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Anomalous behaviour of matter radii of proton-rich Ga, Ge, As, Se and Br nuclei

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Abstract. Proton-rich isotopes of Ga, Ge, As, Se and Br had their total reaction cross-sections (σ_R) measured. Root-mean-squared matter radii were determined from Glauber model calculations, which reproduced the experimental σ_R values. For all isotopic series a decrease of the $r_{\rm rms}$ with increasing neutron number and a correlation with deformation was observed.

PACS. 21.10.Gv Mass and neutron distributions – 25.60.Dz Interaction and reaction cross-sections

1 Introduction

Reaction cross-section measurements have been a very useful tool for the determination of nuclear matter radii. Since the discovery of extended neutron distributions [1], also called neutron halo, in light neutron dripline nuclei using reaction cross-section measurements, the method has gained even more interest. Effective root-mean-squared matter radii could be deduced from these measurements for unstable p and s-d shell nuclei [2]. The matter and charge radii of the Na and Ar isotopic chains were compared, and the increase of neutron skin with isospin was observed for the Na isotopes [3]. For the Ar isotopic chain [4] the increase of the proton skin thickness was observed with decreasing neutron number. Recent charge radius measurements [5] of the neutron-deficient Ti isotopes also show radial increase with decreasing neutron number. We have recently measured the root-mean-squared matter radii of proton-rich isotopes of Ga, Ge, As, Se and Br [6]. The radii were obtained from the reaction cross-sections σ_R measured at intermediate energies (50–60 A MeV), where the reaction cross-section is higher and thus more sensitive to surface phenomena as skin or halo. In this contribution we compare the matter radii of the proton-rich isotopes with nuclear structure information about these nuclei and also with existing proton radius values of stable isotopes.

2 Experimental method

The radioactive ions were produced at GANIL (Grand Accélérateur National d'Ions Lourds, Caen, France), through the fragmentation of a 73 A MeV primary beam of ^{78}Kr, hitting a 90 mg/cm^2 thick $^{\rm nat}$Ni target. Details

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of the experiment were described in a recent paper [6]. The reaction products, a cocktail of many different secondary beams, were delivered after a first selection in the α-spectrometer, to the high-resolution energy-loss magnetic spectrometer SPEG. They were detected in the focal plane of SPEG by a cooled silicon telescope formed by three transmission detectors followed by a thick Si(Li) detector, where all ions of interest were stopped. Particle identification was obtained by combining the energy-loss measurement in the first Si detector with the time-of-flight information obtained between a fast micro-channel plate (MCP) detector located after the α-spectrometer and the second Si detector. The reaction target was the whole Si telescope behind the first thin ΔE detector, used for particle identification.

The spectrum of the energy deposited in the target/detector system has a large peak corresponding to events that have not undergone any nuclear reaction and a low energy tail due to nuclear reactions with energy loss ($Q \leq 0$) in any of the three Si target/detectors. We used two methods in our measurement: one based only on reactions in the second thin ΔE detector at a well defined energy E_0, thus allowing the determination of the reaction cross-section at this energy. The other method is based on reactions in any of the three Si target/detectors. In this case the energy integrated average reaction cross-section is determined.

3 Data analysis

The reaction cross-section was obtained from the reaction probability (ratio between the number of reaction events in the low energy tail and the total number of events in the energy spectrum) for the thin ΔE detector and also for the whole target/detector system. A phenomenological formula was developed by Kox *et al.* [7], which relates the reaction cross-section σ_R with a reduced strong absorption radius r_0.

For stable nuclei the formula gives a good description of a wide variety of target and projectile systems at different energies with a constant value of $r_0 = 1.1$ fm [7].

We have deduced two independent sets of values for the reduced strong absorption radii r_0 using the reaction cross-sections measured in the thin ΔE detector and the energy integrated reaction cross-sections measured in the whole target/telescope system. The agreement between the r_0 values obtained from both methods is good within the uncertainties, indicating that the Kox formula is also adequate to describe σ_R for these radioactive nuclei. In order to improve the accuracy, the weighted average values of the reduced strong absorption radii r_0 were used together with the Kox formula to obtain reaction cross-sections at energy E_0.

3.1 Glauber model calculations

We used the Glauber theory in the optical limit to deduce r.m.s. matter radii from the measured σ_R reaction cross-

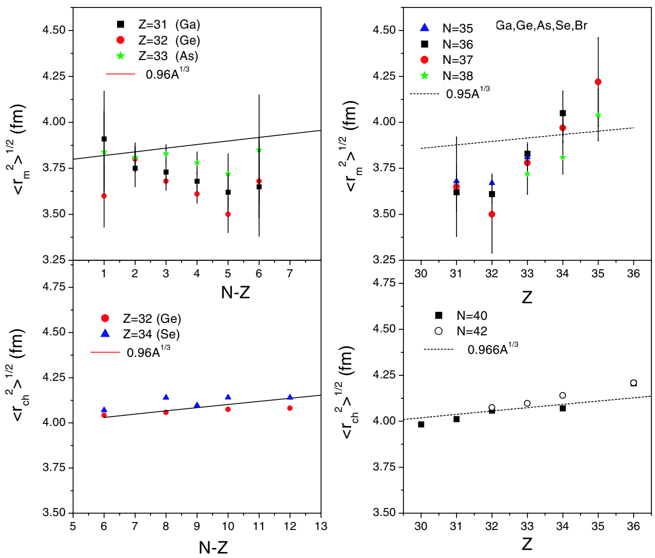

Fig. 1. On the left panel the matter radii of different isotopic chains are compared as a function of $N - Z$, while on the right panel the matter radii of isotonic series are compared as a function of Z. On the lower panels the same comparison is performed for stable isotopes, where the usual $A^{1/3}$ behaviour can be observed.

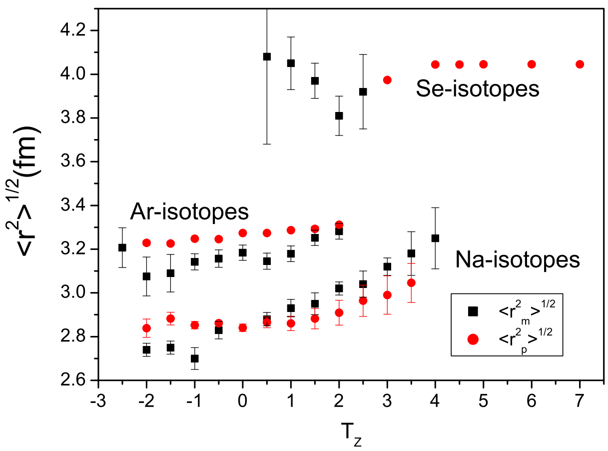

Fig. 2. Comparison between r.m.s matter radii together with the point proton r.m.s. radii calculated from r.m.s. charge radii for the Na and Ar isotopic chains and for our Se data, as a function of T_Z.

sections. In this approximation the elementary N-N cross-section is folded over the static point proton and neutron density distributions of the projectile and target nuclei. The point proton distributions can be deduced from measured charge distributions, deconvoluting the proton size or by using the formula [3] $\langle r_\mathrm{p}^2 \rangle = \langle r_\mathrm{ch}^2 \rangle - \langle r_\mathrm{chp}^2 \rangle$, where the more recent value for the r.m.s. charge radius of the proton $\langle r_\mathrm{chp}^2 \rangle^{1/2} = 0.8791(88)$ fm [8] was used. For the stable ^{28}Si target nucleus ($N = Z$) equal proton and neutron distributions were assumed and were determined by the procedure indicated above. However, for the proton-rich radioactive projectiles of this work neither the charge nor the proton or neutron distributions are known.

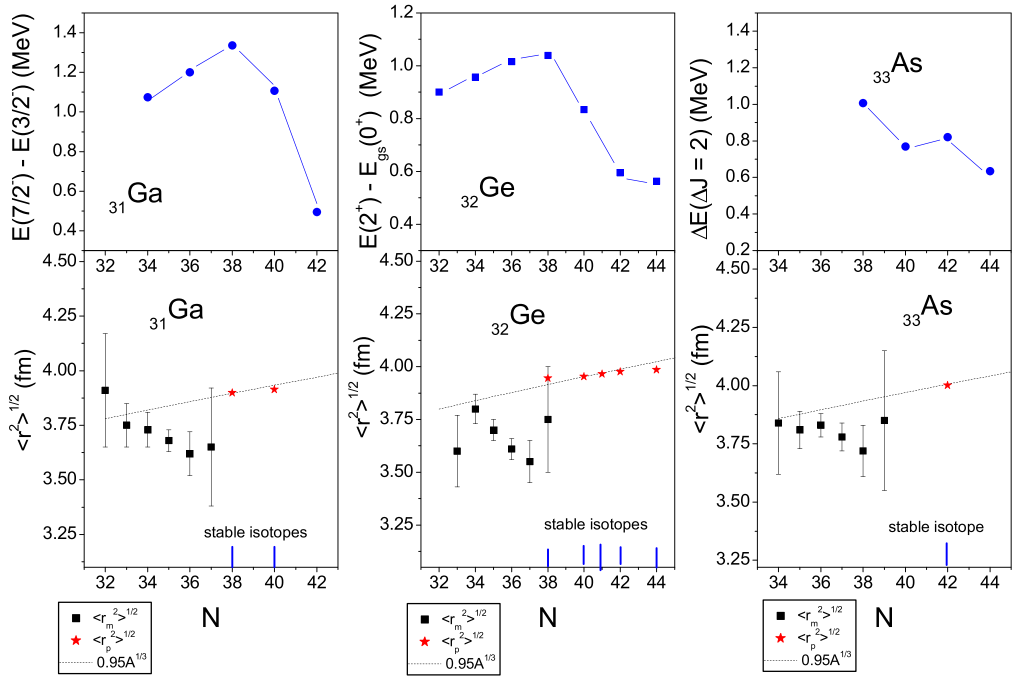

Fig. 3. Lower panel: The r.m.s. matter radii (full squares) of the Ga, Ge, As isotopes as a function of the neutron number N. We also show the r.m.s. proton radii (stars) of the stable isotopes. Upper panel: the excitation energies of the first 2^+ or $J = J_{\rm gs} + 2$ state as a function of N.

We adopted a procedure [3] with two extreme assumptions: In the first assumption the half-density proton radius $R_{\rm p}$ (obtained from charge density measurement of stable isotopes) is constant for the entire isotopic chain; the neutron radii $R_{\rm n} = R_{\rm p}$ for $T_Z = 0, 1/2$ isotopes and $R_{\rm n}$ increases with $N^{1/3}$. The diffusenesses are free parameters to fit the reaction cross-sections. In the second assumption the diffusenesses (obtained from systematics or the measurement of stable isotopes) of the proton and neutron distributions are assumed equal, and $R_{\rm p}$ and $R_{\rm n}$ are varied independently in order to reproduce the reaction cross-sections. The Glauber model calculation was included in a search routine, where the parameters were varied between given limits and the reaction cross-section was calculated for every ensemble of parameters. The reaction cross-sections were reproduced in many searches with several, fairly different proton or neutron distributions. However, the r.m.s. matter radii, which were calculated from these different distributions using a simple averaging formula [3], $\langle r^2_{\rm m}\rangle = (Z/A)\langle r^2_{\rm p}\rangle + (N/A)\langle r^2_{\rm n}\rangle$, were very similar. The uncertainties in the r.m.s. matter radii were scaled by the uncertainties of the total reaction cross-sections, adopting the same relative errors for both quantities. The r.m.s. matter radii obtained from the Glauber calculations are presented in fig. 1. On the left panel the matter radii of different isotopic chains are compared as a function of $N - Z$, while on the right panel the matter radii of isotonic series are compared as a function of Z. We also show on this figure, presented by dotted lines, the values of the nuclear radius given by the usual mass dependence $R = 0.95A^{1/3}$. A quite anomalous and surprising behaviour can be observed on this figure: the matter radii of the proton-rich isotopes decrease with increasing neutron number $N - Z$. On the other hand, when protons are added, the matter radii increase much more rapidly than predicted by the $A^{1/3}$ behaviour. The same comparison is also performed for stable isotopes, where the usual $A^{1/3}$ behaviour can be observed.

The r.m.s. matter radii obtained from the Glauber calculations are calculated from point distributions and before comparing them with measured r.m.s. charge distributions they should be folded with the nucleon matter distribution. However they can be directly compared to the r.m.s. point proton radii (assuming the proton as a point particle). We present on fig. 2 the comparison between r.m.s matter radii obtained from Glauber calculations together with the point proton r.m.s. radii calculated from r.m.s. charge radii for the Na and Ar isotopic chains [3,4,8] and for our Se data, as a function of T_Z. For all three cases and also for all our data (see figs. 3 and 4) the proton radii seem to be larger than the matter radii on the proton-rich side, even for quite high Z values, where no proton halo or skin is expected. This result persists for r.m.s. matter radii measured at very different energies.

In order to better understand the correlation of the matter radii with neutron and proton number, we also compare them with deformation. Instead of using deformation parameters or quadrupole moments, not known for all isotopes of interest, we will compare with the excitation energy of the first 2^+ state for even-even nuclei, or with the excitation energy of the first excited state with $J = J_{\rm gs} + 2$ for odd-even nuclei. It is well known that, the

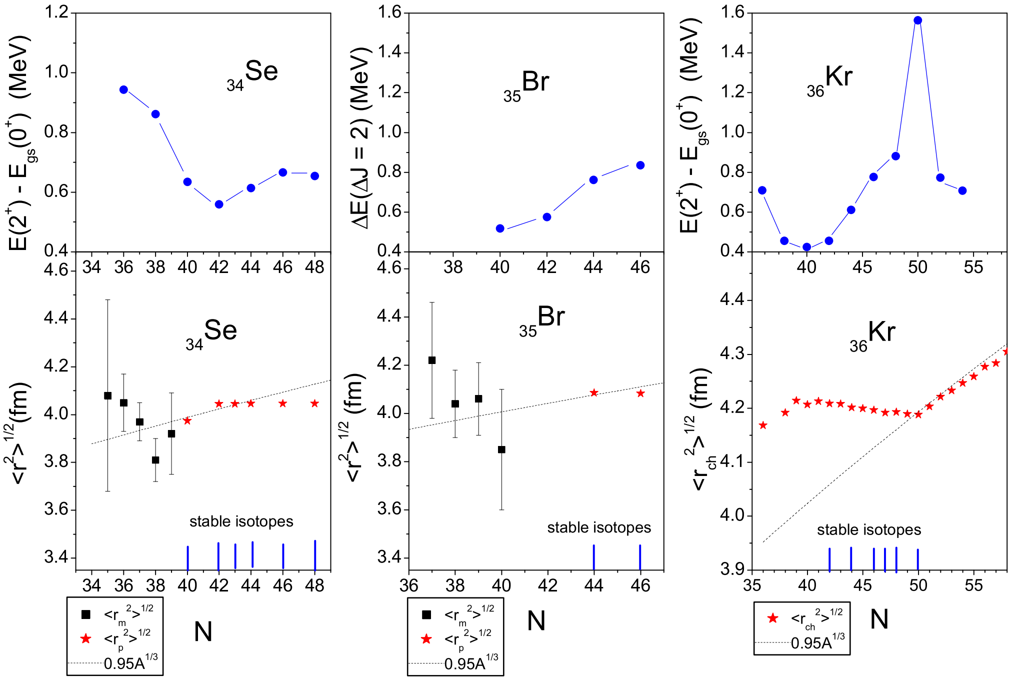

Fig. 4. Lower panel: The r.m.s. matter radii (full squares) and the r.m.s. proton radii (stars) of the Se, Br and Kr isotopes as a function of the neutron number N. Upper panel: the excitation energies of the first 2^+ or $J = J_{gs} + 2$ state as a function of N.

higher this excitation energy, the less collective or the less deformed is the nucleus. In figs. 3 and 4 we present three panels each, respectively the Ga, Ge and As isotopic series on fig. 3 and the Se, Br and Kr on fig. 4: on the lower part of the panels the $\langle r_{\mathrm{m}}^2\rangle^{1/2}$ r.m.s matter radii are shown, together with the point proton r.m.s. radii calculated from r.m.s. charge radii, as a function of the neutron number N.

The comparison is very revealing for the r.m.s. charge radii of the Kr isotopes [9]. The excitation energy presents a strong peak at the magic number $N = 50$, where the radii have a minimum. The increase in radii with decreasing N between $N = 50$ and 40 is correlated with the deformation effect, the excitation energies decrease and the radii increase, the maximum of deformation ocurring for $N = 40$. For $N \leq 40$ the excitation energies again increase and the radii decrease.

Unfortunately, there is no overlap between the proton radii and matter radii for the Ga, Ge, As, Se and Br isotopic chains, however the proton radii (measured for stable isotopes) are larger and with the exception of Se, they follow the $A^{1/3}$ behaviour. The matter radii seem to be strongly correlated with deformations mainly for the Ga, Ge and Se isotopic chains. They present a strong minimum at the N values (respectively $N = 37, 37$ and 38), where the excitation energies present a strong maximum. For lower N values the excitation energies decrease very little (Ga, Ge) or even increase (Se), while the radii increase strongly. Thus this increase in radial extension for the very proton-rich isotopes cannot be attributed to an increase in deformation.

4 Conclusion

In summary, we have measured the reaction cross-sections (σ_R) of proton-rich nuclides of the Ga, Ge, As, Se and Br isotopic chains. We used Glauber model calculations to obtain r.m.s. matter radii from the measured reaction cross-sections. A clear correlation of the total r.m.s. matter radii with neutron number N and with proton number Z was verified. The radii decrease with increasing N, and increase strongly with increasing Z. Around $N = 37, 38$ the Ga, Ge and Se isotopic chains present a maximum in excitation energy and thus a minimum in deformation, which is correlated with a minimum in the matter radii. For lower N values the excitation energies decrease very little (Ga, Ge) or even increase (Se), while the radii increase strongly as was also observed in the Ti isotopes. This can possibly indicate the presence of a proton skin.

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