

Energy of the first excited state of ^{43}Ar M. Morales,^{1,*} P. Jänker,² K. E. G. Löbner,^{3,†} and P. R. Pascholati⁴¹*Instituto de Pesquisas Energéticas e Nucleares, C. P. 11049 CEP, 05422-970 São Paulo, SP, Brazil*²*EAPS Innovation Works, D-81663 Munich, Germany*³*Fakultät für Physik der LMU München, Am Coulombwall 1, D-85748 Garching, Germany*⁴*Instituto de Física da Universidade de São Paulo, C. P. 66318 CEP, 05315-970 São Paulo, SP, Brazil*

(Received 5 November 2008; published 5 March 2009)

Results of proton-proton- γ coincidence measurements using the $^{36}\text{S} + ^9\text{Be}$ reaction revealed a γ ray of 201.27 ± 0.16 keV that most probably corresponds to the transition between the predicted $7/2^-$ first excited state to the $5/2^-$ ground state of ^{43}Ar .

DOI: [10.1103/PhysRevC.79.037302](https://doi.org/10.1103/PhysRevC.79.037302)

PACS number(s): 23.20.Lv, 25.70.Gh, 27.40.+z

The study of nuclei with $Z \approx 20$ and $20 \leq N \leq 28$ attracted much attention since the observation of deformation in the doubly magic ^{40}Ca [1,2]. Recently, experiments with radioactive beams brought new questions concerning the shell structure of nuclei in this region. The number of protons in the $1s_{1/2}0d_{3/2}$ orbits has a large influence on the energies of the neutrons in the $0f_{7/2}$ orbital [3], as shown in experiments with neutron-rich P, S, and Cl isotopes [4,5]. Masses and low-energy levels of the neutron-rich Ar isotopes, which are closer to those of the Ca isotopes, provide very important information on the nucleon-nucleon interactions between $(0d_{3/2})^{-2}$ and $(0f_{7/2})^n$ configurations. Due to difficulties in producing ^{43}Ar , little information is known about its nuclear structure. The mass and four excited states of ^{43}Ar were determined by Jelley *et al.* [6] using the $^{48}\text{Ca}(\alpha, ^9\text{Be})^{43}\text{Ar}$ reaction. Another excited state was observed by Maréchal *et al.* [7] using proton scattering with a radioactive beam of ^{43}Ar . Results of γ -ray spectroscopy of the ^{43}Cl β decay, reported more than 20 years ago by Huck *et al.* [8], revealed several excited states, which were confirmed more recently by Winger, Mantica, and Ronningen [9]. Although around 20 excited states of ^{43}Ar were established from these studies, the presently known first excited state of 762 keV observed in the ^{43}Cl decay probably does not correspond to the theoretically predicted $7/2^-$ first excited state, as pointed out by Winger, Mantica, and Ronningen [9].

Doubts about the placement of the first excited state of ^{43}Ar motivated us to report results obtained with the $^{36}\text{S} + ^9\text{Be}$ reaction studied with charged-particle γ coincidence measurements. New information on the neutron-rich potassium isotopes ^{42}K and ^{43}K obtained with this reaction were published some years ago [10], and the evidence of the first excited state of ^{43}Ar was previously mentioned in the Ph.D thesis of one of the authors [11]. In the following paragraphs of this report, experimental and theoretical evidences are used to defend the hypothesis that the first excited state of ^{43}Ar has not been observed yet. Then, an analysis of the results obtained with the $^{36}\text{S} + ^9\text{Be}$ reaction is developed to interpret one γ ray

observed in coincidence with two protons as the deexcitation of the first excited state of ^{43}Ar .

The nucleus ^{43}Ar has two paired protons in the $0d_{3/2}$ orbit and five neutrons in the $0f_{7/2}$ shell. Applying the shell model naively, spin-parity $J^\pi = 7/2^-$ is predicted for its ground state, as well as for the ground state of other nuclei with an even number of protons and an odd number of neutrons in the $0f_{7/2}$ level. The same prediction is valid for nuclei with an even number of neutrons and one unpaired proton in the $0f_{7/2}$ level. However, experimental data reveal that this prediction fails in several cases for nuclei with N or $Z = 25$, as shown in Table I.

Two interesting peculiarities are quite evident in Table I. The first one is that most of the nuclei have the ground and first excited states assigned as $5/2^-$ and $7/2^-$, respectively; exceptions occur for ^{45}Ca and ^{53}Mn , both with single closed shells of $N = 20$ and $Z = 28$, respectively. The second evidence is that the energies of the first excited state of all nuclei, except ^{43}Ar , assume values of less than 380 keV. The energy of the known first excited state of ^{43}Ar is 762 keV, which is much larger than the corresponding energy of all other nuclei. In addition to this systematic evidence, theoretical calculations for the first excited state of ^{43}Ar performed by Warburton [20] and Gloeckner, Lawson, and Serduke [21] predict values of 22 and 159 keV, respectively, and assignments of $5/2^-$ for the ground state and $7/2^-$ for the first excited state.

The analysis of ^{43}Ar states deserves more comments. The β decay of ^{43}Ar to ^{43}K [22] allows the assignment of $3/2^-$ or $5/2^-$ for the ground state of ^{43}Ar , while its assignment as $7/2^-$ is discarded due to inconsistency with $\log(ft)$ values. In the recent revision of nuclei with $A = 43$, Cameron and Singh [12] adopted the preference for a $5/2^-$ assignment. The presently known first excited state with energy of 762 keV was observed in the β decay of ^{43}Cl [8,9]. The ground state of ^{43}Cl has a probable assignment of $1/2^+$ or $3/2^+$. In both cases, the direct feeding of a $7/2^-$ level of ^{43}Ar would be unfavored, and also the intensity of γ rays involving levels with $J > 5/2$ would be very low. Moreover, there are indications that the ground state assignment of Cl nuclei changes from $3/2^+$ to $1/2^+$ for the neutron-rich isotopes ^{41}Cl and ^{43}Cl [5,23,24], a fact that strongly hinders the observation of a $7/2$ level using the β decay of ^{43}Cl . From these arguments one concludes that

* moralles@ipen.br

† Deceased.

TABLE I. Spin-parity assignments of the ground and first excited states and energies (keV) of the first excited state of nuclei with N (or Z) = 25 and even Z (or N). Asterisk indicates single closed shell. References: ^{43}Ar [12], ^{45}Ca [13], ^{47}Ti [14], ^{49}Cr and ^{49}Mn [15], ^{51}Fe and ^{51}Mn [16], ^{53}Mn [17], ^{55}Mn [18], ^{57}Mn [19].

Nucleus	Z	N	Ground state		1st excited state	
			J^π		J^π	Energy
^{43}Ar	18		3/2 ⁻ , 5/2 ⁻		Unknown	762
^{45}Ca	20*		7/2 ⁻		5/2 ⁻	174
^{47}Ti	22	25	5/2 ⁻		7/2 ⁻	159
^{49}Cr	24		5/2 ⁻		7/2 ⁻	272
^{51}Fe	26		5/2 ⁻		7/2 ⁻	254
^{49}Mn		24	5/2 ⁻		7/2 ⁻	261
^{51}Mn		26	5/2 ⁻		7/2 ⁻	237
^{53}Mn	25	28*	7/2 ⁻		5/2 ⁻	378
^{55}Mn		30	5/2 ⁻		7/2 ⁻	126
^{57}Mn		32	5/2 ⁻		5/2 ⁻ , 7/2 ⁻	83

the presently known 762 keV level does not correspond to the expected 7/2⁻ first excited state of ^{43}Ar .

In fusion-evaporation reactions, levels of large angular momenta can be accessed. Known excited states with angular momenta up to 7 and 15/2 for ^{42}K and ^{43}K , respectively, were observed by our group using the $^9\text{Be}(^{36}\text{S}, xn\gamma p\alpha)X$ reaction [10]. This reaction was studied in three experiments of twofold coincidences: recoil-nuclei γ and charged-particle γ and γ - γ . The charged-particle γ coincidences were measured with five Compton-suppressed Ge detectors, eleven telescopes placed at forward angles, and seven pin-diodes at backward angles. The kinematics of the reaction allowed only particles with $Z = 1$ at backward angles. Because of the granularity of the particle detection, two-charged-particle γ coincidences were also observed with expressive statistics. For the present analysis the spectra of only three of the five Ge detectors were used, because of the low-energy resolution presented by two of them. The relevant results concerning the analysis of proton-proton γ coincidences is described below. For more details about the experimental setup, see Ref. [10].

The experiment was performed at the Tandem Accelerator of the Maier-Leibnitz-Laboratorium der Universität München und der Technischen Universität München. Targets of 610 $\mu\text{g}/\text{cm}^2$ Be evaporated on 36 mg/cm^2 Au backing were irradiated with a 95 MeV ^{36}S beam. The energy of the beam was chosen to optimize the production of ^{43}Ar predicted with the CASCADE evaporation model code [25]. Calculated cross sections for several reaction channels of the $^9\text{Be}(^{36}\text{S}, xn\gamma p\alpha)X$ reaction are presented in Table II. The presence of C and O in the target was evidenced by the observation of characteristic γ rays of Ca and Ti isotopes in coincidence with α particles and of γ rays of Sc and V isotopes in coincidence with protons. Table II shows also the isotopes produced in reactions with ^{12}C and ^{16}O (contaminants).

Figures 1(a) to 1(d) show the spectra of γ rays in coincidence with one and two charged particles, where the pronounced peaks are identified by energy and isotope assignment. All the γ -ray spectra shown here correspond

TABLE II. Cross sections σ (mb) of products of the $^{36}\text{S} + ^9\text{Be}$ reaction ($E_{\text{LAB}} = 95$ MeV) calculated with the code CASCADE [25] and isotopes produced in the reactions with contaminants ^{12}C and ^{16}O .

Channel	$^{36}\text{S} + ^9\text{Be}$		$^{36}\text{S} + ^{12}\text{C}$	$^{36}\text{S} + ^{16}\text{O}$
	σ	product	product	product
2n	120	^{43}Ca	^{46}Ti	^{50}Cr
3n	290	^{42}Ca	^{45}Ti	^{49}Cr
np	52	^{43}K	^{46}Sc	^{50}V
2np	118	^{42}K	^{45}Sc	^{49}V
n α	33	^{40}Ar	^{43}Ca	^{47}Ti
2n α	205	^{39}Ar	^{42}Ca	^{46}Ti
2 α	4.5	^{37}S	^{40}Ar	^{44}Ca
2 α n	4.0	^{36}S	^{39}Ar	^{43}Ca
p α	0.9	^{40}Cl	^{43}K	^{47}Sc
np α	0.5	^{39}Cl	^{42}K	^{46}Sc
2p	0.2	^{43}Ar	^{46}Ca	^{50}Ti
2pn	0.0	^{42}Ar	^{45}Ca	^{49}Ti

to the sum of the spectra measured with the three selected Ge detectors. The good quality of particle identification is verified by comparing the spectrum in coincidence with one proton [Fig. 1(b)] with the one in coincidence with one α particle [Fig. 1(d)]. The highest peaks of 107 and 151 keV produced in the 2np channel (^{42}K) are almost absent in the α - γ coincidence spectrum, while the very intense peak of 572 keV produced in the n α channel (^{40}Ar) is very weak in the p- γ coincidence spectrum. However, the accidental events are not negligible, because γ transitions that are produced in single-charged-particle evaporation channels have significant intensities in coincidence spectra with two charged particles [Fig. 1(a) and Fig. 1(c)]. On the other hand, γ rays originated in the two-charged-particle channels are easily identified because their peaks, which are hidden in the one-particle coincidence spectra, become pronounced in the two-particle coincidence spectra. These peaks correspond to known transitions of nuclei produced in 2p, xn2p, p α , or xn p α channels. Representative examples are the 964 and 1542 keV transitions of ^{49}Ti , produced in the 2pn channel of the reaction with the contaminant ^{16}O , and several transitions of ^{40}Cl , produced in the p α channel of the reaction with ^9Be . An exception is the peak of 201 keV, which appears in coincidence with two protons but could not be assigned to any isotope. It must be emphasized that the assignment of most of the peaks belonging to the strongest reaction channels have the support of γ - γ coincidence spectra [see Ref. [10]].

A further analysis was performed by the subtraction of accidental events in the αp - γ and pp - γ spectra. The fraction of accidental events was approximated by the relative intensity of γ rays that should be present only in the one-charged-particle γ spectra, but are also present in the two-charged-particle γ spectra. Using the 107 keV γ ray of ^{42}K and the 1461 keV γ ray of ^{40}Ar , fractions of p- γ and α - γ accidental coincidences in the αp - γ spectrum were calculated. Figure 2(a) shows the 140 to 460 keV region of the αp - γ spectrum subtracted from accidental events. The effect of the subtraction

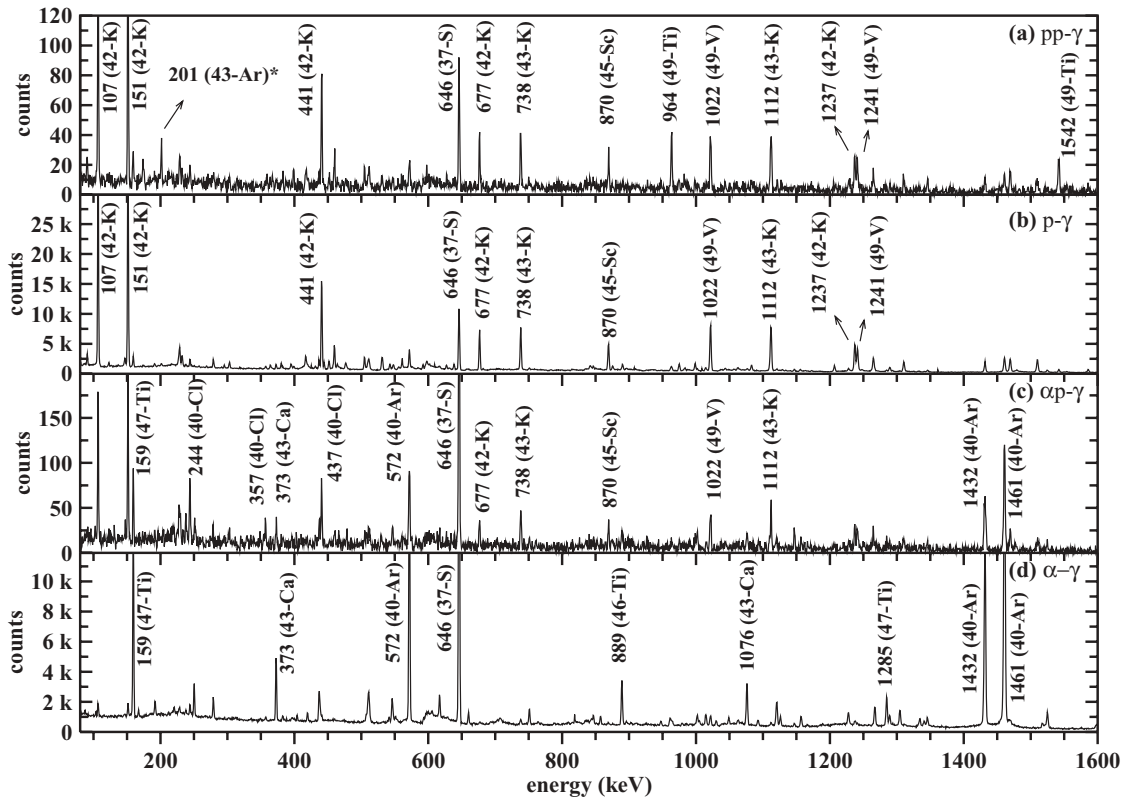


FIG. 1. Spectrum of γ rays in coincidence with (a) two protons, (b) one proton, (c) one proton and one α particle, and (d) one α particle. The asterisk indicates the transition belonging to ^{43}Ar proposed in this work.

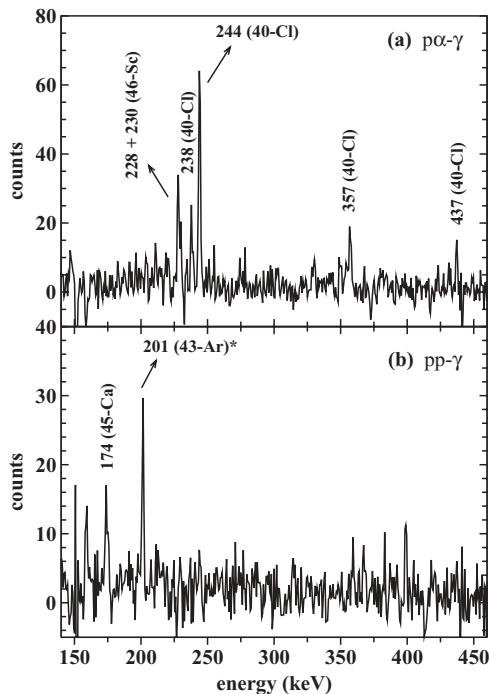


FIG. 2. Low-energy part of the γ -ray spectrum in coincidence with (a) one proton and one α particle and (b) two protons. These spectra were obtained by subtraction of accidental contributions from coincidences with one charged particle.

is evident from the disappearance of peaks of ^{42}K (151 and 441 keV) and ^{47}Ti (159 keV). On the other hand, peaks that originated in channels involving proton and α -particle evaporation, like $^{16}\text{O}(^{36}\text{S}, n p \alpha)^{46}\text{Sc}$ and $^9\text{Be}(^{36}\text{S}, p \alpha)^{40}\text{Cl}$, become more pronounced. The γ rays of ^{40}Cl , in particular, were observed by Balamuth, Hüttmeier, Arrison and [26] and Kozub *et al.* [27] using the same reaction but for beam energy of 100 MeV. According to calculations shown in Table II, at a beam energy of 95 MeV the production of ^{43}Ar is predicted to be approximately one third of the production of ^{40}Cl . Because the results of this type of calculation provide only an indication of the cross-section magnitudes, it is expected that ^{43}Ar is produced in amounts of the same order of ^{40}Cl . If γ rays of ^{43}Ar involving transitions of low-energy levels are present in the pp - γ spectrum, one expects to observe them with intensities that are similar to the ones observed for ^{40}Cl . Figure 2(b) shows the pp - γ spectrum subtracted from accidental events using the same procedure employed for Fig. 2(a). One observes the presence of the 174.17 ± 0.20 keV γ ray, which corresponds to the decay of the first excited state of ^{45}Ca produced in the $^{12}\text{C}(^{36}\text{S}, 2 p n)^{45}\text{Ca}$ reaction, and a second γ ray of 201.27 ± 0.16 keV, which could not be assigned to any isotope listed in Table II. The most reasonable interpretation for this γ ray seems to be the decay of the first excited state to the ground state of ^{43}Ar . The explanation of why other known transitions of ^{43}Ar determined from the β decay of ^{43}Cl were not observed in this experiment is based on two

arguments. The first one refers to the angular momenta of the populated states: the fusion-evaporation reaction populates predominately states of high angular momenta, while the β decay of ^{43}Cl is expected to populate states with $J \leq 5/2$, as discussed before. The second argument is related to the low statistics of the high-energy part of our spectrum: the strongest transitions observed in the β decay of ^{43}Cl have energies of more than 700 keV and would not produce observable events in our spectrum.

In conclusion, theoretical predictions and the results of the present work strongly suggest that the 201 keV γ ray observed in coincidence with two protons correspond to the decay of the first excited state of ^{43}Ar produced in the reaction $^9\text{Be}(^{36}\text{S}, 2p)^{43}\text{Ar}$.

M. Moralles acknowledges the financial support of CAPES, CNPq, and FAPESP.

-
- [1] R. W. Bauer, A. M. Bernstein, G. Heymann, E. P. Lippincott, and N. S. Wall, *Phys. Lett.* **14**, 129 (1965).
- [2] W. J. Gerace and A. M. Green, *Nucl. Phys.* **A93**, 110 (1967).
- [3] E. Caurier, G. Martinez-Pinedo, F. Nowacki, A. Poves, and A. P. Zucker, *Rev. Mod. Phys.* **77**, 427 (2005).
- [4] F. Sarazin, H. Savajols, W. Mittig, F. Nowacki, N. A. Orr, Z. Ren, P. Roussel-Chomaz, G. Auger, D. Baiborodin, A. V. Belozorov, C. Borcea, E. Caurier, Z. Dlouhý, A. Gillibert, A. S. Lalleman, M. Lewitowicz, S. M. Lukyanov, F. de Oliveira, Y. E. Penionzhkevich, D. Ridikas, H. Sakurai, O. Tarasov, and A. de Vismes, *Phys. Rev. Lett.* **84**, 5062 (2000).
- [5] O. Sorlin, Zs. Dombrádi, D. Sohler, F. Azaiez, J. Timár, Y. E. Penionzhkevich, F. Amorini, D. Baiborodin, A. Bauchet, F. Becker, M. Belleguic, C. Borcea, C. Bourgeois, Z. Dlouhy, C. Donzaud, J. Duprat, L. Gaudefroy, D. Guillemaud-Mueller, F. Ibrahim, M. J. Lopez, R. Lucas, S. M. Lukyanov, V. Maslov, J. Mrazek, C. Moore, F. Nowacki, F. Pougheon, M. G. Saint-Laurent, F. Sarazin, J. A. Scarpaci, G. Sletten, M. Stanoiu, C. Stodel, M. Taylor, and C. Theisen, *Eur. Phys. J. A* **22**, 173 (2004).
- [6] N. A. Jelley, K. H. Wilcox, R. B. Weisenmiller, G. J. Wozniak, and J. Cerny, *Phys. Rev. C* **9**, 2067 (1974).
- [7] F. Maréchal, T. Suomijärvi, Y. Blumenfeld, A. Azhari, D. Bazin, J. A. Brown, P. D. Cottle, M. Fauerbach, T. Glasmacher, S. E. Hirzebruch, J. K. Jewell, J. H. Kelley, K. W. Kemper, P. F. Mantica, D. J. Morrissey, L. A. Riley, J. A. Scarpaci, H. Scheit, and M. Steiner, *Phys. Rev. C* **60**, 064623 (1999).
- [8] A. Huck, G. Klotz, A. Knipper, C. Miché, C. Richard-Serre, and G. Walter, in *Proceedings of the 4th International Conference on Nuclei Far from Stability*, Helsingor, Denmark (1981).
- [9] J. A. Winger, P. F. Mantica, and R. M. Ronningen, *Phys. Rev. C* **73**, 044318 (2006).
- [10] M. Moralles, P. Jänker, H. Leitz, K. E. G. Löbner, K. Rudolph, F. J. Schindler, H. G. Thies, T. Winkelmann, P. R. Pascholati, and B. A. Brown, *Phys. Rev. C* **58**, 739 (1998).
- [11] M. Moralles, Ph.D. thesis, Universidade de São Paulo, Brazil, 1994.
- [12] J. A. Cameron and B. Singh, *Nucl. Data Sheets* **92**, 783 (2001).
- [13] T. W. Burrows, *Nucl. Data Sheets* **65**, 1 (1992).
- [14] T. W. Burrows, *Nucl. Data Sheets* **74**, 1 (1995).
- [15] T. W. Burrows, *Nucl. Data Sheets* **76**, 191 (1995).
- [16] H. Xiaolong, *Nucl. Data Sheets* **107**, 2131 (2006).
- [17] H. Junde, *Nucl. Data Sheets* **87**, 507 (1999).
- [18] H. Junde, *Nucl. Data Sheets* **64**, 723 (1991).
- [19] M. R. Bhat, *Nucl. Data Sheets* **85**, 415 (1998).
- [20] E. K. Warburton, *Phys. Rev. C* **44**, 268 (1991).
- [21] D. H. Gloeckner, R. D. Lawson, and F. J. D. Serduke, *Phys. Rev. C* **9**, 2071 (1974).
- [22] A. Huck, G. Klotz, A. Knipper, C. Miché, G. Walter, and C. Richard-Serre, *Phys. Rev. C* **18**, 1803 (1978).
- [23] X. Liang, R. Chapman, F. Haas, K. M. Spohr, P. Bednarczyk, S. M. Campbell, P. J. Dagnall, M. Davison, G. de Angelis, G. Duchène, Th. Kröll, S. Lunardi, S. Naguleswaran, and M. B. Smith, *Phys. Rev. C* **66**, 037301 (2002).
- [24] J. Ollier, R. Chapman, X. Liang, M. Labiche, K. M. Spohr, M. Davison, G. de Angelis, M. Axiotis, T. Kröll, D. R. Napoli, T. Martinez, D. Bazzacco, E. Farnea, S. Lunardi, and A. G. Smith, *Phys. Rev. C* **67**, 024302 (2003).
- [25] F. Pühlhofer, *Nucl. Phys.* **A280**, 267 (1977).
- [26] D. P. Balamuth, U. J. Hüttmeier, and J. W. Arrison, *Phys. Rev. C* **48**, 2648 (1993).
- [27] R. L. Kozub, J. F. Shriner, M. M. Hindi, R. Holzmann, R. V. F. Janssens, T. L. Khoo, W. C. Ma, M. Drigert, U. Garg, and J. J. Kolata, *Phys. Rev. C* **37**, 1791 (1988).