Discovery of ^{109}Xe and ^{105}Te: Superallowed α Decay near Doubly Magic ^{100}Sn

S. N. Liddick,[1] R. Grzywacz,[2,3] C. Mazzocchi,[2] R. D. Page,[4] K. P. Rykaczewski,[3] J. C. Batchelder,[1] C. R. Bingham,[2,3] I. G. Darby,[4] G. Drafta,[2] C. Goodin,[5] C. J. Gross,[3] J. H. Hamilton,[5] A. A. Hecht,[6] J. K. Hwang,[5] S. Ilyushkin,[7] D. T. Joss,[4] A. Korgul,[2,5,8,9] W. Królas,[9,10] K. Lagergren,[9] K. Li,[5] M. N. Tantawy,[2] J. Thomson,[4] and J. A. Winger[1,7,9]

[1]*UNIRIB, Oak Ridge Associated Universities, Oak Ridge, Tennessee 37831, USA*
[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*
[4]*Department of Physics, University of Liverpool, Liverpool L69 7ZE, United Kingdom*
[5]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*
[6]*Department of Chemistry, University of Maryland, College Park, Maryland 20742, USA*
[7]*Department of Physics and Astronomy, Mississippi State, Mississippi 39762, USA*
[8]*Institute of Experimental Physics, Warsaw University, Warszawa, PL 00-681, Poland*
[9]*Joint Institute for Heavy-Ion Research, Oak Ridge, Tennessee 37831, USA*
[10]*Institute of Nuclear Physics, Polish Academy of Sciences, PL 31-342 Kraków, Poland*

(Received 16 May 2006; revised manuscript received 23 June 2006; published 21 August 2006)

Two new α emitters ^{109}Xe and ^{105}Te were identified through the observation of the $^{109}\text{Xe} \rightarrow {}^{105}\text{Te} \rightarrow {}^{101}\text{Sn}$ α-decay chain. The ^{109}Xe nuclei were produced in the fusion-evaporation reaction $^{54}\text{Fe}(^{58}\text{Ni}, 3n)^{109}\text{Xe}$ and studied using the Recoil Mass Spectrometer at the Holifield Radioactive Ion Beam Facility. Two transitions at $E_\alpha = 4062 \pm 7$ keV and $E_\alpha = 3918 \pm 9$ keV were interpreted as the $l = 2$ and $l = 0$ transitions from the $7/2^+$ ground state in ^{109}Xe ($T_{1/2} = 13 \pm 2$ ms) to the $5/2^+$ ground state and a $7/2^+$ excited state, located at 150 ± 13 keV in ^{105}Te. The observation of the subsequent decay of ^{105}Te marks the discovery of the lightest known α-decaying nucleus. The measured transition energy $E_\alpha = 4703 \pm 5$ keV and half-life $T_{1/2} = 620 \pm 70$ ns were used to determine the reduced α-decay width δ^2. The ratio $\delta^2_{^{105}\text{Te}}/\delta^2_{^{213}\text{Po}}$ of ~ 3 indicates a superallowed character of the α emission from ^{105}Te.

DOI: 10.1103/PhysRevLett.97.082501 PACS numbers: 23.60.+e, 21.10.Dr, 21.10.Pc, 27.60.+j

Alpha decay has long proven to be a useful tool to investigate the low-energy structure of neutron-deficient nuclides near magic shell closures [1]. The presence of an island of α emission in the neutron-deficient Sn region provided initial evidence that the $N, Z = 50$ shell closures apply to ^{100}Sn (e.g., [2,3]). In the classical Gamow picture, α decay occurs through the preformation of an α particle in the nucleus and its subsequent tunneling through Coulomb and centrifugal barriers [4]. Close to the $N = Z$ line, above ^{100}Sn, protons and neutrons are expected to occupy identical orbitals. This may result in an enhancement of the preformation probability of an α particle within the nucleus and the development of so-called superallowed α decay [2].

The low-energy structure of nuclei around doubly magic ^{100}Sn provides a benchmark for the development and interpretation of shell structure models. Significant recent work has been devoted to elucidate the single-particle structure around ^{100}Sn (e.g., Refs. [5–8]). While a shell-model description of the odd-mass Sn, Te, and Xe isotopes requires knowledge of five single-particle energies ($\nu d_{5/2}$, $\nu g_{7/2}$, $\nu s_{1/2}$, $\nu d_{3/2}$, $\nu h_{11/2}$), the energy separation between the lowest single-particle states $\nu d_{5/2}$ and $\nu g_{7/2}$ is of particular importance for the low-energy structure in these nuclei and yet they have not been measured. There are numerous theoretical estimates for the $\nu g_{7/2}$-$\nu d_{5/2}$ energy separation which range from -0.05 to 1.9 MeV ([9,10], and references therein). Experiments performed in this region investigating the low-energy structure of the Sn, Te, and Xe isotopes suggest that the $\nu g_{7/2}$-$\nu d_{5/2}$ energy separation is below 0.3 MeV [5–9,11–14]. Experimental efforts are needed to improve this constraint and ultimately identify the low-energy excited states in ^{101}Sn. Further interest in the decay rates of nuclei around ^{100}Sn comes from the study of astrophysical processes, for which this region has been cited as the end of the rapid proton capture process due to the Sn-Sb-Te cycle [15].

The development of new experimental techniques has continually increased the number of nuclei that are accessible for spectroscopic study [5,6,16]. However, despite many experimental efforts [17,18], new neutron-deficient isotopes of Xe and Te have not been observed since the discovery of ^{110}Xe and ^{106}Te over 25 years ago [19]. The current work focuses on the first identification of ^{109}Xe and ^{105}Te through the observation of their α-decay chain. This marks the closest approach to the $N = Z$ line above ^{100}Sn and provides an opportunity to search for superallowed α decay and extends the $5/2^+$ and $7/2^+$ level systematics to ^{105}Te.

The ^{109}Xe nuclei were produced in the $^{54}\text{Fe}(^{58}\text{Ni}, 3n)^{109}\text{Xe}$ fusion-evaporation reaction with beam energies between 220 and 225 MeV on a 470 $\mu\text{g/cm}^2$ thick ^{54}Fe target. Mass 109 reaction products were separated according to the ratio between atomic mass and ionic charge using the Holifield Radioactive Ion Beam Facility Recoil Mass Spectrometer [20]. The separated beam passed through the mylar foil of a high efficiency microchannel plate counter, a 0.15 mg/cm^2 thick Al degrader, and implanted with ~60 MeV into a 40 mm × 40 mm × 66 μm double-sided silicon strip detector (DSSD) with 1-mm wide strips. The DSSD and all ancillary detectors were read out by digital electronics [21]. To ensure that the sequential ^{109}Xe and ^{105}Te α decays (time difference of only hundreds of nanoseconds) were correctly recorded, a novel acquisition mode was developed. If a preamplifier signal was beyond a preset threshold, ~9.2 MeV, it was considered to be an implanted ion and the energy and time of the event were recorded. This limit was chosen to exceed the expected sum of the ^{109}Xe and ^{105}Te α energies. If a signal was below this limit, 25 μs of the pulse shape (trace) was recorded starting 1 μs before the leading edge. Examples of traces for the ^{109}Xe → ^{105}Te → ^{101}Sn α-decay chain are shown in Fig. 1. The ability to identify two α particles closely spaced in time, milliseconds after the correlated ion implantation into the DSSD, demonstrates an advantage of digital electronics.

A total of 100 α-α decay events were attributed to the ^{109}Xe → ^{105}Te → ^{101}Sn decay chain. The maximum time allowed between an implant and correlated decay events in the same DSSD pixel was limited to 200 ms. The energy calibration was obtained from known ^{109}Te and ^{108}Te α lines. The ^{108}Te resulted from the proton decay of ^{109}I.

The α energy spectra for ^{109}Xe and ^{105}Te are shown in Figs. 2(a) and 2(b). The energies of the two α transitions from ^{109}Xe are 3918 ± 9 and 4062 ± 7 keV. After decay-recoil energy correction the Q_α for the two transitions are 4067 ± 10 and 4217 ± 8 keV, respectively, leading to an energy of 150 ± 13 keV for the excited state in ^{105}Te. The α branching ratios to the excited and ground states of ^{105}Te are (30 ± 6)% and (70 ± 6)%, respectively, assuming all ^{109}Xe decays proceed through α emission. The energy of the ^{105}Te α line is 4703 ± 5 keV, leading to Q_α of 4889 ± 6 keV. No fine structure was observed in the ^{105}Te α decay, but a 5% limit can be placed on the branching ratio of the decay to an excited state in ^{101}Sn.

The time distribution for the ^{109}Xe decay is shown on a logarithmic time axis in Fig. 2(c) constructed from the time difference between an implant in the DSSD and a subsequent correlated ^{109}Xe α decay. Using the method of Ref. [22] the half-life of ^{109}Xe is 13 ± 2 ms. The half-lives of the low and high energy α transitions from ^{109}Xe are 10 ± 3 ms and 15 ± 3 ms, respectively. The time distribution for ^{105}Te was derived by histogramming the time differences obtained from a fit to the ^{109}Xe-^{105}Te double α traces. As the time between the two α pulses decreases, it becomes increasingly difficult for the analysis algorithm to identify the signal as a double pulse. The efficiency for identifying double pulses decreases at time differences below 0.5 μs, though the algorithm is still sensitive to time differences as low as 0.25 μs. The half-life of ^{105}Te is 620 ± 70 ns.

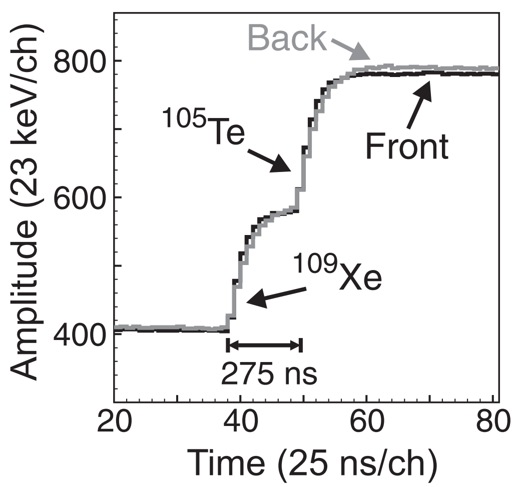

FIG. 1. Part of a signal trace, from 0.5 to 2.0 μs, recorded for a ^{109}Xe → ^{105}Te → ^{101}Sn α-decay chain event. The time difference between the ^{109}Xe and ^{105}Te α particles is 275 ns, and traces from both the front (black line) and back (gray line) strips of the DSSD are shown.

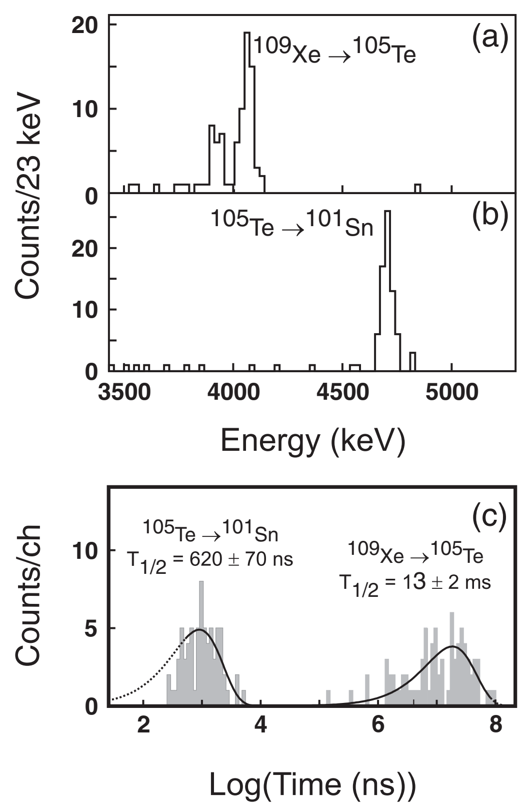

FIG. 2. Energy spectra from 3500 to 5250 keV for the α decay of (a) ^{109}Xe and (b) ^{105}Te. (c) Decay spectrum for ^{109}Xe and ^{105}Te on a logarithmic time axis and fit according to the method described in Ref. [22]. Only times above 0.5 μs were used in the ^{105}Te half-life fit, which is indicated by the solid line.

The ground state spin and parity of ^{101}Sn was previously suggested to be $5/2^+$, arising from the $\nu d_{5/2}$ orbital [11]. The observation of only one α transition between ^{105}Te and ^{101}Sn suggests that the ground state of ^{105}Te is $I^\pi = 5/2^+$. A large α branch from ^{109}Xe to the excited state in ^{105}Te is interpreted as a result of the $l = 0$ character of the α transition which compensates for the decreased α energy compared to the higher energy $l = 2$ transition to the ground state. Thus the ground state of ^{109}Xe and the excited state of ^{105}Te are both tentatively assigned as $I^\pi = 7/2^+$ states, resulting in the decay scheme presented in Fig. 3. The spin and parity deduced for the ground state of ^{109}Xe agree with those proposed for the ^{111}Xe ground state [7] where in both cases excited levels have not been identified. The current results for ^{109}Xe are also consistent with the observation of fine structure in the α decay of ^{111}Xe to the tentative $5/2^+$ ground and $7/2^+$ first excited state in ^{107}Te [12]. The ordering of the ground and excited state in ^{105}Te agree systematically with those in the heavier ^{107,109,111}Te isotopes [7,13]. The $5/2^+$ and $7/2^+$ states in ^{109,111}Te have been identified as predominately having $\nu d_{5/2}$ and $\nu g_{7/2}$ parentage [13,14].

The Q_α values as a function of proton number are shown in Fig. 4(a) for nuclei in the ^{100}Sn and ^{208}Pb regions [23]. The expected increase in Q_α approaching doubly magic ^{100}Sn is observed in the new data for ^{109}Xe and ^{105}Te. In Fig. 4(b) the Q_α values for the Te and Xe isotopes are shown. When the odd- and even-mass isotopes are considered separately, there is an apparent linear trend between the neutron number and the Q_α value. If this systematic trend of the Q_α values is extended, Q_α for ^{104}Te can be expected to be greater than 5 MeV.

The reduced α-decay width δ^2 can be calculated using the tunneling probability P of an α particle through the potential barrier, using the WKB approximation, and the partial α-decay rate λ_α for a given transition, $\delta^2 = \lambda_\alpha h/P$. The reduced α-decay widths relative to ^{212}Po ($W_\alpha = \delta^2/\delta^2_{^{212}\mathrm{Po}}$) [16] for all three observed α transitions are given in Fig. 3. The nucleus ^{212}Po is used as a reference for δ^2 values due to its simple nuclear structure; it may be pictured as an α cluster outside the doubly magic ^{208}Pb core [24]. The W_α values for the two ^{109}Xe transitions are 0.9 ± 0.3 to the ^{105}Te ground state and 0.8 ± 0.2 to the excited state. These widths should be considered upper limits since no consideration was given to other decay modes such as a small β branch (estimated as 4% assuming a $T^\beta_{1/2}$ of 368 ms [25]). The W_α of the ^{105}Te transition is 2.0 ± 0.3. The difference between W_α for ^{109}Xe and ^{105}Te is not unexpected, as mixing between single-particle states becomes more pronounced away from the doubly magic ^{100}Sn.

When protons and neutrons occupy identical orbitals, the result may be an enhancement of the α preformation factor S, which is proportional to the α-decay width ($S = \delta^2/\nu h$, where ν is the frequency at which the α particle encounters the Coulomb barrier). A large increase in the preformation factor is expected to lead to superallowed α decay [3]. The W_α values for the lightest Te isotopes are compared to Po nuclei [23,26] with similar valence structure in Table I. An enhancement of 2.7 ± 0.7 is observed in the relative width of ^{105}Te compared to ^{213}Po, and it is apparent that the enhancement of α-decay widths is increasing as mass decreases suggesting that the $^{104}\mathrm{Te} \rightarrow {}^{100}\mathrm{Sn}$ transition is the best candidate for superallowed α decay. Additionally, the enhancements for both ^{105}Te and ^{106}Te are consistent. However, since only two points are shown for odd and even masses it is difficult to determine how quickly the enhancement increases. Thus, a lower limit of the enhancement expected in ^{104}Te is taken to be 3. Combined with the extrapolated ^{104}Te Q_α an upper limit for the half-life of 100 ns for the α decay of ^{104}Te is

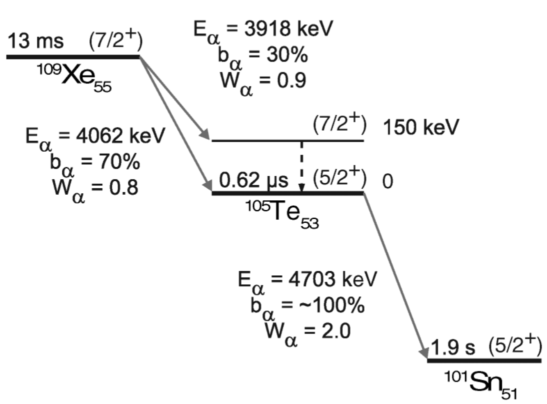

FIG. 3. Alpha decay scheme for the $^{109}\mathrm{Xe} \rightarrow {}^{105}\mathrm{Te} \rightarrow {}^{101}\mathrm{Sn}$ decay chain. Figure is not to scale. See text for uncertainties on half-lives, energies, branching ratios, and W_α.

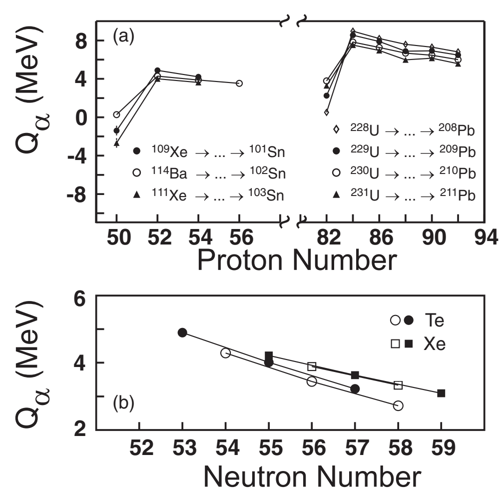

FIG. 4. (a) Q_α as a function of proton number for the different α decay chains in the ^{100}Sn and ^{208}Pb regions [23]. The strong double shell closures at ^{100}Sn and ^{208}Pb give rise to a peak in Q_α at proton numbers of 52 and 84, respectively. (b) Q_α for the ^{100}Sn region separated into even- and odd-mass α emitters.

TABLE I. W_α for isotopes in the $Z = 50$ and $Z = 82$ [23,26] regions. In each row are nuclei in the two different regions with corresponding valence structures with respect to the appropriate doubly magic core (either ^{100}Sn or ^{208}Pb). The last column shows the enhancement of the W_α value.

Valence	Nuclide	W_α	Nuclide	W_α	$W_\alpha^{Te}/W_\alpha^{Po}$
α	^{104}Te	3[a]	^{212}Po	1.0	3[a]
$\alpha + n$	^{105}Te	2.0 ± 0.3	^{213}Po	0.73 ± 0.14	2.7 ± 0.7
$\alpha + 2n$	^{106}Te	4.63 ± 0.56	^{214}Po	1.53 ± 0.02	3.02 ± 0.37
$\alpha + 3n$	^{107}Te	1.45 ± 0.63	^{215}Po	1.16 ± 0.01	1.25 ± 0.54
$\alpha + 4n$	^{108}Te	2.19 ± 0.27	^{216}Po	1.59 ± 0.01	1.38 ± 0.17

[a]Lower limit; see text for details.

deduced. The measurement of this half-life represents a significant experimental challenge but may still be feasible with the digital electronics used in our work.

An accurate understanding of nuclei around doubly magic ^{100}Sn requires a knowledge of single-particle energies, in particular, the energy separation between the $\nu d_{5/2}$ and $\nu g_{7/2}$ single-particle orbitals. Viewed from an extreme single-particle shell-model perspective, this energy separation can be extracted from the energy of the first excited state in ^{101}Sn. The energy systematics of $5/2^+$ and $7/2^+$ states as a function of neutron number can be extended to ^{105}Te (see Fig. 5). The simultaneous break with systematic trends at $N = 53$ for both Sn and Te isotopes may suggest that the $7/2^+$ level is converging toward the single-particle energy separation between the $\nu d_{5/2}$ and $\nu g_{7/2}$ single-particle orbits. Although configuration mixing may influence the trends, one could expect the excited $7/2^+$ state in ^{101}Sn to be around 160 keV.

In summary, the first identification of ^{109}Xe and ^{105}Te has been made through the detection of the α-decay chain

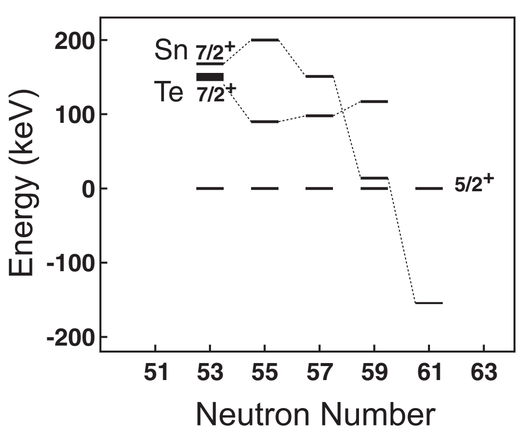

FIG. 5. Energy systematics of the $7/2^+$ level relative to the $5/2^+$ state for Te and Sn isotopes as a function of neutron number. Data were taken from the current work (heavy black line) and from Ref. [7] (and references therein).

^{109}Xe $\rightarrow$ ^{105}Te $\rightarrow$ ^{101}Sn and marks the closest approach to the $N = Z$ line above ^{100}Sn. The half-lives of the two α decays were determined to be 13 ± 2 ms and 620 ± 70 ns for ^{109}Xe and ^{105}Te, respectively. The Q_α values are 4067 ± 10 and 4217 ± 8 keV for the α transitions from ^{109}Xe and 4889 ± 6 keV for the ^{105}Te α decay. The observed enhancement between the W_α for ^{105}Te and the analogous ^{213}Po indicates the superallowed character of the α decay of ^{105}Te. Fine structure was observed in the α decay of ^{109}Xe $\rightarrow$ ^{105}Te placing the energy difference between the tentatively assigned $5/2^+$ ground state and $7/2^+$ excited state at 150 ± 13 keV. Further experiments are anticipated to measure both the fine structure in the ^{105}Te α decay to ^{101}Sn and attempt to measure the α-decay chain ^{108}Xe $\rightarrow$ ^{104}Te $\rightarrow$ ^{100}Sn.

This work was supported in part by the UNIRIB consortium and under U.S. DOE Grants No. DE-AC05-060R23100 (ORAU), No. DE-FG02-96ER40983 (UT), No. DE-AC05-00OR22725 (ORNL), No. DE-FG02-96ER-41006 (MississippiSU), and No. DE-FG05-88ER40407 (Vanderbilt), and the U.K. Engineering and Physical Sciences Research Council.

Note added in proof.—^{105}Te has been independently identified by Seweryniak *et al.* [27].

[1] A. Andreyev *et al.*, Nature (London) **405**, 430 (2000).
[2] R. D. Macfarlane and A. Siivola, Phys. Rev. Lett. **14**, 114 (1965).
[3] E. Roeckl, Radiochimica Acta **70/71**, 107 (1995).
[4] G. Gamow, Z. Phys. **51**, 204 (1928).
[5] C. Fahlander *et al.*, Phys. Rev. C **63**, 021307(R) (2001).
[6] D. Seweryniak *et al.*, Phys. Rev. C **66**, 051307(R) (2002).
[7] B. Hadinia *et al.*, Phys. Rev. C **70**, 064314 (2004).
[8] H. Grawe *et al.*, Eur. Phys. J. A **27**, 257 (2006).
[9] J. Ressler *et al.*, Phys. Rev. C **65**, 044330 (2002).
[10] B. A. Brown *et al.*, Phys. Rev. C **50**, R2270 (1994).
[11] O. Kavatsyuk *et al.*, GSI Report 2006-1 (to be published).
[12] D. Schardt *et al.*, Nucl. Phys. **A326**, 65 (1979).
[13] Zs. Dombrádi *et al.*, Phys. Rev. C **51**, 2394 (1995).
[14] K. Starosta *et al.*, Phys. Rev. C **61**, 034308 (2000).
[15] H. Schatz *et al.*, Phys. Rev. Lett. **86**, 3471 (2001).
[16] Z. Janas *et al.*, Eur. Phys. J. A **23**, 197 (2005).
[17] C. Mazzocchi *et al.*, Phys. Lett. B **532**, 29 (2002).
[18] A. Hecht *et al.*, AIP Conf. Proc. **819**, 355 (2006).
[19] D. Schardt *et al.*, Nucl. Phys. **A368**, 153 (1981).
[20] C. J. Gross *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **450**, 12 (2000).
[21] R. Grzywacz, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 649 (2003).
[22] K.-H. Schmidt *et al.*, Z. Phys. A **316**, 19 (1984).
[23] G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003).
[24] K. Varga *et al.*, Phys. Rev. Lett. **69**, 37 (1992).
[25] P. Möller *et al.*, At. Data Nucl. Data Tables **66**, 131 (1997).
[26] G. Audi *et al.*, Nucl. Phys. **A729**, 3 (2003).
[27] D. Seweryniak *et al.*, Phys. Rev. C **73**, 061301(R) (2006).