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Some Remarks on the Discovery of ^{244}Md

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In two recent papers by Pore *et al.* and Khuyagbaatar *et al.*, discovery of the new isotope ^{244}Md was reported. The decay data, however, are conflicting. While Pore *et al.* report two isomeric states decaying by α emission with $E_\alpha(1) = 8.66(2)$ MeV, $T_{1/2}(1) = 0.4^{+0.4}_{-0.1}$ s and $E_\alpha(2) = 8.31(2)$ MeV, $T_{1/2}(2) \approx 6$ s, Khuyagbaatar *et al.* [Phys. Rev. Lett. **125**, 142504 (2020).] report only a single transition with a broad energy distribution of $E_\alpha = (8.73–8.86)$ MeV and $T_{1/2} = 0.30^{+0.19}_{-0.09}$ s. The data published in Pore *et al.* are very similar to those published for ^{245m}Md [$E_\alpha = 8.64(2)$, 8.68(2) MeV, $T_{1/2} = 0.35^{+0.23}_{-0.16}$ s [V. Ninov, F. P. Heßberger, S. Hofmann, H. Folger, G. Münzenberg, P. Armbruster, A. V. Yeremin, A. G. Popeko, M. Leino, and S. Saro, Z. Phys. A **356**, 11 (1996).]]. Therefore, we compare the data presented for ^{244}Md in Pore *et al.* with those reported for ^{245}Md in Ninov *et al.* and also in Khuyagbaatar *et al.* We conclude that the data presented in Pore *et al.* shall be attributed to ^{245}Md with small contributions (one event each) from ^{245}Fm and probably ^{246}Md.

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Introduction.—Discovery of ^{244}Md was first reported by Pore *et al.* [1]. They used the reaction ^{209}Bi(^{40}Ar, 5n)^{244}Md at a bombarding energy of ≈220 MeV, which corresponds to an excitation energy of the compound nucleus ^{249}Md of $E^* \approx 46$ MeV at a production in the center of the target. They observed four events after the mass spectrometer FIONA at a position where events with mass number $A = 244$ were expected, and six α decay chains in the BGS focal plane detector. The latter were attributed to the decay of two states in ^{244}Md, one with $E_\alpha = 8.308 \pm 0.019$ MeV, $T_{1/2} \approx 6$ s (1 event), and one with $E_\alpha = 8.663 \pm 0.023$ MeV, $T_{1/2} = 0.4^{+0.4}_{-0.1}$ s (4 events). In a publication by Khuyagbaatar *et al.*, identification of ^{244}Md was reported using the reaction ^{197}Au(^{50}Ti, 3n)^{244}Md [2]. The experiment was performed at two bombarding energies of 239.8 and 231.5 MeV (center of target), corresponding to excitation energies of $E^* = 32.7$ and $E^* = 26.2$ MeV. They reported two α activities. One, with an energy range $E_\alpha = (8.7–8.9)$ MeV and a half-life of $T_{1/2} = 0.30^{+0.19}_{-0.09}$ s was observed only at the higher excitation energy (7 events); the second activity was observed at both energies (three events each with full energy release in the stop detector) within an energy range of $E_\alpha = (8.6–8.7)$ MeV and a half-life of $T_{1/2} = 0.33^{+0.15}_{-0.08}$ s. This activity was attributed to the previously reported isotope ^{245}Md. The isotope ^{245}Md was first observed in an experiment performed at the velocity filter SHIP at GSI, Darmstadt, Germany, using the reaction ^{209}Bi(^{40}Ar, 4n)^{245}Md at a bombarding energy of 5.12 AMeV (204.8 MeV) corresponding to an excitation energy of $E^* = 40$ MeV [3]. The authors reported two α energies of $E_\alpha = 8640 \pm 20$, 8680 ± 20 keV, and a half-life of $T_{1/2} = 0.35^{+0.23}_{-0.18}$ s and also a spontaneous fission activity of $T_{1/2} = 0.90^{+0.23}_{-0.16}$ ms. This fission activity with $T_{1/2} = 0.9^{+0.6}_{-0.3}$ ms was also observed by Khuyagbaatar *et al.* [2]. The fission activity was attributed to the ground state decay of ^{245}Md, and the α activity to an isomeric state ^{245m}Md [3]. Previously known data on ^{245}Md were not mentioned in Ref. [1]. For completeness it should be noted that on the basis of detailed spectroscopic investigation of odd-mass mendelevium isotopes performed since then [4], the α activity would nowadays rather be attributed to ^{245g}Md and the fission activity to ^{245m}Md. It further was shown in Ref. [4] that α decay in odd mass mendelevium isotopes populates predominantly the $7/2^-[514]$ Nilsson level in the einsteinium daughter nuclei which decay into the $7/2^+[633]$ Nilsson level and the $9/2^+$ member of the rotational band built up on it. As the $9/2^+$ level decays by highly converted M1 transitions into the $7/2^+$ band head, the line at $E_\alpha = 8680 \pm 20$ keV reported in Ref. [3] is thus certainly the result of energy summing of α particles and conversion electrons.

Comparison of the results for ^{245}Md reported by Ninov et al. [3] and Khuyagbaatar et al. [2] and for ^{244}Md reported by Pore et al. [1].—The data published for ^{245}Md in Refs. [2,3] and ^{244}Md in Ref. [1] are presented in Fig. 1 and Table I. Data of Pore *et al.* (P1-P6) are taken from Table I in Ref. [1]. Data of Khuyagbataar *et al.* (K1–K10) are taken from the Supplemental Material of Ref. [2].

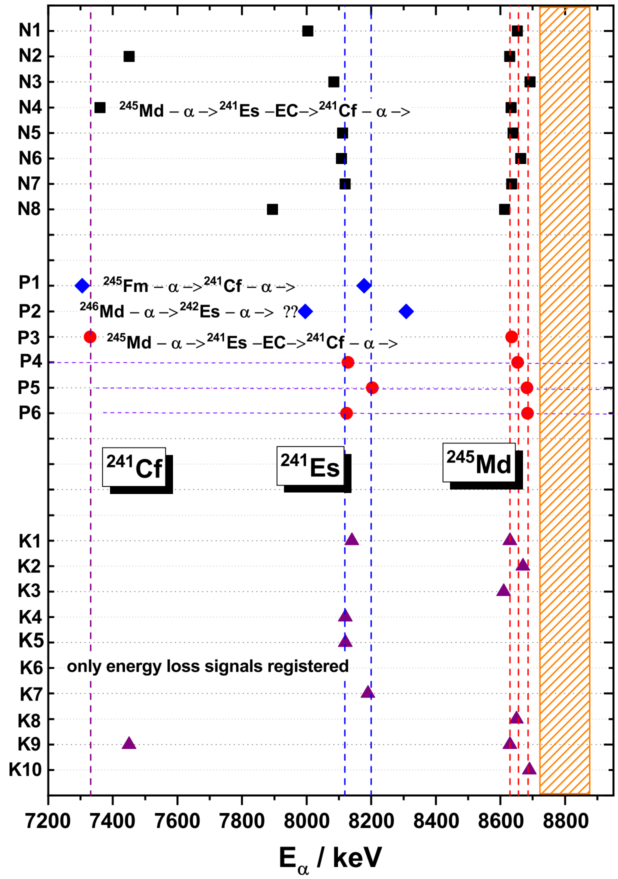

FIG. 1. Summary of decays attributed to ^{245}Md in Ref. [3] (squares) as well as in Ref. [2] (triangles) together with data reported by Pore *et al.* [1] [circles: events attributed to ^{245}Md by the present authors, diamonds: events attributed to ^{245}Fm or (tentatively) to ^{246}Md]. The dashed lines are to guide the eyes: the red lines represent the α energies given for ^{245}Md (8640, 8680 keV) in Ref. [3] and the energy given for ^{244}Md (8663 keV) in Ref. [1]; the blue lines represent the α energy for ^{241}Es (8113 keV) given in Ref. [3] and the highest daughter energy (P5) in Ref. [1]; the purple line represents the literature value of the α energy of ^{241}Cf (7335 keV) [6]. The orange hatched area marks the range of α energies where the events attributed to ^{244}Md in Ref. [2] were observed.

TABLE I. Summary of decays attributed to ^{245}Md in Refs. [2,3] and decays reported by Pore *et al.* [1]. Data from Pore *et al.* are taken from Table I in Ref. [1]; data from Khuyagbaatar *et al.* are from the Supplemental Material of Ref. [2]. No individual decay data are reported in Ref. [3]; these data are taken from the experiment analysis logbook [5].

References	Event number	$E_\alpha(1)$/ MeV	Δt(ER-α1)/s	$E_\alpha(2)$/ MeV	Δt(α1-α2)/s
[3]	N1	8.652	0.0178	8.004	8.254
[3]	N2[a]	8.629	0.1751	7.450	88.083
[3]	N3	8.692	0.00164	8.084	28.406
[3]	N4	8.633	0.1565	7.360	203.876
[3]	N5	8.639	1.1708	8.111	7.639
[3]	N6	8.663	0.0843	8.108	15.763
[3]	N7	8.635	0.2831	8.119	13.573
[3]	N8	8.613	0.0914	7.894	335.005
[2]	K1[b]	8.63	0.564	8.14	4.73
[2]	K2[b]	8.67	0.454	(1.1)	0.24
[2]	K3[b]	8.61	0.423	(1.3)	2.86
[2]	K4[b]	(1.9)	0.120	8.12	6.87
[2]	K5[b]	(2.2)	0.508	8.12	11.5
[2]	K6[b]	(0.9)	0.131	8.09	15.1
[2]	K7[b]	(0.4)	1.42	8.19	2.97
[2]	K8[c]	8.65	0.693	(0.26)	5
[2]	K9[c]	8.63	0.346	7.45	20
[2]	K10[c]	8.69	0.129	missed	missed
[1]	P1	8.178	0.60	7.305	27.34
[1]	P2	8.308	9.18	7.996	14.37
[1]	P3	8.635	0.88	7.330	18.95
[1]	P4[d]	8.653	0.13	8.128	1.20
[1]	P5	8.682	0.31	8.203	10.00
[1]	P6	8.684	1.16	8.124	7.65

[a]Both events were registered within the beam on period.
[b]Observed at $E^* = 26.2$ MeV.
[c]Observed at $E^* = 32.7$ MeV.
[d]The α-α correlation was followed by a third event of $E_\alpha = 7.086 \pm 25$ MeV after $\Delta t = 75.97$ s.

No list of single events was presented by Ninov *et al.* [3]. Data shown here (N1–N8) are taken from a reinspection of the logbook of the corresponding SHIP experiment [5]. Only α-α correlations with full energy release of both α particles in the SHIP "stop detector" are listed.

Evidently the chains P3, P4, and P6 agree with the data reported for ^{245}Md in Refs. [2,3]. The energy of the daughter in P5 is higher than the values reported for ^{241}Es in Ref. [3], but is in agreement with the daughter energy in K7. This event was attributed to ^{245}Md in Ref. [2] as it was registered at $E^* = 26.2$ MeV, where only decays of ^{245}Md were observed. Concerning the daughter energies P4, P5, and P6 can be attributed to the decay $^{245}\mathrm{Md} \xrightarrow{\alpha} {}^{241}\mathrm{Es} \xrightarrow{\alpha}$, while P3 obviously represents the decay $^{245}\mathrm{Md} \xrightarrow{\alpha} {}^{241}\mathrm{Es} \xrightarrow{EC} {}^{241}\mathrm{Cf} \xrightarrow{\alpha}$, in accordance with N4 and the known α decay energy of ^{241}Cf (7.335 MeV [6]). P1 fits to the decay sequence $^{245}\mathrm{Fm} \xrightarrow{\alpha(8.15\ \mathrm{MeV})} {}^{241}\mathrm{Cf} \xrightarrow{\alpha(8.34\ \mathrm{MeV})}$ [6], with ^{245}Fm being the product of the $p3n$ channel. The cross-section ratio $\sigma(p3n)/\sigma(4n) \approx 0.25$ may appear unusually high, but it has to be considered that one approaches the proton drip line, and proton binding energies are already low. The mass evaluation of Wang *et al.* [7] delivers values of, e.g., 1540 ± 210 keV for ^{247}Md and 1360 ± 320 keV for ^{246}Md, significantly lower than the neutron binding energies of 8250 ± 330 keV (^{247}Md) and 7230 ± 400 keV (^{246}Md). And indeed HIVAP calculations [8] deliver even a ratio $\sigma(p3n)/\sigma(4n) \approx 0.5$ (see Fig. 2). It should be reminded that recently notable cross sections for p-evaporation channels have been reported for the reaction $^{50}\mathrm{Ti} + {}^{209}\mathrm{Bi}$ [9,10]. Less clear is chain P2. The decay sequence $^{246}\mathrm{Md} \xrightarrow{\alpha} {}^{242}\mathrm{Es} \xrightarrow{\alpha}$, for which very broad energy distributions in the range $E_\alpha \approx (8.15–8.75)$ MeV

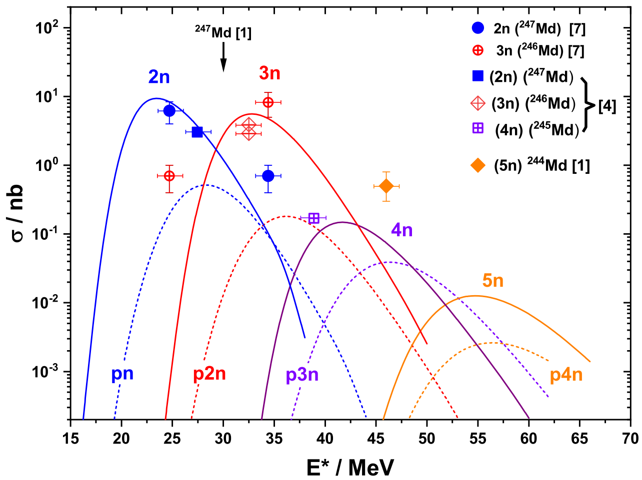

FIG. 2. Excitation function for ^{40}Ar + ^{209}Bi. The energies refer to production in the center of the target. The error bars for the energies refer to the energy loss of ^{40}Ar ions in the bismuth targets [12]. Systematic errors in the accelerator energy are typically 0.2% for the UNILAC accelerator and are neglected. For the data of Pore *et al.* [1] an energy loss of ≈12.5 MeV in the titanium backing foil [12] is considered. No systematic error for the accelerator energy is given by Pore *et al.* Lines are the result of HIVAP [8] calculations; full lines represent *xn* channels, dashed lines represent *pxn* channels. Points are defined in the figure. The arrow marks the energy reported in Ref. [1] for the observation of ^{247}Md.

(^{246}Md) and $E_\alpha \approx (7.75\text{–}8.05)$ MeV (^{242}Es) were observed (see Fig. 5 in Ref. [11]) is a possible candidate. P4 is terminated by an α event of $E_\alpha = 7.086 \pm 0.025$ MeV, which could be attributed to ^{237}Bk, the so far unknown α daughter of ^{241}Es. From atomic mass extrapolation [7] one expects an α decay energy of $E = 7.376 \pm 0.242$ MeV. The lower value could be due to the population of an excited state in ^{233}Am.

Excitation functions.—The reported cross sections for production of $^{244-247}$Md in the reaction ^{209}Bi(^{40}Ar, xn)$^{249-x}$Md [1,5,11] are shown in Fig. 2. In Ref. [3] no cross sections are given. The values given for this experiment are taken from Ref. [5]. The lines are the result of HIVAP [8] calculations, using fission barriers modified to reproduce the 2n (^{247}Md) and 3n (^{246}Md) cross sections. Evidently the 4n cross section from Ref. [5] is reproduced quite well. The excitation energy given by Pore *et al.* [1] appears roughly 4 MeV above the expected maximum for the 4n cross section, and the value is about a factor of 6 higher, but more than 2 orders of magnitude higher than the value expected for the 5n channel. A similiar situation is evident for the 2n channel. Pore *et al.* [1] report the observation of ^{247}Md at a bombarding energy of 200 MeV, which corresponds to an excitation energy $E^* \approx 30$ MeV (arrow in Fig. 2), which is about 6 MeV above the expected maximum for the 2n channel, but still a notable production cross section of ≈2 nbarn is expected here. To conclude, comparison with reported cross sections for *xn* channels and HIVAP calculations indicates that the events attributed to ^{244}Md in Ref. [1] may rather stem from decay of ^{245}Md.

Conclusion.—The decay data for ^{244}Md presented by Pore *et al.* [1] are in disagreement with those published by Khuyagbaatar *et al.* [2]. A critical inspection of the decay data of Pore *et al.* [1] for ^{244}Md and a comparison with reported decay data for ^{245}Md rather suggest that they have observed ^{245}Md. An additional argument supporting that interpretation comes from the excitation function for the production of mendelevium isotopes in the reaction ^{40}Ar + ^{209}Bi. The excitation energy given for the observation of ^{244}Md is about 10 MeV lower than the expected maximum for the 5n channel. Bombarding energy and reported production cross section rather hint at the synthesis of ^{245}Md.

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