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Reaction cross sections and reduced strong absorption radii of nuclei in the vicinity of closed shells $N = 20$ and $N = 28$

A. Khouaja[1,2,3], A.C.C. Villari[1,4], M. Benjelloun[2], G. Auger[1,5], D. Baiborodin[6], W. Catford[7], M. Chartier[8], C.E. Demonchy[1,8], Z. Dlouhy[6], A. Gillibert[9], L. Giot[1,10], D. Hirata[11], A. Lépine-Szily[12], W. Mittig[1], N. Orr[10], Y. Penionzhkevich[13], S. Pitae[1,5], P. Roussel-Chomaz[1], M.G. Saint-Laurent[1], and H. Savajols[1]

1 GANIL, BP 55027 F-14075 Caen Cedex 5, France
2 LPTN Faculty of Sciences, El Jadida BP. 20 24000 El Jadida, Maroc
3 LNS-INFN, 44 S. Sofia 95129 Catania, Italy
4 Physics Division Argonne National Laboratory, 9700 S. Cass Av. Argonne IL 60439, USA
5 Collège de France 11 Place Marcelin Berthelot 75231 Paris Cedex 05, France
6 Nucl. Phys. Ins. ASCR 25068 Rez, Czech Republic
7 University of Surrey Nuclear Physics Dept., Guilford, GU27XH, UK
8 University of Liverpool Dept. of Physics, Liverpool L69 7ZE, UK
9 CEA/DSM/DAPNIA/SPHN, CEN Saclay F-91191 Gif-sur Yvette, France
10 LPC - ISMRA and University of Caen F-6704 Caen, France
11 The Open University Dept. of Physics and Astronomy, Walton Hall Milton Keynes MK6 2HL, UK
12 University of São Paulo IFUSP C.P. 66318 05315-970 São Paulo, Brazil
13 FLNR, JINR Dubna P.O.Box 79 101000 Moscow, Russia

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13 FLNR, JINR Dubna P.O.Box 79 101000 Moscow, Russia

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Abstract. Energy integrated reaction cross-section measurements of around sixty neutron-rich nuclei covering the region of closed shells $N = 20$ and $N = 28$ were performed at intermediate energy (30 - 65 A.MeV) using direct method. In this experiment, silicon detectors were used as active targets. Assuming that the energy dependence of the reaction cross-section is well described by the parametrization of Kox, the reduced strong absorption radii, r_0^2, for 19 new nuclei (^{27}F, ^{27,30}Ne, ^{33}Na, $^{28,34-35}$Mg, $^{36-38}$Al, $^{38-40}$Si, $^{41-42}$P, $^{42-44}$S and ^{45}Cl) are extracted for the first time. An additional 60 radii, also measured in this experiment, are compared to results from literature. The evolution of the reduced strong absorption radius is studied as a function of the neutrons excess. A new quadratic parametrization is therefore proposed for the nuclear radius as a function of the isospin in the region of closed shells $N = 8$ and $N = 28$. According to this parametrization, the skin effect is well reproduced and anomalous behaviour on the radii are observed in ^{23}N, ^{29}Ne, ^{33}Na, ^{35}Mg, ^{44}S, ^{45}Cl and ^{45}Ar nuclei .

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

1 Introduction

Radioactive nuclear beams (RNB) have provided a powerful tool for nuclear physics in the study of nuclear structure for exotic nuclei far from β-stability. For example, Coulomb excitation and mass measurements show evidences of magic shell breaking at $N = 20$ and $N = 28$ for exotic nuclei ^{32}Mg [1] and ^{44}S, respectively [2,3]. Moreover, recent measurements of reaction cross-sections (σ_R) at high-energy, revealed the existence of a new magic number at $N = 16$ [4] which appears only in very neutron-rich nuclei close to the drip-line. Historically speaking [5,6], the measurement of reaction or interaction cross sections involving fast-RNB launched what we could call today fast radioactive ion beam physics [7] and continues to be responsible for major discoveries in this field. Total reaction cross sections experiments can provide important hints of unexplored areas of the nuclear chart since this quantity can be measured with relatively low production yields. Experimentally, the quantity of data obtained up to now is remarkable, but no clear systematic studies have been carried out and no evaluation of the available data exists at present.

In this contribution, we present new intermediate energy measurements of mean energy integrated reaction cross-sections performed at GANIL for neutron rich nuclei in the region defined by ($5 < N < 28$; $7 < Z < 18$). These data correspond to the most exotic nuclei presently attainable in this region. We also investigate systematically the isospin dependence of the squared reduced strong absorption radii r_0^2 obtained from the measured $\bar{\sigma}_R$ and we propose a new parametrization between r_0^2 and isospin.

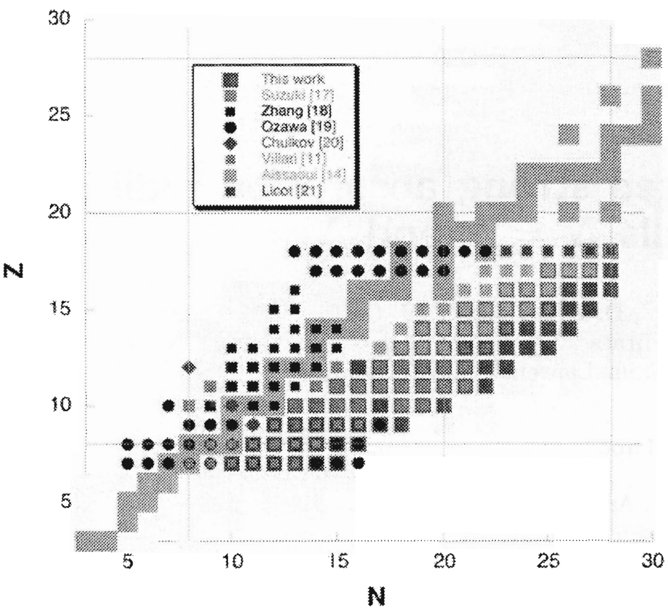

Fig. 1. Representation of the nuclei chart where the yellow region marks nuclei where mass measurements are available, grey are stable nuclei and the other colours and symbols denote nuclei where radii were evaluated in this paper.

This relationship helps to localize anomalous behaviour of the nuclear radius, pointing out where further interesting studies could be performed.

2 Experimental setup

The nuclei of interest were produced via the fragmentation of a 60.3 A.MeV ^{48}Ca primary beam, on a ^{181}Ta production target, placed between the two superconducting solenoids (SISSI) of GANIL [8]. Rotating at 2000 rpm, the production target was composed of three different sectors with thickness of 550 mg/cm2 (89%), 450 mg/cm2 (10%) and 250 mg/cm2 (1%). This ensured a sufficient production of both very and less exotic nuclei, allowing to measure new cross sections while improving significantly known ones. The secondary beam was, after production, selected in flight by the α-shaped spectrometer and transported to the focal plane of SPEG [see ref. [9,10]].

At the focal plane, all produced particles were stopped and detected by a stack of four cooled (about -10^o C) silicon detectors with thicknesses of 50μm (ΔE), 300μm and 6700μm. The first thin detector was used for identification of the produced beam while the second and third acted as active targets. A fourth detector (6700μm ($\bar{E}$)) was mounted downstream and served eventually as target for light nuclei or as detector of light charged particles produced in the reactions with the first three detectors. The Silicon detector-stack was surrounded by a 4π array of 14 NaI γ-detectors to identify quasi-elastic ($Qclosetozero$) reactions. To limit the transmission of an undesired large number of light nuclei, a 25μm Be-degrader was installed between the two dipoles of the α-shaped spectrometer.

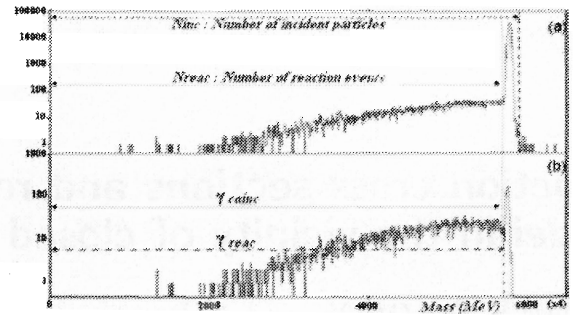

Fig. 2. a) Total energy spectra for ^{25}F. b) Gamma coincidence spectra for the same isotope.

During the experiment, two different magnetic rigidities were selected in order to enhance the production of different regions of the nuclear chart. The incident nuclei could be unambiguously identified by correlating time of flight (TOF) between the production and the detection and energy loss (ΔE), event-by-event.

For the measurements of reaction cross-sections we used a direct method, developed by Villari [11], which is a variant of the known transmission method. This technique is based on the total energy deposited by the incident particles in the silicon-stack. If the energy detected does not correspond to the total kinetic energy of the particle, it is a reaction event (fig. 2). This is easily identified in the energy spectrum of the silicon-stack by a queue towards low energy. There are a few percent quasi-elastic reactions that are not resolved directly in the energy spectrum. These are identified and added to the reaction events via the gamma detector coincidences. The cross section measured by this method is represented by the following relationship:

$$\bar{\sigma}_R = \frac{\int_0^{E_{max}} \sigma_R(E)(dR/dE)dE}{\int_0^{R_{max}} dR} = -\frac{m \ln(1-P_R)}{dN_A R_{max}} \quad (1)$$

Where $m = 28$ is the molecular-weight of Silicon target with density d (g/cm^2), N_A is Avogadro's number, and R_{max} is the range of incident particles, calculated using the table of Hubert et al. [12]. The reaction probability P_R is determined for each colliding isotope by the ratio of reaction events to the incoming ones. More details on the experimental procedure can be found in ref. [11].

3 Strong absorption radius

Assuming that the energy dependence of the reaction cross-section is well described by the parametrization of S.Kox [13,11], the reaction cross-section can be expressed as a function of the squared reduced strong absorption radius, r_0^2, as:

$$\sigma_R(E) = \pi r_0^2 \left[A_P^{1/3} + A_T^{1/3} + a\frac{(A_P\, A_T)^{1/3}}{A_P^{1/3} + A_T^{1/3}} - C(E) \right]^2 \times (1 - \frac{B}{E_{cm}})\,. \quad (2)$$

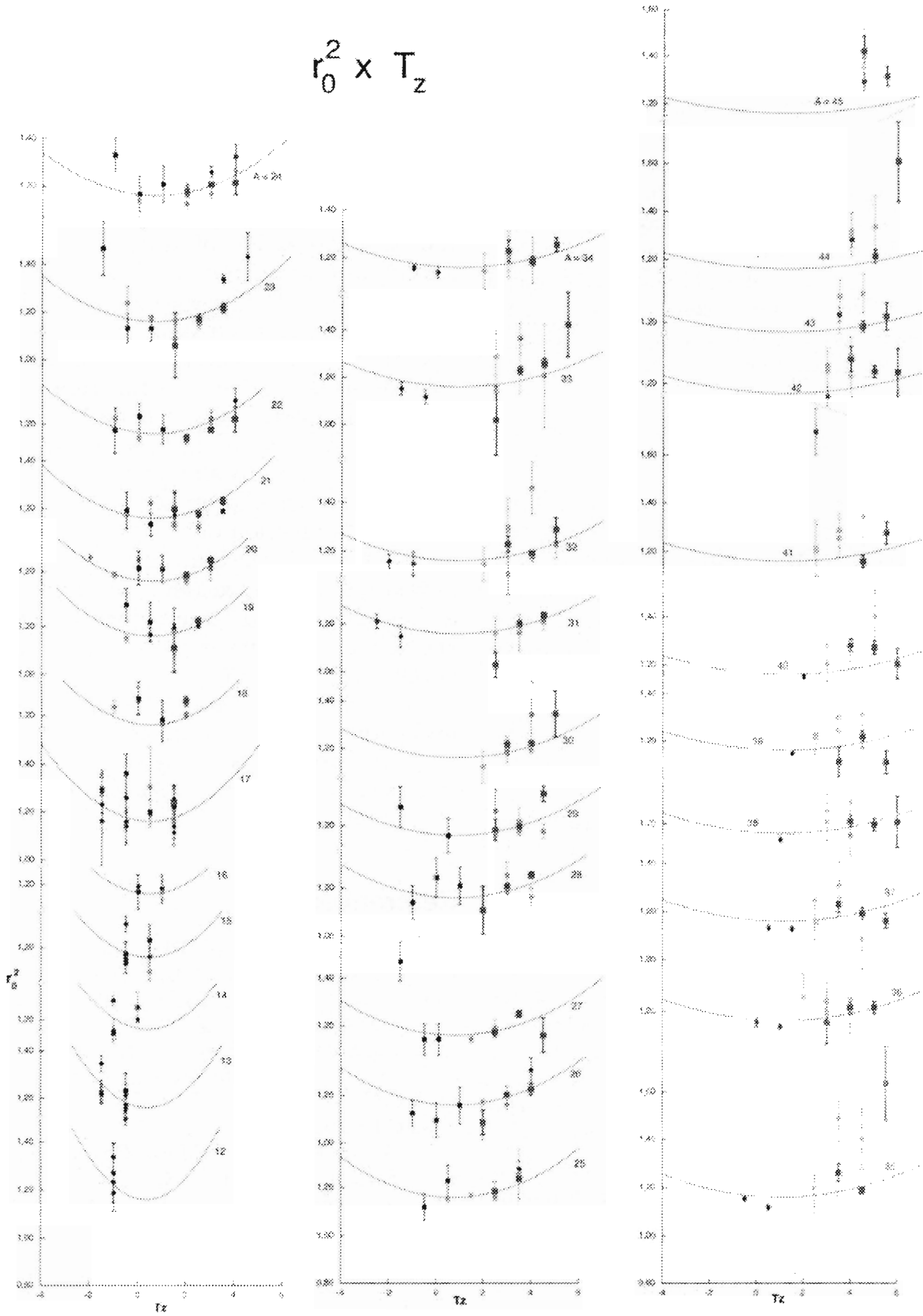

Fig. 3. Squared reduced strong absorption radii as a function of the isospin for masses from A = 12 to A = 45. The different colours refer to different authors (see figure 1). The solid line represents the result of the parametrization given in eq. 3.

Where A_P and A_T are the projectile and target numbers, $a = 1.85$ is the mass asymmetry related to the overlap volume between projectile and target. $C(E)$ is the energy dependent transparency function which can be linearly evaluated, at energy range of $30 - 70\,A$ MeV, by $C(E) = 0.31 + 0.014\,E/A_P$ and at high energy by $C(E) = 1.0$. B and E_{cm} are the Coulomb barrier and incident energy in the centre-of-mass.

From the equations 1 and 2, the squared reduced strong absorption radius r_0^2 is extracted as a function of the reaction probability (P_R) of the measured mean energy integrated reaction cross-section. For a wide variety of target and stable projectile systems, the squared reduced strong absorption radius, at different energies, is a constant and its value is $r_0^2 = 1.21 fm^2$ [13].

Previous measurements have already shown an increase of reduced radii r_0^2 as a function of proton/neutron excess [6,14]. For $Z \leq 13$ neutron-rich isotopes, Mittig et al. [6], have indicated that the reduced strong absorption radius has a linear isotopic dependence as a function of the neutrons excess, as, $r_0^2 = 1 + 0.06(N - Z)$. Later on, Assaoui et al. [14] presented a similar linear trend for $Z \geq 13$ neutron-rich isotopes with $r_0^2 = 32/30 + (N - Z)/30$. These two parametrizations have been built from a limited number of neutron-rich nuclei with reaction cross-sections measured at intermediate energies; they do not take into account the weight effect of mass number A for each isotope. Here, we propose a general relationship for this effect, valid for neutron and proton rich nuclei in a wider range of masses, i.e. $A \leq 50$. Figure (1) shows the nuclei used in the search of this parametrization. The following equation has been obtained by a χ-square fitting of available intermediate and high energy data :

$$r_0^2 = 1.164 - 0.2819\frac{T_Z}{A} + 4.628\frac{T_Z^2}{A^2} \qquad (3)$$

From this equation, the reduced strong absorption radius for $N = Z$ nuclei is $r_0^2 = 1.165 fm^2$, in perfect agreement with $r_0^2 = 1.166\, fm^2$ obtained from charge distribution of stable nuclei [15,16]. Importantly, we observe that the minimum radius is found at $\frac{T_Z}{A} = 0.03$, which also indicates that the minimum radius for an element deviates from $N \sim Z$ with increasing of A.

In Figure (2), the squared reduced strong absorption radii obtained in this work are plotted as a function of the isospin for mass numbers from 14 to 46, together with values deduced from reaction cross-sections obtained at high and intermediate energies. The solid line represents the result of r_0^2 using the new parametrization obtained from equation (3). We observe that for each mass the isospin dependence of the nuclear radius is well reproduced by our parametrization: larger radius for larger isospin, which is more important for lighter masses than for heavier ones. Any anomalous behaviour of the nuclear radius can, therefore, be easily identified by a deviation from the solid line. A typical example can be observed for the larger radii of ^{23}Al and ^{27}P, already suggested by Zhang et al [19] as one-proton halo nuclei. We also observe larger radii for the nuclei: ^{23}N, ^{29}Ne, ^{33}Na, ^{35}Mg, ^{44}S, ^{45}Cl, ^{41}Ar and ^{45}Ar. However, for ^{22}N, ^{24}F and ^{23}O, our results do not deviate from the parametrization, which is not in agreement with the observations of Ozawa et al [19] at high energies, where neutron halo structures have been proposed.

Our parametrization cannot disentangle the effects of halo and strong deformations, both allowing anomalous enhancement of the nuclear radius. For ^{33}Na, our experimental result is compatible with a large rms radius previously calculated via relativistic mean field theory[22], where a 1n-halo structure has been suggested. Moreover, the existence of large deformations of ^{45}Cl and ^{45}Ar were already proposed from mass and coulomb excitation measurements [3,23]. We remark that for the nucleus ^{41}Ar, two results, mainly measured at intermediate energy, are inconsistent: one, obtained by Aissaoui et al. [14], is very close to the new parametrization while the one obtained by Licot et al. [21], is well above the systematics. ^{35}Mg and ^{44}S, as stated above, reveal important deviations from the systematic; both neutron-halo effect and strong deformation could be suggested.

4 Summary and conclusions

In this work, the direct method - where a silicon telescope acts as an active target - is used to measure the mean energy integrated reaction cross-sections $\bar{\sigma}_R$ for a variety of neutron-rich exotic nuclei in the range of closed shells N=20 and N=28. Assuming that the energy dependence of the reaction cross-section is well described by the parametrization of Kox, the square of the reduced strong absorption radius r_0^2 is extracted and compared with results from literature; from which 19 radii (obtained from the reaction cross-sections) are presented for the first time. The evolution of reduced the strong absorption radius is studied as a function of the excess of neutrons, independent of the mass number, incident energy and for both proton- and neutron-rich nuclei, in the region of $7 \leq Z \leq 18$ and $14 \leq A \leq 46$. A new quadratic parametrization is proposed for the evolution of nuclear radius as a function of the isospin. This parametrization reproduces well the skin effect and permits one to give indications of the existence of structure anomalies such as halo effects and large deformations. The existence of anomalous structure is proposed for the first time in the nuclei ^{35}Mg and ^{44}S.

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