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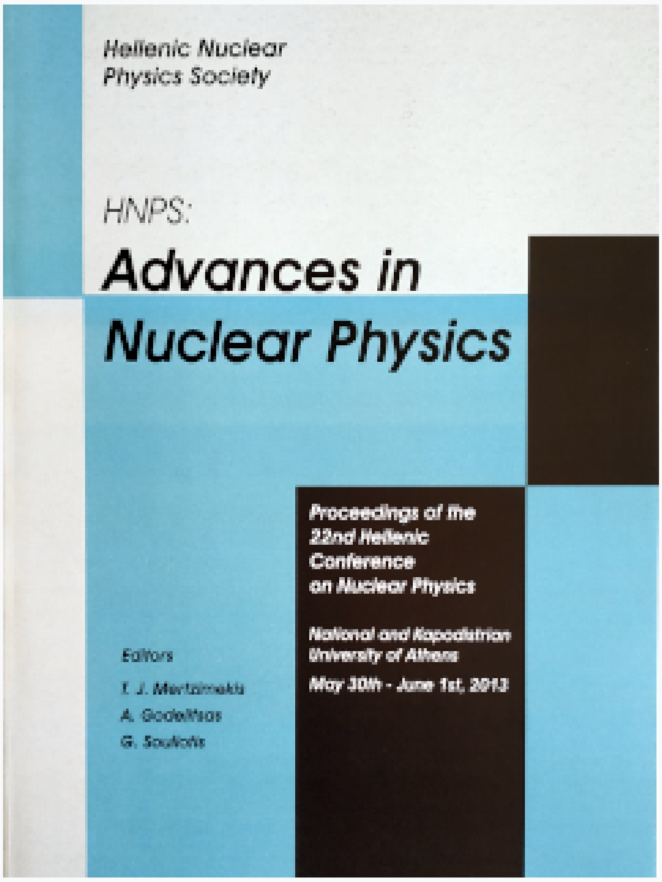

Systematic Study of Neutron-Rich Rare Isotope Production in Peripheral Heavy-Ion Collisions at Beam Energies 15–25 MeV/nucleon

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Systematic Study of Neutron-Rich Rare Isotope Production in Peripheral Heavy-Ion Collisions at Beam Energies 15–25 MeV/nucleon

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Abstract

The production cross sections of projectile-like fragments from collisions of ^{86}Kr projectiles with ^{64,58}Ni and ^{124,112}Sn targets at 15 and 25 MeV/nucleon are studied systematically with emphasis on the neutron-rich isotopes. Our recent experimental data are compared with calculations for the above collisions employing a hybrid approach. The dynamical stage of the projectile-target interaction was described with either the phenomenological deep-inelastic transfer (DIT) model or with the the microscopic constrained molecular dynamics model (CoMD). Subsequently, for the de-excitation of the projectile-like fragments, the statistical multifragmentation model (SMM) or the binary-decay code GEMINI were employed. An overall good agreement with the experimental results was obtained. We point out that our current understanding of the reaction mechanism at beam energies below the Fermi energy suggests that such nuclear reactions, involving peripheral nucleon exchange, can be exploited as a novel route to access extremely neutron-rich rare isotopes toward the r-process path and the hard-to-reach neutron drip-line. For this purpose, we believe that the use of re-accelerated neutron-rich radioactive beams may offer unique and exciting opportunities toward unexplored regions of the nuclear landscape.

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1. Introduction

The study of the nuclear landscape toward the astrophysical r-process path and the neutron drip-line have recently received special attention by the nuclear physics community (see, e.g., [1, 2] and references therein). Closely related to this effort is the efficient production of very neutron-rich nuclides which constitutes a central issue in current and future rare isotope beam facilities (see, e.g., [3–11]).

Neutron-rich nuclides are mainly produced by spallation, fission and projectile fragmentation [12]. Spallation is an efficient mechanism to produce rare isotopes for ISOL-type techniques [13]. Projectile fission is appropriate in the region of light and heavy fission fragments (see, e.g., [14] for recent efforts on ^{238}U projectile fission). Finally, projectile fragmentation offers a universal approach to produce exotic nuclei at beam energies above 100 MeV/nucleon (see, e.g., [15, 16]). This approach is, nevertheless, based on the fact that optimum neutron excess in the fragments is achieved by stripping the maximum possible number of protons (and a minimum possible number of neutrons).

To reach a high neutron-excess in the products, apart from proton stripping, it may be necessary to capture neutrons from the target. Such a possibility is offered by reactions of nucleon exchange at beam energies from the Coulomb barrier [17, 18] to the Fermi energy (20–40 MeV/nucleon) [19, 20]. Detailed experimental data in this broad energy range are scarce at present [18, 21, 22]. In multinucleon transfer and deep-inelastic reactions near the Coulomb barrier [18], the low velocities of the fragments and the wide angular and ionic charge state distributions may limit the collection efficiency for the most neutron-rich products. The reactions in the Fermi energy regime combine the advantages of both low-energy (i.e., near

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and above the Coulomb barrier) and high-energy (i.e., above 100 MeV/nucleon) reactions. At this energy, the synergy of the projectile and the target enhances the N/Z of the fragments, while the velocities are high enough to allow efficient in-flight collection and separation.

Our initial experimental studies of projectile fragments from 25 MeV/nucleon reactions of ^{86}Kr on ^{64}Ni [19] and ^{124}Sn [20] indicated substantial production of neutron-rich fragments. Motivated by recent developments in several facilities that will offer either very intense primary beams [5, 8] at this energy range or re-accelerated rare isotope beams [4, 5, 8, 9], we continued our experimental studies at 15 MeV/nucleon [23]. In this work, after a short overview of the experimental measurements, we present a systematic calculation of the production cross sections based on either the phenomenological deep-inelastic transfer (DIT) model or the microscopic constrained molecular dynamics model (CoMD). The good description of the experimental results with the CoMD code, as well as, with a properly modified version of the DIT code, suggest the possibility of using the present theoretical framework for the prediction of exotic nuclei employing radioactive beams that will soon be available in upcoming facilities. As an example, we present the production cros sections and the rates of neutron-rich nuclei using a radioactive beam of ^{92}Kr at 15 MeV/nucleon.

2. Outline of the experimental method

A detailed presentation of the experimental results appear in [23] in which the mass spectrometric measurements of production cross sections of neutron-rich projectile fragments from the reactions of a 15 MeV/nucleon ^{86}Kr beam with ^{64}Ni, ^{58}Ni and ^{124}Sn, ^{112}Sn targets are given. We also note that the experimental results of the 25MeV/nucleon reactions and the relevant procedures are described in detail in our articles [19–22]. We briefly mention that the use of the high-resolution recoil separator MARS in combination with standard Bρ–ΔE–E (magnetic rigidity, energy-loss, residual-energy) and time-of-flight techniques provided high-resolution information on the atomic number Z, the ionic charge q, the mass number A and the velocity distributions of the projectile fragments. Summation over q provided the yield distributions with respect to Z, A and velocity from which production cross sections were extracted. The measurements were performed inside the grazing angles of the corresponding reactions in a wide Bρ window that enabled efficient collection of heavy projectile residues produced in a broad range of energy damping, from quasielastic to deep-inelastic collisions.

3. Results and Comparisons

In Fig. 1 we present the experimental mass distributions of elements with Z = 35–30 of the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni [23] compared to the calculations with the CoMD code [24, 25] combined with the de-excitation codes SMM [26] (solid line) and GEMINI [27] (dotted line), used for the de-excitation of the quasiprojectiles emerging after the dynamical stage. The results of the calculations are in overall agreement with the experimental data especially for the isotopes close to the projectile with Z = 35–32. We also observe that the microscopic CoMD model is able to describe even the rare neutron-rich products from this reaction that are the products for our main interest. The overestimation of the cross sections for the products with Z = 31,30 is related to issues of the excitation energy as calculated by CoMD and are currently under further investigation.

Subsequently, motivated by our previous studies [19, 20], we employed Tassan-Got's phenomenological model of deep inelastic transfer (DIT) [28] coupled with SMM [26] or GEMINI [27]. The results of this standard version of DIT were not satisfactory. We thus proceeded with our modified version of the DIT model (DITm) [29] in which we have introduced a detailed description of the nuclear surface and the neutron skin of the involved nuclei. In Fig 2, we present the experimental mass distributions of elements with Z = 35–30 of the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni [23] and compare them to the results of the modified DIT (DITm) calculations (dotted line) and to the results of the CoMD calculations (solid line) using SMM as the de-excitation code. From this figure we observe that the modified DIT code describes the experimental results rather well at these beam energies. Moreover, it can better describe the products further away from the projectile, that cannot be well described by CoMD, as we mentioned previously.

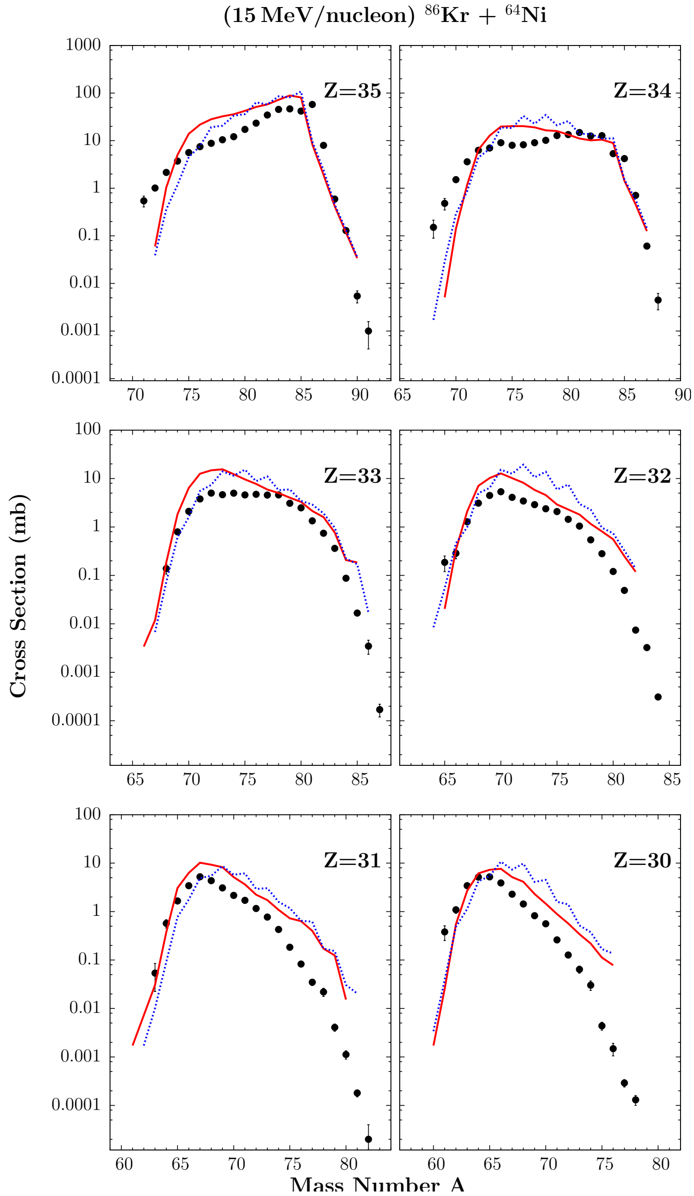

Figure 1: (Color online) Experimental mass distributions (symbols) of elements with Z = 35–30 observed in the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni [23] compared to the results of CoMD/SMM calculations (solid red line) and CoMD/GEMINI calculations (dotted blue line).

We mention that a thorough comparison of the data with the calculations for the 15 MeV/nucleon, as well as the 25 MeV/nucleon reactions has been performed that will appear in [30]. After this systematic comparison of the calulations with the experimental data of the stable ^{86}Kr beam, we proceeded to investigate what results we would obtain by using a neutron-rich radioactive beam, such as ^{92}Kr. In Fig. 3 we present again the experimental mass distributions (black symbols) of the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni, the CoMD/SMM calculations for this reaction (solid line) and, furthermore, the CoMD/SMM calculations for the reaction ^{92}Kr(15 MeV/nucleon)+^{64}Ni (dotted line). We observe that by using the neutron-rich radioactive beam of ^{92}Kr, we obtain more neutron-rich products. This is primarily true for the isotopes near the projectile. We point out that, e.g., for bromine (Z=35), isotopes that have up to 15 more neutrons (A

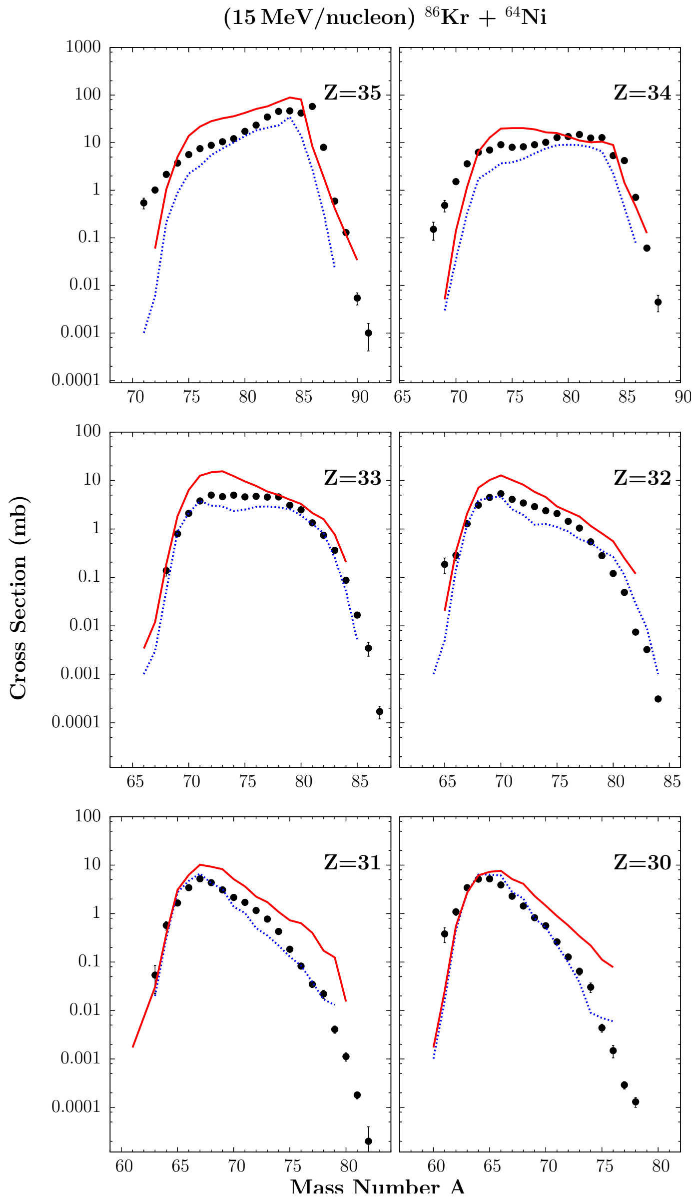

Figure 2: (Color online) Experimental mass distributions (symbols) of elements with Z = 35–30 observed in the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni [23] compared to the results of CoMD/SMM calculations (solid red line) and DITm/SMM calculations (dotted blue line).

= 96) than the corresponding stable isotope (A = 81) can be obtained. This observation indicates that by using neutron-rich radioactive beams, and through the mechanism of peripheral multinucleon transfer, we will have the possibility to produce even more neutron-rich nuclides toward neutron drip line.

In Table I, we present the predicted cross-sections and the production rates of neutron rich isotopes from the reaction of the radioactive beam of ^{92}Kr (15 MeV/nucleon) with ^{64}Ni. For the rate calculations, the ^{92}Kr beam with intensity 0.5 pnA (3.1×10^9 particles/sec) is assumed to interact with a ^{64}Ni target of 20 mg/cm^2 thickness. We see that we have the possibility to produce extremely neutron-rich isotopes in these energies with the use of re-accelerated radioactive beams, such as ^{92}Kr, that will be available in upcoming rare-isotope facilities (e.g. [10, 11]).

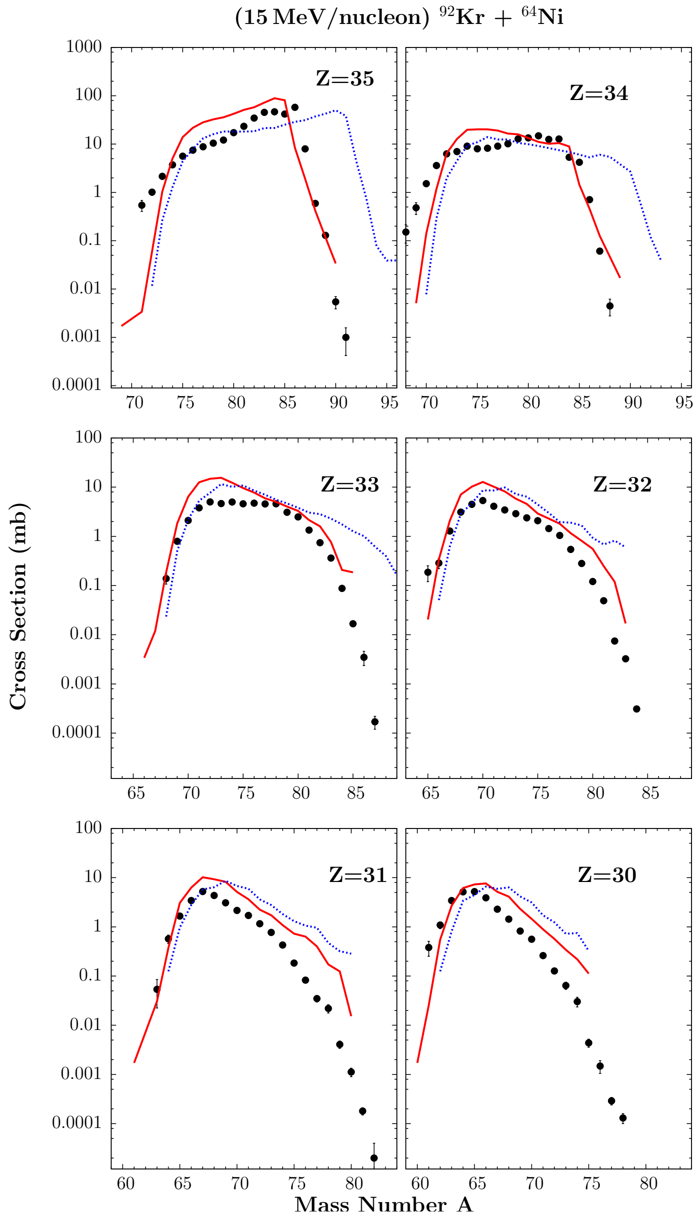

Figure 3: (Color online) Experimental mass distributions (symbols) of elements with Z = 35–30 observed in the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni [23], calculations CoMD/SMM for the reaction ^{86}Kr(15 MeV/nucleon)+^{64}Ni (solid red line), calculations CoMD/SMM for the reaction ^{92}Kr(15 MeV/nucleon)+^{64}Ni (dotted blue line).

4. Summary and Conclusions

In the present work, we perfomed a systematic study of the production cross sections of projectile-like fragments from collisions of ^{86}Kr projectiles with ^{64,58}Ni and ^{124,112}Sn targets at 15 and 25 MeV/nucleon with emphasis on the neutron-rich isotopes. Our experimental data were compared with systematic calculations employing a two-step approach. The calculations for the dynamical stage of the projectile-target interaction were carried out using either the phenomenological deep-inelastic transfer (DIT) model or the the microscopic constrained molecular dynamics model (CoMD). For the de-excitation of the projectile-like fragments, the statistical multifragmentation model (SMM) or the binary-decay code GEMINI were employed. An overall

Table 1: Cross sections and rate estimates (last column) of very neutron-rich isotopes from the reaction ^{92}Kr (15 MeV/nucleon) + ^{64}Ni. For the rates, a radioactive beam of ^{92}Kr with intensity 0.5 pnA (3.1×10^9 particles/sec) is assumed to interact with a ^{64}Ni target of 20 mg/cm^2 thickness.

Rare Isotope	Reaction Channel	Cross Section (mb)	Rate (sec^{-1})
^{93}Kr	-0p+1n	18.8	1.1×10^4
^{94}Kr	-0p+2n	2.3	1.3×10^3
^{95}Kr	-0p+3n	0.63	3.8×10^2
^{96}Kr	-0p+4n	0.2	1.2×10^2
^{92}Br	-1p+1n	4.5	2.7×10^3
^{93}Br	-1p+2n	0.75	4.5×10^2
^{94}Br	-1p+3n	0.078	47
^{95}Br	-1p+4n	0.040	23
^{96}Br	-1p+5n	0.008	5
^{90}Se	-2p+0n	2.7	1.6×10^3
^{91}Se	-2p+1n	0.6	3.5×10^2
^{92}Se	-2p+2n	0.12	70
^{93}Se	-2p+3n	0.04	23

good agreement with the experimental results was observed. With the current understanding of the reaction mechanism at these beam energies, we suggest that these nuclear reactions, involving peripheral nucleon exchange, be exploited as an efficient route to access neutron-rich rare isotopes toward the r-process path and the neutron drip-line. Therefore, future experiments in several accelerator facilities [12] can be planned that will enable a variety of nuclear structure and nuclear reaction studies in unexplored regions of the nuclear chart.

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[1] J. Erler et al, Nature **486**, 509 (2011).
[2] J. Äystö, W. Nazarewicz, M. Pfützner, C. Signorini, eds, Proceedings of the Fifth International Conference on Exotic Nuclei and Atomic Masses (ENAM'08), Ryn, Poland, September 7–13 (2008); Eur. Phys. J. A **42** (2009).
[3] D. F. Geesaman, C. K. Gelbke, R. V. F. Janssens, B. M. Sherrill, Ann. Rev. Nucl. Part. Sci. **56**, 53 (2006)
[4] FRIB main page: www.frib.msu.edu
[5] GANIL main page: www.ganil.fr
[6] GSI main page: www.gsi.de
[7] RIBF main page: www.rarf.riken.go.jp/Eng/facilities/RIBF.html
[8] ATLAS main page: www.phy.anl.gov/atlas/facility/index.html
[9] EURISOL main page: www.eurisol.org
[10] RISP main page: www.risp.re.kr/eng/pMainPage.do
[11] K. Tshoo, Y. K. Kim, Y. K. Kwon et al, Nucl. Instrum. Meth. B **317**, 242 (2013).
[12] Y. Blumenfeld, T. Nilsson and P. Van Duppen, Phys. Scr. T152 014023 (2013).
[13] A. Kelić, M. V. Ricciardi, K. -H. Schmidt, BgNS Transactions, **13**, 98 (2009).
[14] H. Alvarez-Pol et al., Phys. Rev. C **82**, 041602 (2010).
[15] O. B. Tarasov et al., Phys. Rev. C **80**, 034609 (2009).
[16] S. Lukyanov et al., Phys. Rev. C **80**, 014609 (2009).
[17] V. V. Volkov, Phys. Rep. **44**, 93 (1978).
[18] L. Corradi, G. Pollarolo, S. Szilner, J. Phys. G **36**, 113101 (2009).

[19] G. A. Souliotis et al., Phys. Lett. B **543**, 163 (2002).
[20] G. A. Souliotis et al., Phys. Rev. Lett. **91**, 022701 (2003).
[21] G. A. Souliotis et al., Nucl. Instrum. Methods **B 204** 166 (2003).
[22] G. A. Souliotis et al., Nucl. Instum. Methods **B 266**, 4692 (2008).
[23] G. A. Souliotis et al., Phys. Rev. C **84**, 064607 (2011).
[24] M. Papa et al., Phys. Rev. **C 64**, 024612 (2001).
[25] M. Papa et al, J. Comp. Phys. **208**, 403 (2005).
[26] J. Bondorf et al., Phys. Rep. **257**, 133 (1995).
[27] R. Charity et al., Nucl. Phys. **A 483**, 391 (1988); Phys. Rev. **C 58**, 1073 (1998).
[28] L. Tassan-Got and C. Stephan, Nucl. Phys. **A 524**, 121 (1991).
[29] M. Veselsky and G.A. Souliotis, Nucl. Phys. **A 765**, 252 (2006).
[30] P.N. Fountas, G.A. Souliotis and M. Veselsky, to be submitted in Phys. Rev. C (2014).