Reduction of the Spin-Orbit Splittings at the $N = 28$ Shell Closure

L. Gaudefroy,[1,2] O. Sorlin,[2,1] D. Beaumel,[1] Y. Blumenfeld,[1] Z. Dombrádi,[3] S. Fortier,[1] S. Franchoo,[1] M. Gélin,[2] J. Gibelin,[1] S. Grévy,[2] F. Hammache,[1] F. Ibrahim,[1] K. W. Kemper,[4] K.-L. Kratz,[5,6] S. M. Lukyanov,[7] C. Monrozeau,[1] L. Nalpas,[8] F. Nowacki,[9] A. N. Ostrowski,[5,6] T. Otsuka,[10] Yu.-E. Penionzhkevich,[7] J. Piekarewicz,[4] E. C. Pollacco,[8] P. Roussel-Chomaz,[2] E. Rich,[1] J. A. Scarpaci,[1] M. G. St. Laurent,[2] D. Sohler,[11] M. Stanoiu,[12] T. Suzuki,[13] E. Tryggestad,[1] and D. Verney[1]

[1]*IPN, IN2P3-CNRS,F- 91406 Orsay Cedex, France*
[2]*GANIL, BP 55027, F-14076 Caen Cedex 5, France*
[3]*Institute of Nuclear Research, H-4001 Debrecen, Pf. 51, Hungary*
[4]*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*
[5]*Institut für Kernchemie, Universität Mainz, D-55128 Mainz, Germany*
[6]*HGF Virtual Institute for Nuclear Structure and Astrophyics (VISTARS), D-55128 Mainz, Germany*
[7]*FLNR/JINR, 141980 Dubna, Moscow Region, Russia*
[8]*CEA-Saclay, DAPNIA-SPhN, F-91191 Gif sur Yvette Cedex, France*
[9]*IReS, Université Louis Pasteur, BP 28, F-67037 Strasbourg Cedex, France*
[10]*Department of Physics, University of Tokyo, Hongo, Bunkyo-ku, Tokyo, 113-0033 Japan*
[11]*Institute of Nuclear Research, H-4001 Debrecen, POB 51, Hungary*
[12]*GSI, D-64291, Darmstadt, Germany*
[13]*Department of Physics, Nihon University, Sakurajosui, Setagaya-ku, Tokyo 156-8550, Japan*

(Received 6 April 2006; published 30 August 2006)

The $N = 28$ shell closure has been investigated *via* the ^{46}Ar$(d, p)^{47}$Ar transfer reaction in inverse kinematics. Energies and spectroscopic factors of the neutron $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ states in ^{47}Ar were determined and compared to those of the ^{49}Ca isotone. We deduced a reduction of the $N = 28$ gap by 330(90) keV and spin-orbit weakenings of $\simeq 10(2)$ and 45(10)% for the f and p states, respectively. Such large variations for the f and p spin-orbit splittings could be accounted for by the proton-neutron tensor force and by the density dependence of the spin-orbit interaction, respectively. This contrasts with the picture of the spin-orbit interaction as a surface term only.

DOI: 10.1103/PhysRevLett.97.092501 PACS numbers: 25.45.Hi, 21.10.Jx, 21.10.Pc, 27.40.+z

In their pioneering works, Goeppert-Mayer and Haxel *et al.* [1] introduced a strong spin-orbit (SO) coupling in the nuclear potential to reproduce the "magic numbers" above 20. Guided by the existence of such a term in atomic physics, they postulated it to be proportional to $-\boldsymbol{\ell} \cdot \mathbf{s} r^{-1} \partial_r V(r)$, $\boldsymbol{\ell}$ and $\mathbf{s}$ being, respectively, the angular momentum and the spin of the considered nucleon and $V(r)$ the central nuclear potential. It is attractive for nucleons having their angular momentum aligned with respect to their spin (denoted as $\ell_\uparrow$) and repulsive in case of antialignment ($\ell_\downarrow$). Since then, a wide consensus has developed that the SO interaction is maximum at the surface and vanishes in the interior of the nucleus where the potential varies slowly. A slight weakening of this interaction is predicted by the relativistic mean field (RMF) models for very neutron-rich nuclei in which the surface diffuseness is greatly increased [2].

Recently, two theoretical predictions have suggested new effects inducing strong SO-like modifications. (i) RMF calculations by Todd-Rutel *et al.* [3] predict a dramatic quenching of the SO splitting between the neutron $p_{1/2}$ and $p_{3/2}$ orbitals in ^{46}Ar and ^{206}Hg arising from the modification of their *central* proton densities. If true, it would contradict the long-standing assumption that the SO interaction is of *surface* nature solely and reinforce the validity of the RMF approach for modeling the SO interaction. (ii) Otsuka *et al.* [4] propose that the proton-neutron tensor interaction could also strongly modify the energies of the $\ell_\uparrow$ and $\ell_\downarrow$ components when specific proton and neutron orbitals are filled.

At the stability line, 28 is the first "magic number" arising from the SO coupling which lowers the $1f_{7/2}$ orbital with respect to the $2p_{3/2}$ one. Recent experimental studies of the neutron-rich $^{40-44}_{16}$S [5–7] nuclei suggested an erosion of the neutron $N = 28$ shell closure from the development of quadrupole deformation. However, such Coulomb excitation and γ-spectroscopy experiments yield only indirect information on shell gaps since they mainly probe the collective states of the nuclei. Transfer reactions, such as (d, p), on the other hand, yield direct information through the measurement of single-particle energies (SPE) and spectroscopic factors (SF) [8].

The present work aims at determining the evolution of the $N = 28$ shell gap and the SO couplings for the p and f orbitals between the ^{49}Ca and ^{47}Ar nuclei. A pure ^{46}Ar radioactive beam of $10.2(1)A \cdot$ MeV was delivered by the SPIRAL facility [9] at a mean intensity of 2×10^4 pps. Mass excess, SPE, and SF have been obtained for ^{47}Ar using the ^{46}Ar$(d, p)^{47}$Ar transfer reaction in inverse kinematics. A stable beam of ^{40}Ar at $10.7(1)A \cdot$ MeV was used in similar experimental conditions for comparison with the study of ^{41}Ar obtained in direct kinematics [10]. This also aimed to validate the energy and efficiency calibrations for the study of ^{47}Ar. The position of the beam (which had an angular dispersion smaller than 2 mrad) on the target was obtained event by event with a resolution (FWHM) of 1 mm using a position-sensitive multiwire proportional chamber (MWPC) [11] placed 11 cm downstream from a 0.38(6) mg/cm^2 thick CD_2 target in which the reaction took place. The MWPC also monitored the beam intensity with an efficiency of 96(4)%. The energy and angle of the reaction protons were measured with the MUST detector array [12] comprising eight highly segmented double-sided Si detectors covering polar angles ranging from 110 to 170° with respect to the beam direction. The transferlike products ^{47}Ar(^{46}Ar) were selected and identified by the SPEG [13] spectrometer in the case of a neutron pickup to bound (unbound) states in ^{47}Ar. The choice of the beam line optics and of the magnetic rigidity limited the transmission of the nuclei, in particular, for transfer to unbound states [14].

The exclusive (inclusive) excitation energy spectrum of ^{47}Ar was constructed using the energy and angle of the reaction protons detected with (without) the ^{47}Ar nucleus in coincidence. The exclusive spectrum of Fig. 1(c) displays (d, p) reaction events only. It was used to ascertain the origin of the peaks observed in the inclusive spectrum which also contained backgrounds arising from the deuteron breakup and reactions with the C target nuclei. The first component was estimated by phase space calculations, whereas the second one was determined in a separate run using a pure C target. They were normalized to the high and low energy tails of the excitation energy spectrum, respectively [see Fig. 1(a)]. After background subtraction, the energy spectrum of Fig. 1(b) was fitted using a sum of 9 Gaussian curves of width $\sigma = 175$ keV whose mean energies are reported in Table I. The Q value of the transfer reaction to the ground state (GS) of ^{47}Ar is $Q = 1.327(80)$ MeV, leading to a mass excess $\Delta m(^{47}\mathrm{Ar}) = -25.20(9)$ MeV. This value differs by 700 keV from that of Ref. [15], where the authors suspected that the GS of ^{47}Ar may not have been discriminated from an important background. The present mass excess value gives rise to an $N = 28$ gap of 4.47(9) MeV in ^{46}Ar, which is 330(90) keV smaller than in ^{48}Ca.

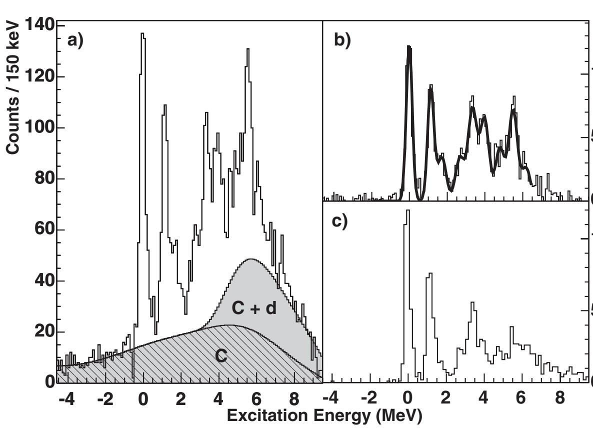

FIG. 1. (a) Inclusive excitation energy spectrum of ^{47}Ar displaying C-induced background (denoted as C), and the sum of the deuteron breakup and C-induced backgrounds ($C + d$). (b) Background subtracted inclusive spectrum fitted by means of 9 Gaussian curves. (c) Exclusive spectrum.

Proton angular distributions are shown in Fig. 2 for the first three states, the group of three peaks between 2.6 and 4 MeV, and the 5.5 MeV state of ^{47}Ar. Distorted wave Born approximation (DWBA) calculations were performed using the DWUCK4 [16] code and two sets of global optical potentials for the entrance [17,18] and exit [19,20] channels of the (d, p) reaction. Figure 2 displays the result obtained with the optical potentials of Ref. [18,19]. These calculations were fitted to the angular distributions to infer the transferred angular momentum ℓ and the vacancy $(2J+1)C^2S$, [C^2S being the spectroscopic factor (SF), J the total spin value] of individual orbitals in ^{47}Ar. The use of different combinations of these four potentials yields a variation of the vacancy values by less than 15%. The first two peaks were attributed to $\ell = 1$ transfer to p states and the third one to an $\ell = 3$ transfer to an f state. The angular distribution of the three peaks around 3.4 MeV [Fig. 2(d)] was reproduced with a combination of $\ell = 3$ and $\ell = 4$ components. The $\ell = 3$ part is most likely contained in the first two peaks as the $\ell = 4$ transfer to the $g_{9/2}$ state is located at $\simeq$4 MeV in other $N = 29$ isotones. An $\ell = 4$ value was unambiguously attributed to the 5500(85) keV state. The ℓ and vacancy values are reported in Table I.

The present set of optical potentials also reproduced (within 10%) the adopted vacancy values of ^{49}Ca when analyzing the angular distributions of Ref. [21]. This point is essential as ^{49}Ca will serve as a reference nucleus, for comparison to ^{47}Ar, for evaluating the evolution of nuclear structure at $N = 28$. Agreement (within 15%) was also found between the $(2J+1)C^2S$ values for ^{41}Ar and those published in Ref. [10].

TABLE I. Experimental energies in keV (E^*), angular momenta (ℓ), vacancies $(2J+1)C^2S$ of the levels identified in ^{47}Ar are compared to shell model calculations.

Experiment			Shell model		
E^*	ℓ	$(2J+1)C^2S$	E^*	J^π	$(2J+1)C^2S$
0	1	2.44(20)	0	$3/2^-$	2.56
1130(75)	1	1.62(12)	1251	$1/2^-$	1.62
1740(95)	3	1.36(16)	1365	$7/2^-$	0.8
2655(80)	3,(4)	1.32(18)	2684	$5/2^-$	0.78
3335(80)	3,(4)	2.58(18)	3266	$5/2^-$	2.76
3985(85)	4,(3)	3.40(40)	⋯	⋯	⋯
4790(95)	⋯	⋯	⋯	⋯	⋯
5500(85)	4	2.10(10)	⋯	⋯	⋯
6200(100)	⋯	⋯	⋯	⋯	⋯

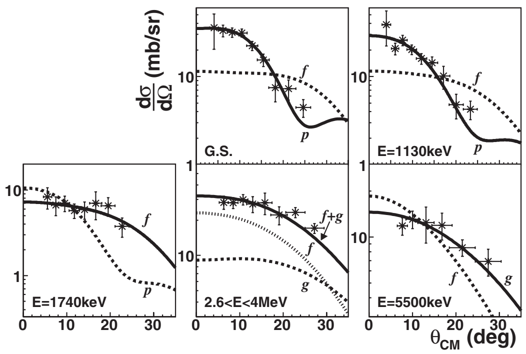

FIG. 2. (a)–(d) Experimental proton angular distribution of states in ^{47}Ar. The curves correspond to DWBA calculations assuming transfer to p, f, and g states.

The structure of ^{47}Ar was calculated in the shell model (SM) framework using the ANTOINE code [22] and the $sdpf$ interaction [23] where the proton (neutron) excitations were restricted to the sd (fp) orbitals. There is a remarkably good agreement between experimental and calculated results (see Table I) for the first five levels, for which total spin values J were attributed. For a closed-shell nucleus, the total vacancy is expected to be equal to $2J + 1$ for the valence orbitals, and 0 for occupied ones. The GS vacancy value [2.44(20)] is compatible with a $p_{3/2}$ state; a $p_{1/2}$ state would have a maximum vacancy value of 2. The missing vacancy value (1.56) of the $p_{3/2}$ GS counterbalances the excess (1.36 instead of 0) of the 1740 keV state, meaning that some of the $f_{7/2}$ neutrons have moved to the $p_{3/2}$ orbital in ^{46}Ar. The first excited state $p_{1/2}$ almost fulfills the sum rule [$(2J + 1)C^2S = 1.62(12)$ instead of 2] as well as in the ^{49}Ca isotone $(2J + 1)C^2S = 1.82(30)$ [21]. We identify about 65% of the strength of the $f_{5/2}$ orbital in the 2.65 and 3.33 MeV states. As the SM calculations reproduce the energy and the summed vacancy values of the $f_{5/2}$ states, the missing part of the $f_{5/2}$ strength has been inferred from calculations. The deduced SPE (defined as the SF-weighted mean energy) is 3450 keV, to be compared to 3104 keV taking into account the observed states only.

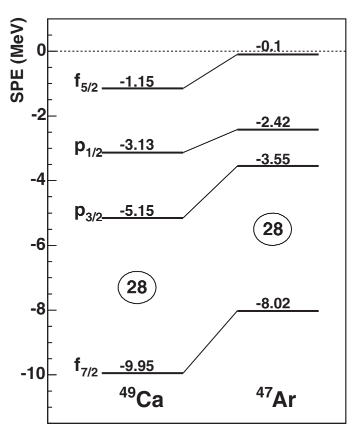

FIG. 3. Neutron single-particle energies (SPE) of the fp orbitals for the ^{47}Ar$_{29}$ and ^{49}Ca$_{29}$ nuclei (see text for details).

Figure 3 displays the experimental SPE of the $f_{7/2}$ and $f_{5/2}$ orbitals and the energy of the first $p_{3/2}$ and $p_{1/2}$ states in ^{49}Ca and ^{47}Ar. In addition to the reduction of the $N = 28$ gap, the f and p SO splittings have been reduced by about 875(130) keV and 890(120) keV, respectively, between ^{49}Ca and ^{47}Ar. Mean field (MF) calculations with the finite-range ($D1S$) [24] interactions predict correctly the weakened $N = 28$ shell gap but do not find any SO variation. Zero-range calculations using Skyrme forces reproduce neither. The observed asymmetric variations of the $\ell_{\uparrow,\downarrow}$ orbitals can be explained by a weakened $\boldsymbol{l} \cdot \mathbf{s}$ interaction, which increases (decreases) the energy of the $\ell_\uparrow$ ($\ell_\downarrow$) orbitals with respect to MF calculations. Such surprising reductions cannot be attributed to a modification of the surface diffuseness between ^{49}Ca and ^{47}Ar which is expected to be smaller than 5%. Therefore, other effects must be involved.

The present variations of the $N = 28$ shell gap (δG) and of the SO splittings (δSO) between ^{49}Ca and ^{47}Ar could be caused by the removal of 2 protons from the $d_{3/2}$ and $s_{1/2}$ orbitals. As these orbitals are quasidegenerate in ^{48}Ca [25] protons are removed equiprobably, i.e., 1.33 from $d_{3/2}$ and 0.66 from $s_{1/2}$. Similar values are obtained with SM calculations. Because of the proton-neutron interaction, the removal of protons induces a differential energy change of the neutron orbitals. This interaction acts on the $f_{7/2}$ and $p_{3/2}$ orbitals to modify the size of the $N = 28$ gap and on the $\ell_\downarrow$ and $\ell_\uparrow$ orbitals to reduce the SO splittings. A *major* contribution of these changes is due to the monopole part of the proton-neutron matrix elements $V^{\rm pn}$ which is defined in Ref. [4]. As ^{46}Ar can be considered as a good semimagic nucleus [26] the remaining nuclear correlations, as quadrupole ones, will be neglected in the following.

The reduction of the $N = 28$ shell gap δG between ^{49}Ca and ^{47}Ar can be written in the first order as:

$$\delta G = 1.33(V^{\rm pn}_{d_{3/2}p_{3/2}} - V^{\rm pn}_{d_{3/2}f_{7/2}}) + 0.66(V^{\rm pn}_{s_{1/2}p_{3/2}} - V^{\rm pn}_{s_{1/2}f_{7/2}}).$$

These matrix element differences can be determined from the $N = 21$ isotones in which the d and s proton orbitals are well separated. The removal of 2 protons from the $d_{3/2}$ orbital between ^{41}Ca and ^{39}Ar gives an energy of $2(V^{\rm pn}_{d_{3/2}p_{3/2}} - V^{\rm pn}_{d_{3/2}f_{7/2}})$ which amounts to 675 keV. Similarly the 2 protons removed from the $s_{1/2}$ orbital between ^{37}S and ^{35}Si induce an energy change of $2(V^{\rm pn}_{s_{1/2}p_{3/2}} - V^{\rm pn}_{s_{1/2}f_{7/2}})$ equal to -264 keV. By using these values of matrix element differences, we expect that $\delta G =$ 362 keV. The excellent agreement with the experimental value, 330(90) keV, validates the assumptions on the number of removed s and d protons between ^{49}Ca and ^{47}Ar and on the small amount of correlations. The removal of additional protons would gradually reduce the size of the spherical $N = 28$ gap, eventually by about 1 MeV in ^{42}Si. This would imply a disruption of the $N = 28$ shell closure through particle-hole excitations, which are already seen in ^{47}Ar by the partial vacancy value of the $p_{3/2}$ orbital.

The SO reductions from ^{49}Ca to ^{47}Ar can be derived similarly to the variation of the shell gap δG, leading to a generic expression for the p and f states:

$$\delta \mathrm{SO} = 1.33(V^{\mathrm{pn}}_{d_{3/2}\ell_{\downarrow}} - V^{\mathrm{pn}}_{d_{3/2}\ell_{\uparrow}}) + 0.66(V^{\mathrm{pn}}_{s_{1/2}\ell_{\downarrow}} - V^{\mathrm{pn}}_{s_{1/2}\ell_{\uparrow}}).$$

The (spin-independent) central part of these proton-neutron interactions, which is the largest fraction of V^{pn} matrix elements, does not come into play for the SO reduction as it cancels out in the previous equation. Residual parts of the interaction, denoted by $\tilde{V}^{\mathrm{pn}}$, such as the tensor [4] and/or density-dependent proton-neutron forces [3], not taken into account in the MF calculations, could explain such variations. The tensor interaction $\tilde{V}^{\mathrm{pn}}_{d_{3/2}\ell_{\downarrow\uparrow}}$ depends on the proton(π)-neutron(ν) relative spin-angular momentum orientations. It has the largest contribution for the $\nu 1f_{\downarrow\uparrow}$ orbitals because $\pi 1d_{3/2}$ and $\nu 1f_{\downarrow\uparrow}$ wave functions exhibit the same number of nodes, contrary to $\pi 1d_{3/2}$ and $\nu 2p_{\downarrow\uparrow}$ ones. The tensor force does not contribute to $\tilde{V}^{\mathrm{pn}}_{s_{1/2}\ell_{\downarrow\uparrow}}$ as the $s_{1/2}$ orbital has no preferred orientation. The $\tilde{V}^{\mathrm{pn}}_{s_{1/2}\ell_{\downarrow\uparrow}}$ interaction is proportional to the derivative of the scalar and vector densities in the interior of the nucleus, where the $s_{1/2}$ protons are located [3]. This has its largest impact on the SO splitting of the p orbitals, as the large centrifugal barrier precludes neutrons located in the f orbitals from probing the nuclear interior. We therefore assume that deviations of the SO splitting from the MF contribution are *mainly* due to proton-neutron tensor interaction and density-dependent terms for the f and p states, respectively.

For the f orbitals these deviations are expressed as:

$$\delta \mathrm{SO} = 1.33(\tilde{V}^{\mathrm{pn}}_{d_{3/2}f_{5/2}} - \tilde{V}^{\mathrm{pn}}_{d_{3/2}f_{7/2}}).$$

The tensor part of the matrix elements $\tilde{V}^{\mathrm{pn}}_{d_{3/2}f_{\downarrow\uparrow}}$ has been calculated to be $+280$ keV and -210 keV for the $f_{5/2}$ and $f_{7/2}$ orbitals, respectively. The SO splitting is expected to be reduced by about 650 keV, to be compared to the experimental value of 875(130) keV. This relatively good agreement demonstrates that the reduction of the $f_{5/2} - f_{7/2}$ SO splitting can be explained by the proton(d)-neutron(f) tensor force almost solely. We should, however, bear in mind that we cannot firmly establish the intensity of this force as we have not detected the full strength of the $f_{5/2}$ orbital.

The removal of 0.66 proton from the $s_{1/2}$ shell between the ^{48}Ca and ^{46}Ar nuclei reduces the charge density in the interior of the nucleus by about 20%. According to the RMF calculations by Todd-Rutel *et al.* [3] it induces a $p_{1/2} - p_{3/2}$ SO reduction of 30%. This value almost agrees with the experimental data in which a variation of 45(10)% is found, favoring the natural treatment of SO in the relativistic approach. Such a sensitivity to the nuclear interior is not seen for the f orbitals for which a variation of at most 5% in the SO splitting is predicted, independent of the proton occupancy of the $s_{1/2}$ orbital.

In summary, the neutron single-particle energies $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ have been determined in ^{47}Ar and compared to the ^{49}Ca isotone. A reduction of the $N = 28$ gap by 330(90) keV is found. Reduction of the SO splittings of $\simeq$10(2) and 45(10)% have been observed for the f and p orbitals, respectively. Such large variations could be accounted for by the proton-neutron tensor interaction [4] for the f states, the density dependence of the SO interaction in the interior of the nucleus [3] for the p states, and by possible correlations beyond the nuclear mean field. The two first mechanisms, experimentally surmised for the first time, are seen to induce dramatic variations of the SO splittings between neighboring nuclei. Hence, when moving through the nuclear chart away from stability, structural changes may be much more rapid than expected solely from the variation of the surface diffuseness of the nuclei.

[1] M. Goeppert-Mayer, Phys. Rev. **75**, 1969 (1949); O. Haxel *et al.*, Phys. Rev. **75**, 1766 (1949).
[2] G. A. Lalazissis *et al.*, Phys. Lett. B **418**, 7 (1998).
[3] B. G. Todd-Rutel *et al.*, Phys. Rev. C **69**, 021301(R) (2004).
[4] T. Otsuka *et al.*, Phys. Rev. Lett. **95**, 232502 (2005).
[5] H. Scheit *et al.*, Phys. Rev. Lett. **77**, 3967 (1996).
[6] T. Glasmacher *et al.*, Phys. Lett. B **395**, 163 (1997).
[7] D. Sohler *et al.*, Phys. Rev. C **66**, 054302 (2002).
[8] J. P. Schiffer *et al.*, Phys. Rev. Lett. **92**, 162501 (2004).
[9] A. C. C. Villari *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 31 (2003).
[10] S. Sen *et al.*, Nucl. Phys. A **250**, 45 (1975).
[11] S. Ottini-Hustache *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **431**, 476 (1999).
[12] Y. Blumenfeld *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **421**, 471 (1999).
[13] L. Bianchi *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **276**, 509 (1989).
[14] L. Gaudefroy *et al.*, Eur. Phys. J. A **27**, 309 (2006).
[15] W. Benenson *et al.*, Phys. Lett. **162B**, 87 (1985).
[16] P. D. Kunz, University of Colorado (unpublished).
[17] W. W. Daehnick *et al.*, Phys. Rev. C **21**, 2253 (1980).
[18] G. L. Wales and R. C. Johnson, Nucl. Phys. **A274**, 168 (1976).
[19] R. L. Varner *et al.*, Phys. Rep. **201**, 57 (1991).
[20] C. M. Perey and F. G. Perey, ADNDT **17**, 1 (1976).
[21] R. Abegg *et al.*, Nucl. Phys. **A303**, 121 (1978); Y. Uozumi *et al.*, Nucl. Phys. **A576**, 123 (1994).
[22] E. Caurier, ANTOINE code (IReS, Strasbourg 1989–2002); E. Caurier and F. Nowacki, Acta Phys. Pol. B **30**, 705 (1999).
[23] S. Nummela *et al.*, Phys. Rev. C **63**, 044316 (2001).
[24] S. Péru *et al.*, Eur. Phys. J. A **9**, 35 (2000).
[25] P. D. Cottle *et al.*, Phys. Rev. C **58**, 3761 (1998).
[26] A. Gade *et al.*, Phys. Rev. C **71**, 051301(R) (2005).