.19 ± 0.01 mBq/m^3. The latter nearly covers the

[3] This rather refers to an effective solidification time as the absorption of tellurium and antimony into the melted lava happens while the lava cools from respective condensation temperature down to the lava solidification temperature. During this time some volatile and gaseous decay products might reenter the residual gas.

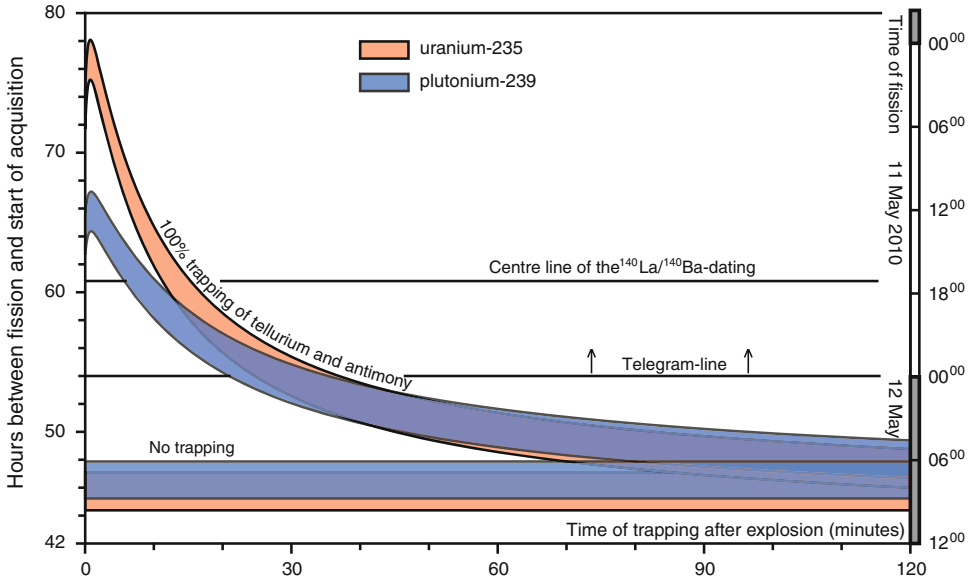

Fig. 4 The effect of iodine precursor trapping on ^{135}Xe/^{133}Xe-dating. The *borderlines* of the areas refer to the one-sigma limits of the measured ratio. The "telegram-line" gives the latest time-zero possible if the event was the one referred to by the 12 May 2010 official telegram about fusion success

detection limit, which provides a second indication that the fuel was uranium. The meteorological analyses showed that radioxenon most likely appeared at Geojin also after 13 May. A second sample might then have been stronger as it was probably more exposed due to late cloud arrival during sampling of the first. It is therefore possible that South Korea detected ^{133m}Xe and could draw conclusions about the fuel from measurements they selected not to make public.[4]

There is not much other open data available to corroborate the observations of Sb/Te trapping. There is one occasion, however. After the first North Korean nuclear test on 9 October 2006 ^{133}Xe and ^{135}Xe were detected in three samples collected by the United States just west of northern Honshu in Japan at an altitude of about 700 m around 19:30 on 11 May 2010 [22]. With an ^{135}Xe/^{133}Xe activity ratio 66 h after the explosion of 1.51 ± 0.26 the solidification time was estimated by *Xebate* to be between a half and a full hour. The effective lava solidification after the 2006 explosion thus occurred later than after the 2010 one. This is quite reasonable as the yield of the 2006 explosion was at least 10 times higher and was reasonably much less decoupled.

Atmospheric transport modelling (ATM)

An extensive meteorological study on the possible source regions for the May 2010 detections was recently published [4]. All measurements were utilized to see how well hypothetical emissions in the preceding period could reproduce the aerosol and radioxenon detection patterns. It was done for consecutive 3-h intervals at the three points in North Korea considered in the previous article [1]; the established test site at Mt. Mantap, a tunnel system at Hagap and the nuclear laboratories at Yongbyon. Figure 5 is adapted from this work and it shows the squared model/measurement correlation as a function of release-time for the first two sites. It is clearly seen that the prompt and delayed emissions must have been 1–1.5 days apart. Yongbyon showed quite low correlation for radioxenon and is not included in the figure. The Hagap correlation fits very well the radionuclide ratio dating, while the Mt. Mantap correlation peaks some 10 h later.

The ATM also estimated the prompt emission at some 400 PBq ^{140}Xe (∼5 TBq ^{140}Ba) and the delayed one at 0.1 PBq ^{133}Xe [4], which correspond to 9 and 6 tons TNT equivalents respectively for a plutonium charge and 3 and 6 tons for a uranium one. As the uncertainties in ATM calculations are difficult to estimate it is fair to summarize this with that both the prompt and the delayed releases corresponded to about one to ten tons TNT equivalent.

The explosive yield of the test

The emission estimates of one to ten tons TNT equivalents put a lower limit on the test itself. It is possible, but not given, that the processes at the prompt venting and the purge would cleanse the cavity almost completely of noble gases available at those respective moments. Here ends, however, the hard conclusions that can be drawn from the radionuclide data. There is no way the full yield of the May

[4] The results of the first radioxenon sample were disclosed in October 2010 by a South Korean politician and lawmaker, Kim Seon-dong and reported by the press [1]. The correctness of this public data was confirmed in a direct e-mail contact by the author with the office of Mr. Kim in May 2012.

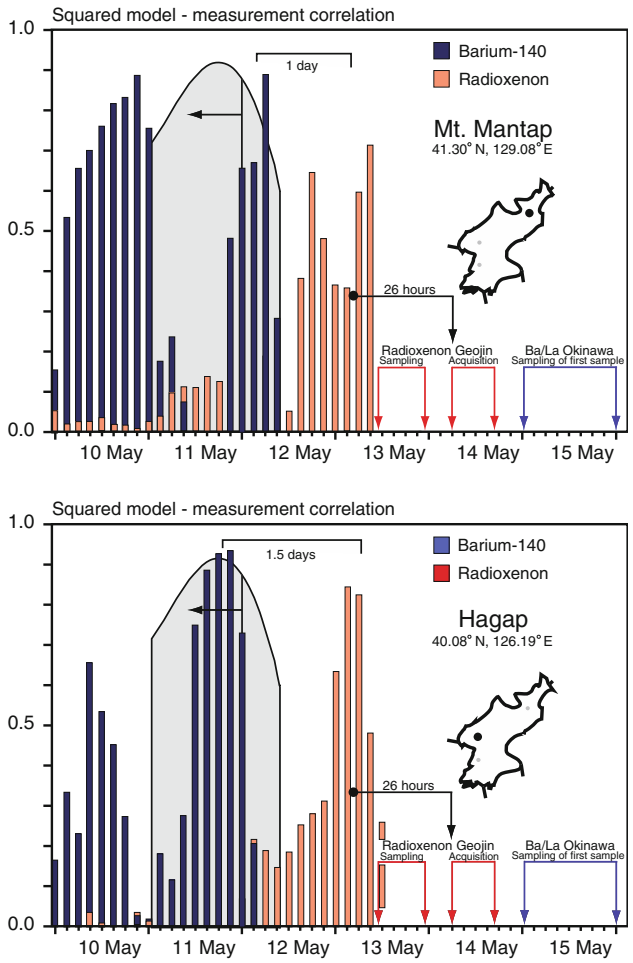

Fig. 5 Correlation between hypothetical ^{140}Ba and radioxenon emissions at Mt. Mantap and Hagap and the observations at respectively Okinawa/Ussuriysk and Geojin/Takasaki as a function of the emission time. *Dark/blue bars* refer to ^{140}Ba and *light/red* ones to ^{133}Xe. In the background the pdf of the lanthanum/barium-dating trimmed by the radioxenon analysis is shown for comparison. The approximate times between the prompt and delayed releases as well as between the latter and the start of acquisition are marked. The 11/12 May *midnight line* and *arrow* mark the constraint possibly posed by the telegram. (Color figure online)

2010 test could be determined from available radionuclide observations and the same also applies to any ambition to tell whether the test involved fusion. These two things were misrepresented in a pre-publication report [23] about the previous article, which together with political uneasiness and other, probably lower, motivations led to a widespread dismissal of the message in the previous analysis [1]. Seemingly to side this, a group at Lamon–Doherty Earth Observatory studied seismic records for the relevant days at a three-component seismic station at Mudanjiang in eastern China [24], just 380 km north of Mt. Mantap and 580 km NNE of Hagap. Their conclusion was that no well-coupled underground explosion occurred on 11 May 2010 above about one ton near Mt. Mantap or above a little more elsewhere in North Korea. The study provided valuable insight, but it did not in any way contradict the radionuclide findings, especially if decoupling is taken into account.

The unusually strong prompt emission of noble gases in May 2010 indicated that the test actually was decoupled, as an explosion in an air-filled cavity produces a gas pressure of some 10 MPa [25], which is an effective driving force for venting. The cavity volume for full decoupling of a 1 kt explosion [26] is some 30,000 m^3 and as it broadly scales with the yield, a 10–40 ton test would be fully decoupled at 300–1,200 m^3. This shouldn't be a problem to excavate in a mine especially as the effect is not particularly sensitive to the aspect ratio [26]. A parallel case in the United States is, *Mill Yard*, a tunnel-test in Nevada 1985 at a reported yield of 21 tons, which was analysed to have had a decoupling factor of 44–70 [16, 26] corresponding to an apparent yield of 0.3–0.5 tons.

Summary and discussion

The May 2010 event shows that the CTBTO verification system is a very powerful set-up that is able to detect and identify nuclear explosions of substantially lower yields than it was initially designed for.

All the unique radionuclide observations 13–22 May 2010 in East Asia including ATM analyses and the seismic non-detections are consistent with a low-yield (around one ton to tens of tons TNT equivalent) nuclear explosion in North Korea on 11 May 2010. This is clearly demonstrated in Figs. 4 and 5.

^{141}Ce found in relevant laboratory measurements strongly supports ^{140}Ba in implying a nuclear explosive source. The ratios of these nuclides were used to estimate the underground transport time of the promptly vented noble gases to somewhat less than 10 s.

An improved analysis of the mass-140 data from Okinawa gave a best time-zero fit at around 17:10 on 11 May 2010 with a FWHM of 2.2 days.

Taking the effects of early precursor trapping in the cooling lava into account takes the radioxenon time-zero estimate backward from the morning of 12 May to the early evening preceding day (or even earlier that day). The impact of trapping on the radioxenon signature is a very important understanding for the future work of CTBTO, especially for analysing suspected small explosions. Dismissing this effect can result in timing errors of up to 34 h.

There are several indications that the fuel of the May 2010 device was uranium rather than plutonium. A stronger conclusion on this issue can probably be done by countries with exclusive access to all national xenon data from the relevant time and area.

The unusually strong prompt venting implies that the explosion was decoupled. With a seismic constraint of less than 1 ton apparent yield the real yield could have been tens of tons.

It is indicated in Fig. 5, although not proven, that the May 2010 test was carried out further south than the classical test site. This is reasonable as it would be more convenient to do small-scale experiments closer to the Yongbyon Nuclear Centre. It is conceivable then that more low-yield tests have been done or will be done at such a site without being detected, tests that might have contributed or will contribute e.g. to miniaturisation of the weapons.[5] It is often claimed that very low-yield tests have no military significance, but this is not necessarily true if they are conducted as part of a series ending with one or several kt-range tests. When the Korean Central News Agency released a report on 12 February 2013 [28] about the North Korean nuclear test that day, they specifically referred to "*the use of a smaller and light A-bomb unlike the previous ones*". It further said it was their third underground nuclear test, which seemingly contradicts the conclusions of this paper, but with the addition "*at the site for underground nuclear test in the northern part of the DPRK*", it can rather be taken to indicate there is another experimental site. This discussion fits well the report from the U.S. Defence Intelligence Agency (DIA) that accidentally went public in March this year [29] saying that DIA has "*moderate confidence that North Korea has nuclear weapons that are capable of delivery by ballistic missiles*".

Finally, there are two technically possible, but very unlikely, alternative explanations to the May 2010 radionuclide signatures. It could have been an underground nuclear explosion in China or Russia just across the North Korean border. It could also have been a designed test, or provocation, of the CTBTO verification system. Releasing the relevant nuclides in the air close to the stations would not require much material but it could be quite delicate to produce and deliver the individual compositions at the right times, especially for the radioxenon stations.

References

1. De Geer L-E (2012) Radionuclide evidence for low-yield nuclear testing in North Korea in April/May 2010. Sci Glob Secur 20:1–29
2. ENSDF (Evaluated Nuclear Structure Data File) (2012) National Nuclear Data Center (NNDC) at Brookhaven, USA. http://www.nndc.bnl.gov/ensdf/. Accessed 15 Jan 2012
3. JEFF 3.1.1. (Joint Evaluated Fission and Fusion File) (2013) Nuclear Energy Agency, reached via JANIS 3.2. http://www.oecd-nea.org/janis/. Accessed 20 May 2013
4. Wotawa G (2012) Meteorological analysis of the detection of xenon and barium/lanthanum isotopes in May 2010 in Eastern Asia. J Radioanal Nucl Chem. doi:10.1007/s10967-012-2012-7
5. McLaughlin TP et al (2000) A review of criticality accidents, 2000 revision. Los Alamos Report, LA-13638, May 2000
6. Pakhomov SA, Dubasov YV (2010) Estimation of explosion energy yield at Chernobyl NPP accident. Pure Appl Geophys 167:575–580
7. Wright CM (2013) Low-yield nuclear testing by North Korea in May 2010: assessing the evidence with atmospheric transport models and xenon activity calculations, radionuclide evidence for low-yield nuclear testing in North Korea in April/May 2010. Sci Glob Secur 21:3–52
8. De Geer L-E et al (1978) Particulate radioactivity, mainly from nuclear explosions, in air and precipitation in Sweden mid-year 1975 to mid-year 1977. FOA report C 40089-T2(A1) (1978). Also published in Environmental Quarterly Report EML-349, Environmental Measurements Laboratory, New York
9. Mishra UC, Sethi SK, Negi BS (1977) Analysis of fission product mixtures in fresh fallout from Chinese nuclear explosion of January 23, 1976 by Ge(Li) gamma-ray spectrometry. Atomkernenergie 29:49–55
10. NOAA-Air Resources Laboratory (2013). http://www.ready.noaa.gov/READYamet.php. Accessed 10 May 2013
11. Ihantola S, Toivonen H, Moring M (2013) ^{140}La/^{140}Ba ratio dating of a nuclear release. J Radioanal Nucl Chem. doi:10.1007/s10967-013-2504-0
12. Hinkley DV (1969) On the ratio of two correlated normal random variables. Biometrica 56:635–639
13. Kalinowski MB (2011) Characterisation of prompt and delayed atmospheric radioactivity releases from underground nuclear tests at Nevada as a function of release time. J Environ Radioact 102:824–836
14. Smith DK (1995) Characterization of nuclear explosive melt debris. Radiochim Acta 69:157–167
15. Smith DK (1993) A review of literature pertaining to the leaching and sorption of radionuclides associated with nuclear explosive melt glasses. Lawrence Livermore Laboratory report, UCRL-ID-113370
16. Sykes LR (1994) Dealing with decoupled nuclear explosions under a comprehensive test ban treaty, Phillips Laboratory report PL-TR-94-2301
17. Baker EH (1967) The boiling point relation for tellurium at elevated pressures. J Chem Soc A: 1558–1560
18. Panel on Basic Research Requirements in Support of Comprehensive Test Ban Monitoring, National Research Council (1997) Research Required to Support Comprehensive Nuclear Test Ban Treaty Monitoring, Committee on Seismology, Board on Earth Sciences and Resources, Commission on Geosciences, Environment, and Resources, National Academies Press, Washington, DC. www.nap.edu/catalog.php?record_id=5875
19. Radionuclide experts from six U.S. Organizations: Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Pacific Northwest Laboratory, Air Force Technical Applications Center, Environmental Measurements Laboratory, and National Oceanic and Atmospheric Administration, Source Term Review. A Report of the Peer Review of the Conference on Disarmament International Monitoring System Expert Group, CD/NTB/WP.224 Part II, 1996
20. DPRK Succeeds in Nuclear Fusion (2010) Korean News Service, News from the Korean Central News Agency of DPRK,

[5] In a recent article two renowned U.S. experts indicate that North Korea, possibly with Pakistani support, is developing advanced nuclear test tunnel designs with quite ambitious traps and closures. That might counteract noble gas emissions even when they are driven by the high pressures created by decoupled explosions [27].

Pyong-yang, 12 May 2010. http://www.kcna.co.jp/index-e.htm. Accessed 20 May 2013
21. England TR, Rider BF (1994) Evaluation and compilation of fission product yields. Los Alamos National Laboratory Report LAUR-94-3106
22. Sloan C (2007) A review of the North Korean nuclear test. Presentation at the INGE (International Noble Gas Experiment) Workshop in Las Vegas 5-9 Nov, 2007
23. Brumfiel G (2012) Isotopes hint at North Korean nuclear test. Nature News (03 February 2012). www.nature.com/news/isotopes-hint-at-north-korean-nuclear-test-1.9972. Accessed 3 Feb 2012
24. Schaff DP, Kim W-Y, Richards PG (2012) Seismological constraints on proposed low-yield nuclear testing in particular regions and time periods in the past, with comments on "radionuclide evidence for low-yield nuclear testing in North Korea in April/May 2010" by Lars-Erik De Geer. Sci Glob Secur 20:155–171
25. National Research Council (2012) The comprehensive nuclear test ban treaty—technical issues for the United States. National Academies Press, Washington, DC. www.nap.edu/catalog.php?record_id=12849
26. Leith W (2001) Geologic and engineering constraints on the feasibility of clandestine nuclear testing by decoupling in large underground cavities, U.S. Department of the Interior, U.S. Geological Survey, Reston, Virginia, Open File Report 01-28
27. Pabian FV, Hecker SS (2012) Contemplating a third nuclear test in North Korea. Bull Atom Scient. www.thebulletin.org/contemplating-third-nuclear-test-north-korea. Accessed 1 May 2003
28. KCNA (2013) Report on Successful 3rd Underground Nuclear Test, Rodong Sinmun 13 Feb. 2013
29. Alexander D, Kim C, Kim N (2013) North Korea can launch nuclear missiles, U.S. spy agency says. Reuters, New York, 11 Apr 2013