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THE NEW ISOTOPE $^{242}$Bk*

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ABSTRACT

A new isotope of berkelium has been identified through bombardments of $^{235}$U with $^{11}$B, $^{238}$U with $^{10}$B, and $^{232}$Th with both $^{14}$N and $^{15}$N at the Lawrence Berkeley Laboratory 88-inch cyclotron. The new activity decays by electron capture with a half-life of $7.0 \pm 1.3$ minutes. The alpha-branching ratio for this isotope is less than 1% and that for spontaneous fission is less than 0.03%. Analysis of the excitation functions, the chemical behavior of the isotope, and the milking of the $^{242}$Cm daughter leads to the positive identification of this isotope as $^{242}$Bk. A preliminary search was made for $^{241}$Bk but was unsuccessful.

Examination of the (H.I., pxn)(Cm) and (H.I.,αxn)(Am) transfer products in comparison with the (H.I., xn)(Bk) compound nucleus products produced in the above reactions revealed transfer reaction cross-sections to be equal to or greater than the compound nucleus cross-sections. The data suggest that in some cases the yield of an isotope produced via a pxn or αxn transfer reaction might be higher than its production via an xn compound nucleus reaction.

NUCLEAR REACTIONS, COMPOUND NUCLEUS, PROTON AND ALPHA TRANSFER REACTIONS:

$^{235}$U($^{10}$, $^{11}$B,X)I; $^{238}$U($^{10}$B,Q)R; $^{232}$Th($^{14}$, $^{15}$N,M)T; measured excitation functions for $^{242}$Bk; measured σ for $^{238}$Am, $^{239}$Am, $^{240}$Am, $^{240}$Cm, $^{242}$Cm, $^{243}$Bk.
I. INTRODUCTION

Recently, extensive efforts have concentrated on promising mechanisms for the production of superheavy elements.\(^1,^2\) Very little work, however, has concentrated on investigating neutron deficient actinide isotopes. Berkelium, in particular, has been ignored. Until this work, the lightest isotope of berkelium known was \(^{243}\text{Bk}\), the first berkelium isotope discovered,\(^3\) although there is some evidence for a spontaneously fissioning \(^{242}\text{Bk}\) isomer.\(^4\)

In this paper we report on our investigation of the electron capture decay of neutron deficient berkelium isotopes produced in reactions of \(^{10}\text{B}\) and \(^{11}\text{B}\) with \(^{235}\text{U}\), \(^{10}\text{B}\) with \(^{238}\text{U}\), and \(^{14}\text{N}\) and \(^{15}\text{N}\) with \(^{232}\text{Th}\). We report also on the high yields of \((\text{H.I.}, \text{pxn})\) and \((\text{H.I.}, \alpha\text{xn})\) transfer products observed in comparison to the yields of \((\text{H.I.}, \text{xn})\) compound nucleus products.
II. EXPERIMENTAL

The targets were prepared by electrospraying the nitrates dissolved in acetone onto 1-mil thick beryllium backing foils kept at ~250°C. The 0.5 cm² area targets were heated to red-hot in an induction furnace to insure conversion of the target material to the oxides. The uranium targets were isotopically enriched: $^{238}$U, 99.9% (Q material); $^{235}$U, 94.1%; while the thorium isotopes were present in natural abundance. The typical target thickness was ~400 μg/cm².

The $^{10}$B$^+$, $^{11}$B$^+$, $^{14}$N$^+$, and $^{15}$N$^+$ beams of energies from 63 MeV to 112 MeV provided by the 88-inch cyclotron at the Lawrence Berkeley Laboratory were collimated to a 0.4 cm² area and degraded, before entering the target, to energies between 52 and 93 MeV (Figure 1). The degrading foils were beryllium or havar and served also as the upstream window of the target cooling system. The beam intensities were between 2.5 and 5 μA.

Target cooling was accomplished by passing cold nitrogen gas from liquid nitrogen between the target and an upstream window of havar or beryllium. The berkelium products recoiling from the target were caught in a thin aluminum catcher foil which was cooled with 150 torr of helium and was located 0.5 cm from the target. After passing through the target assembly and the catcher foil, the beam was stopped in a Faraday cup. Two rare-earth magnets were placed in front of the target to avoid inaccurate beam readings due to secondary electrons.
Immediately following the irradiation, the catcher foil was dissolved in hot 8M HN\textsubscript{3} in the presence of Hg\textsuperscript{+2}. The berkelium products were oxidized to +4 using CrO\textsubscript{3} and were extracted into bis(2-ethylhexyl) orthophosphoric acid (HDEHP) in n-dodecane.\textsuperscript{6} After being back-extracted into 1.5M H\textsubscript{2}O\textsubscript{2}/10M HN\textsubscript{3}, the berkelium products were plated on 1-inch diameter platinum discs for X-ray, gamma, and/or alpha counting. The time from the end of bombardment (EOB) to the detector was 12-14 minutes with a chemical yield of ~50%.

Curium/americium samples were extracted using a standard transplutonium chemistry consisting of lanthanum carrier and fluoride precipitations; a Dowex 1 x 8 HN\textsubscript{3} column; a sat HCl MP-50 column; a BaCl\textsubscript{2} precipitation; a Dowex 1 x 8 HCl column; and a TTA extraction of the final curium/americium fraction.\textsuperscript{7,8}

Alpha particles were measured with 300 mm\textsuperscript{2} gold-plated surface barrier detectors which were calibrated using a combination of thin \textsuperscript{233}U (4.824 MeV), \textsuperscript{241}Am (5.485 MeV), \textsuperscript{244}Cm (5.805 MeV), and \textsuperscript{252}Cf (6.118 MeV) sources and a linear pulse generator. After suitable amplification, the pulses were fed into a 4096-channel pulse-height analyzer which was divided into 1024-channel sections allowing simultaneous use of four separate detectors. The absolute detection efficiency for \textsuperscript{241}Am was typically 20% and the FWHM at 5.485 MeV was 20 keV.

X- and gamma rays were analyzed using a shielded 60-cm\textsuperscript{3} volume coaxial-germanium, lithium drifted, diode detector connected, after amplification, to a 4096-channel pulse-height analysis system. Energy calibrations and detector efficiencies
were measured using an NBS Mixed Radionuclide Gamma-Ray Emission-Rate Point Source Standard (SRM 4216-B) which contained nine nuclides covering energies from 88.03 keV ($^{109}$Cd) to 1332.48 keV ($^{60}$Co). The resolution for the curium $\text{Ka}_1$ X-ray peak (109.27 keV) was 1.5 keV FWHM and the efficiency for this peak when measured 0.5 cm from the detector face was 15%. A sample X-ray spectrum is shown in Figure 2.
III. RESULTS

Evidence for a short-lived component in the curium $K_{\alpha_1}$ and $K_{\alpha_2}$ X-rays was found in the bombardment of $^{235}\text{U}$ with $^{11}\text{B}$ at 60 MeV-lab even though the time from EOB to the detector was 25 minutes. Subsequent bombardments using a shortened chemistry confirmed this component as having a half-life of $7.0\pm1.3$ minutes. A typical decay curve of the curium $K_{\alpha_1}$ and $K_{\alpha_2}$ X-rays is shown in Figure 3. The short-lived component stands out quite strongly and is easily resolved from the longer-lived activity of $^{243}\text{Bk}$ ($t_{1/2} = 4.5$ h). The excitation function for this activity from $^{11}\text{B}$ on $^{235}\text{U}$, shown in Figure 4, agrees quite well in peak energy and width with calculations of Alonso\textsuperscript{9} for the $(^{11}\text{B},4n)$ reaction. However, the experimental cross-section, $\sigma_{\text{max}} = 10\pm2\mu$b, is approximately a factor of 20 below that calculated.

As a further check on the mass number and for this short-lived activity, $^{232}\text{Th}$ was bombarded with $^{15}\text{N}$. Once again, the experimental excitation function, Figure 5, agrees well in energy and width with calculations, but the $\sigma_{\text{max}} = 9\pm1\mu$b is $\sim 25$ times lower than predicted.

The 7-minute activity was also produced in the reactions $^{10}\text{B}$ on $^{238}\text{U}$ ($\sigma_{\text{max}} = 8.9$ $\mu$b) and $^{14}\text{N}$ on $^{232}\text{Th}$ ($\sigma_{\text{max}} = 0.48$ $\mu$b). The bombarding energy in the $^{10}\text{B}$ case corresponded to a $6n$ reaction and in the $^{14}\text{N}$ case to a $4n$ reaction. Once more the cross-sections were lower than expected by approximately a factor of 20.

A search was made for $^{241}\text{Bk}$ by bombarding $^{235}\text{U}$ with $^{10}\text{B}$.
at energies from 52-60 MeV. This energy range should have maximized
241Bk production while the yield of 242Bk should have been several
orders of magnitude lower. No activity with a half-life greater
than 3 minutes and a cross-section greater than 2 μb was observed.

Since one of the best ways to confirm the Z and A of a
new isotope is to identify positively its daughter in the
original parent chemical fraction, a number of separate bombard­
ments were milked for the 242Cm daughter of 242Bk. A total of
twelve 25-minute bombardments was performed using 11B on 235U
at 60 MeV-lab. Berkelium was separated from the dissolved
catcher foil within 4.5 minutes from EOB, and the final berkelium
fractions from all the runs were pooled. 244Cm tracer was added
and a day later a curium fraction was removed from this combined
berkelium pool with a chemical yield of 70%. From the amount of
242Cm present (Figure 6) the cross-section for 242Bk was found
to be 9.3±1.5 μb, in excellent agreement with the direct
measurements. The 242Cm was identified on the basis of both
α-energy and half-life. The 241Am tracer was used to calibrate
the columns.

It was conceivable that the lower than expected cross­
sections could have been due to the decay of 242Bk by alpha
particle emission or even spontaneous fission. A number of
berkelium fractions were alpha counted within 8 minutes from
EOB. No alpha particle activities at all were observed in the
first few hours of counting. Several catcher foils were counted
1 minute after EOB. As in the chemistry runs, no (unidentified)
alpha particle activities were seen. Direct gamma- and X-ray counting of the catcher foils was attempted but was unsuccessful due to the intense β-, γ- and X-ray background in the foils.

That the light berkelium isotopes do not decay by spontaneous fission has been shown by L. P. Somerville. He bombarded uranium isotopes with $^{10}$B and $^{11}$B at various energies and no unidentified fission activity was observed resulting in the deduction of a fission branch of less than 0.03% for $^{242}$Bk. Eastham and Grant bombarded $^{232}$Th with $^{14}$N at the energy corresponding to the peak yield for the 4n reaction and set a cross-section upper limit for the spontaneous fission of $^{242}$Bk at 50 nb for a half-life greater than 2 ns.

Since the cross-sections measured for the (H.I., xn) compound nucleus reactions were much lower than expected, the question was raised as to what products were being produced. It was decided to examine the (H.I., pxn) and (H.I., axn) products, curium and americium respectively, produced directly in the same reactions and at the same energies used to produce $^{242}$Bk. In the first experiment $^{235}$U was bombarded with a total of 16.9 µA-hrs of $^{11}$B$^+3$. Curium and americium were chemically separated from the catcher foil and the final chemical fraction was analyzed for the emission of both gamma rays and alpha particles.

The results are given in Table 1. $^{238}$Am, $^{239}$Am, and $^{240}$Am were detected by gamma-ray analysis, while $^{240}$Cm and $^{242}$Cm were detected by emission of alpha particles. The berkelium data were not determined in the same bombardments as the curium and americium but are given for comparison. After correcting
the total yield of $^{242}\text{Cm}$ for the amount of $^{242}\text{Bk}$ which decayed to $^{242}\text{Cm}$, there remains a considerable yield of $^{242}\text{Cm}$ from other than the (H.I., xn) compound nucleus mechanism. The total contribution of $^{242}\text{Am}$ decay to the production of $^{242}\text{Cm}$ should be very small since the emission or transfer of only one alpha particle and no neutrons or other particles has a very small probability, especially at excitation energies greater than 35-40 MeV. Data were also obtained from reactions of $^{10}\text{B}$ with $^{238}\text{U}$ and $^{14}\text{N}$ with $^{232}\text{Th}$, as shown in Table 1. In the $^{10}\text{B}$ case only information about proton-out products was gained since the $\alpha(1-3)n$ products were too long-lived to be seen.
IV. DISCUSSION
A. Berkelium-242

From the data presented, there seems little reason to doubt that the observed 7-minute component of the curium X-rays found in the berkelium chemical fraction is due to $^{242}\text{Bk}$. The most convincing evidence is the presence of $^{242}\text{Cm}$ in the proper amount in the berkelium chemical fraction. The only way it could be present is from the decay of the $^{242}\text{Bk}$ parent. Both the decay mode and half-life for this new activity are in good agreement with predictions$^{12,13}$ for $^{242}\text{Bk}$. Thus, the shape of the excitation functions, the projectile energy corresponding to $\sigma_{\text{max}}$, the decay mode, the value of the half-life, and the cross-bombardments all lend additional support to the conclusion that this activity is indeed $^{242}\text{Bk}$.

A bit of concern was raised over the discrepancy between the calculated cross-sections and those measured experimentally. The cross-section calculation code employed, JORPLE, developed by J. R. Alonso et al.$^{9,14}$ and J. O. Rasmussen$^{15}$ and based on a computer code of Siikeland and Lebeck$^{16}$, considers the formation of the compound nucleus followed by competition between fission and neutron emission as the major modes of deexcitation. Consideration is given to the interaction potential, which is analogous to that of Thomas$^{17}$ and of Rasmussen et al.$^{14,15}$; to angular momentum effects; to nuclear deformation; to fusion probability using the Hill-Wheeler transmission formula;$^{18}$ to compound nucleus formation using the formula of Blatt and
and finally to deexcitation of the compound nucleus by neutron evaporation which is based on the Jackson model, corrected for fission competition using the empirical formula of Sikkeland et al. for the ratio of neutron emission to fission.

As in all calculations of this sort, the cross-sections obtained are extremely sensitive to the parameters used such as \( r_0, d \) (diffuseness), nuclear shape and \( \Gamma_n/\Gamma_f \). The parameters employed in the calculations gave the best overall fits to the experimental data available through 1973 for heavy ion reactions for ions up to neon in this region of the table of isotopes. This does not mean, however, that these parameters give best fits in isolated regions such as on the very neutron deficient side of \( \beta \)-stability. Further, no consideration is given to evaporation of particles other than neutrons, although it is generally assumed that neutron emission is greatly favored over that of charged particles in this \( Z \) region. Neither are considerations applied to particular entrance channel problems of admittedly, perhaps, only a few specific projectiles, such as the break-up or dissociation of the projectile. Because these corrections are, in general, of little or no consequence, they are ignored. On the other hand, as in the case of the parameter values in isolated or local cases, they may indeed become important.

The excitation functions calculated from this code agree quite well in shape, energy, and cross-section with most of the experimental data in the actinide region. Unfortunately, however,
there appear to be large discrepancies in cross-sections in the region of neutron deficient actinide isotopes. Williams\textsuperscript{22} lists a number of cases where the experimental cross-sections are factors of 20-30 below those calculated. Thus, it does not appear that the low cross-sections measured in this work are out of line with other reported results. As mentioned, the parameters used in these calculations were obtained from best fits to a wide range of actinide data. It is quite possible that one or more of the values used is incorrect for this neutron deficient region of the actinides. The most likely parameter value to be in error is $\frac{\Gamma_n}{\Gamma_f}$. This value is determined from an empirical formula of Sikkeland\textsuperscript{21} which is based only on data available though 1967. The change required in $\frac{\Gamma_n}{\Gamma_f}$ to match the experimental cross-section is to lower the empirical value by approximately a factor of three. Such a change falls within the errors allowed in $\frac{\Gamma_n}{\Gamma_f}$ by Gavron et al.\textsuperscript{23} for the neutron deficient actinide isotopes.

An important question is: Is this the ground state of $^{242}$Bk or is it an isomeric state? Certainly the assignment of this activity as an isomer of berkelium would help explain the "low" cross-section (for this case). In order to gain further information about the decay scheme for this isotope and to perhaps answer this question, X-ray/gamma-ray coincidence measurements should be performed. This would reveal any correlations between gamma emission and the electron capture decay of the isotope, i.e., whether or not the decay was to the ground state of curium. A major obstacle to this attempt is the
low production cross-section of the isotope. It is unlikely that enough activity can be produced to yield any useful information, especially if chemistry must be performed. Perhaps the best possibility would exist with an on-line mass separator which could isolate the berkelium and transport it to a coincidence detection system in a minimum amount of time. The limiting factor would be the degree of separation and transportation efficiency.

An additional consideration for the lower-than-expected yields of compound nucleus products could be entrance channel effects, that is, projectile break-up due to the Coulomb field of the target nuclei. While from this work there is no direct evidence for such a phenomenon, it is well-known that both $^6$Li and $^7$Li are predisposed to break-up into $^3$He, p2n, and $\alpha$, p2n, respectively. $^{24,25}$ Unternährer and co-workers $^{26}$ have demonstrated $^9$Be break-up and Ollerhead et al. $^{25}$ reported limited data on the break-up of $^{10}$B and $^{11}$B. If Coulomb dissociation of the projectile were to occur prior to the formation of the compound system, the fusion yields would certainly be lower than expected. In fact, it has been found, both in this work and in that by others $^{27}$, that fusion yields from boron reactions are uniformly lower than expected.
B. (H.I., pxn) AND (H.I., αxn) REACTION PRODUCTS

In 1967 Fleury et al. measured the production of 240Cm and 242Cm produced in the reactions of 10B and 11B with 238U. They interpreted the excitation functions to be due to a compound nucleus mechanism. Presumably, 242Bk and 240Bk were produced which then decayed to their curium daughters prior to the chemical separations. The cross-sections they reported were significantly higher than those measured in this work for 242Bk. In light of our measurements, it did not seem reasonable to us that cross-sections as high as several hundred microbarns for 242Cm could have come only from the decay of 242Bk as assumed by Fleury. Indeed, this work has shown that such is not the case. Only a small contribution to the curium cross-section comes from the decay of berkelium. The primary yield of 242Cm (and presumably 240Cm) has been shown to be due to either direct production of 242Cm (240Cm) or to the evaporation of a proton and 3 (5) neutrons from the compound nucleus. The latter seems extremely unlikely due to the high Coulomb barrier operating against charged particle emission from a nucleus with a Z as high as 97.

This work further demonstrates the high yields of alpha-out products in heavy ion reactions in the actinide region. The reaction showing the highest yield is the α2n reaction while the next highest yield is found with the α3n reaction. Again, it is unlikely that these products result from alpha particle evaporation, but rather, they are most probably formed via a
transfer mechanism. To this effect, Hahn et al.\textsuperscript{30} have demonstrated that αxn products from $^{12}$C + $^{239}$Pu are indeed the result of a transfer mechanism rather than a compound nucleus mechanism. They found, as well, that the α2,3n product yields (Cf) were much higher than the 2,3,4n compound nucleus yields (Fm). This is not too surprising since $\frac{\Gamma_n}{\Gamma_f}$ is lower for fermium than for californium leading to an increase in the number of fermium nuclei lost to fission.

Of particular note here is that the yields of the α2,3n products from $^{12}$C + $^{239}$Pu are within a factor of 2-3 of those reported for the compound nucleus reaction from $^{12}$C + $^{238}$U producing the identical californium isotopes.\textsuperscript{31} Bimbot et al.\textsuperscript{32} also find significant αxn yields from $^{12}$C projectiles. Further, Brandshtetr et al.\textsuperscript{33} have found the α4n ($^{246}$Cf) product from $^{16}$O + $^{238}$U to be equal in yield to the 4n ($^{246}$Cf) product from $^{12}$C + $^{238}$U. Perhaps most interesting is that Kutznetsov et al.\textsuperscript{34,35} have reported αxn reaction products with cross-sections four times larger than the corresponding compound nucleus reaction using boron as the projectile.

These same trends were found in this work using boron and nitrogen projectiles on uranium and thorium targets. The compound nucleus cross-sections are significantly lower than those for pxn and αxn products from the same projectile-target combination. While no data were measured to confirm that these products result from direct or transfer reactions, it seems reasonable that such is the case. The particle "transferred" to the $^{235}$U target in
the boron bombardments to produce americium would be $^7\text{Li}$ followed by neutron emission. In support of this, Hubert et al.\textsuperscript{36} found very high yields of lithium transfer products in studies of boron on tantalum. $^8\text{Be}$ would be the particle transferred to form curium isotopes from a $^{235}\text{U}$ target. Hahn\textsuperscript{27} has studied $^8\text{Be}$ transfers in this actinide region and found their yields to be significant.
V. SUMMARY AND COMMENT

In summary, then, a new isotope of berkelium, mass number 242, has been produced in reactions of boron on uranium and nitrogen on thorium with a $\sigma_{\text{max}} = 10 \ \mu b$. It decays by electron capture with a half-life of 7.0±1.3 minutes. Yields of proton- and alpha-out transfer products were found in excess of the compound nucleus products suggesting that in some instances it may be more profitable to produce neutron deficient actinide isotopes via a (H.I., p- or axn) transfer mechanism rather than via a (H.I., xn) compound nucleus mechanism.

Perhaps a last comment should be added concerning the effect these results may have on the current problems connected with claiming the discovery of new elements and/or isotopes. There are currently two major modes of identification for new elements which are too short-lived to be chemically separated. One method employs spontaneous fission detection techniques, while the other method relies on alpha particle identification and, where possible, genetic links to known daughters and grand daughters. The use of spontaneous fission measurements as the sole identification method for new elements suffers from a severe drawback: no positive A or Z identification of the decaying species is provided. This is in contrast to alpha particle analysis where genetic links can be observed during the decay of the parent and daughters leading to both positive Z and A identification of the newly observed activity. Since the spontaneous fission technique does not give unambiguous information concerning
Z or A, the assumption is often made that the new activity observed is the result of a compound nucleus mechanism which has long been considered to produce activities in the highest yield, i.e., the assumption is made that \( Z_1 + Z_2 = Z_{1+2} \). The yield of proton or alpha evaporation products is reasonably assumed to be negligible in this high Z region. Therefore, when a new spontaneous fission activity is produced in a heavy ion reaction, the claim is often made that a new element or isotope has been produced. However, data from this study and from the other work referenced here show that while the assumption that proton and alpha particle evaporation product yields are negligible may be valid, the assumption that the yields of these very same products produced via a transfer mechanism are negligible is not. In fact, it now has been shown that the \((\text{H.I.}, pxn)\) and \((\text{H.I.}, axn)\) product yields can be as much as 100 times greater than the \((\text{H.I.}, xn)\) product yields from the same projectile-target combination. It is not valid to assume that the activities produced in the greatest yields are due to a compound nucleus mechanism in heavy ion reactions. Therefore, the observation of a new spontaneous fission activity in a heavy ion bombardment may, indeed, be due to the compound nucleus, but it may have an even greater probability of being due to an element one or two Z units lower than the compound nucleus. These results emphasize the great care that must be taken when a new activity is to be identified. With only spontaneous fission as the method of detection, it is not possible to determine uniquely the Z or
the A of the new activity. Before a new element can be claimed, it must be shown that directly produced nuclei, i.e., non-compound nuclei, are not responsible for the new observations, especially when doubt may exist about the Z identification of the new discovery.
ACKNOWLEDGEMENTS

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<th>Product</th>
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TABLE 1 (Con't.)
Yield of pxn and axn Products

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<th>Product</th>
<th>Reaction</th>
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<tbody>
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<td></td>
<td>$\alpha; 242 \text{Am} \beta^-$</td>
<td>0.52 $\mu$b</td>
</tr>
<tr>
<td>240Cm</td>
<td>p5n</td>
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<td>a2n</td>
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REFERENCES


10. L. P. Somerville, Lawrence Berkeley Laboratory, private communication.


12. N. N. Kolesnikov and A. G. Demin, Joint Institute for Nuclear Research, Dubna, JINR-P6-9420 (1975) and JINR-P6-9421 (1975).
27. R. L. Hahn, Oak Ridge National Laboratory, private communication.
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$^{11}$B + $^{235}$U

60 MeV

0.9 $\mu$ A-hr

$t_{1/2} = 7.0$ min

$^{243}$Bk background

XBL 786-1078
$^{11}$B + $^{235}$U

$\tau_{1/2} = 7$ m

FWHM = 5 MeV

$E_{LAB}$ (MeV)

$\sigma_{\mu,b}$
\[ \sigma \mu b \] vs. \[ E_{LAB} \text{ (MeV)} \]

- \[ ^{15}\text{N} + ^{232}\text{Th} \]
- \[ 7m = t_{1/2} \]
- \[ \text{FWHM} = 10 \text{ MeV} \]
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