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* Experience performed at the GANIL National Facility.

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Abstract :

Total reaction cross-sections of neutron rich nuclei from C to Mg in a thick Si-target have been measured using the detection of the associated γ-rays in a 4π-geometry. This cross-section strongly increases with neutron excess, indicating an increase of as much as 15 % of the reduced strong absorption radius with respect to stable nuclei.

* Experience performed at the GANIL National Facility.

High primary beam intensities and production rates of exotic nuclei at the GANIL accelerator allow the measurement of properties of nuclei far from stability. Recently, we reported on the mass-measurement[1,2] of neutron rich nuclei. The present work reports the measurement of total reaction cross-sections of some of these nuclei. Tanihata et al. have recently measured[3,4] total reaction cross-sections for He, Li and Be isotopes. These results have stimulated considerable interest, and were quite well reproduced by theoretical calculations[5,6] using the Glauber model and a Hartree-Fock like variational calculation for the nuclear structure. An important difference, however, was observed for ^{11}Li.

The experimental arrangement used for mass-measuremenents[1,2] suits well the simultaneous measurement of total reaction cross-sections. A Ta target (350 and 500 mg/cm^2) near the exit of the accelerator was bombarded with a 60 MeV/nucleon ^{40}Ar beam of 1 μAe. Part of the secondary particles produced were transported to the magnetic spectrograph SPEG[7]. At the focal plane, a non dispersive doubly achromatic tuning of the line ensures a maximum beam envelop extend of about 2 x 2 cm^2. Hence, all the particles hit a telescope consisting of two 300 μm ΔE and a 6000 μm E solid state Si-detectors. The telescope was surrounded by an array of six hexagonal NaI (Tℓ) detectors 13.1 cm thick and 23.5 cm long, covering a solid angle of 87 % of 4π. Behind the solid state detectors, a smaller NaI (Tℓ) detector (7.5 cm thick and 10 cm long) permitted to detect γ rays and charged particles in a close-up-geometry (fig. 1). The particles were identified by the energy-loss signal of the first ΔE detector and the time of flight T between this detector and a microchannel plate device positioned 80 meters up stream. For a given Bρ-value, T and $\sqrt{\Delta E}/T$ are essentially proportional to A/Z and Z, respectively.

The raw uncorrected reaction probability P^{nc}_{reac} is given by the number of coincidences between the ΔE counter and any set of NaI detectors divided by the singles in the ΔE detector. The reaction probability P^{nc}_{reac} was of the order of several percent in the present measurements.

Several corrections were applied in order to obtain the reaction cross-section :

- correction for random coincidences (about 2 %),

- correction for ambiguous identification : background due to tails in the identification functions was substracted (about 1 %),
- efficiency correction.

The last one is the most important. A detection efficiency of the six detector array of 70 % for a single photon was measured using a calibrated ^{60}Co source. A geometrical calculation and the measured multiplicity lead to a probability of 84 % that at least one detector fires. The coincidence probability between this array and the smaller NaI (Tℓ) was found to be around 70 %, thus the combined detection probability was about 95%, with an estimated uncertainty of 5 %. This uncertainty contributes mainly to the *uncertainty of the absolute value of the cross-section. No dependence* of this correction on mass or atomic number is expected.

Applying these corrections, we obtain the corrected reaction probabilty P_{reac}. The total reaction cross-section is obtained using the relation

$$\sigma_R = P_{reac} \times 28.085/(N_A.R) \qquad (1)$$

N_A is the Avogadro number, 28.085 g/mol is the weight of the unenriched Si of the detectors that constitute the target and R is the range of the incident particles in Si. R was taken fromm the tables of F. HUBERT et al.[8], which are in good agreement (1.4%) with recent measurements[9]. The incident energy of the particles is well known by the Bρ-value of the beam line. Two values of Bρ were used, 2.611 and 2.876 Tm. The thickness of the first ΔE-detector must be substracted from the total range since a correct identification implies that no reaction has occured in this detector.

The measured cross-sections correspond to thick target yields, and represent a *mean value over energy from* E_{max} *at the exit of the first* ΔE counter to the Coulomb barrier energy V_{cb}. Due to the selection by the magnetic rigidity, the energy E_{max} varies from one nucleus to the other and is typically 40 to 60 MeV/nucleon . Here we are mainly interested in the variation of the nuclear properties as a function of neutron excess. It is then necessary to reduce the experimental P_{reac} to a quantity independent of the energy. So is the reduced geometrical strong absorption radius r_0, as defined by

$$\sigma_R(E) = \pi r_0^2 \; f(E) \qquad (2)$$

where the energy dependence f(E) can be estimated in appropriate models.

$$\text{Then } P_{reac} = \frac{N_A}{28} \int \sigma_R(E)\, dR = \frac{N_A}{28} \pi r_0^2 \int_{E_{max}}^{V_{cb}} f(E) \frac{dR}{dE}\, dE \qquad (3)$$

where $dE/_{dR}$ is the stopping power which was approximated by $dE/dR \alpha\ E^{-0.73}$.

We used for f(E) the empirical formula of Kox et al.[10].

$$f(E) = (A_1^{1/3} + A_2^{1/3} + \frac{aA_1^{1/3}\ A_2^{1/3}}{A_1^{1/3} + A_2^{1/3}} - C(E))^2\ (1 - \frac{Bc}{E_{c.m.}}) \qquad (4)$$

This formula reproduces very well[10] the experimental data over a large energy domain and for many systems. It contains a correction for assymmetry proportional to a = 1.9, an energy dependent transparency term C(E), and a correction for the Coulomb barrier. We have used a linear dependence for C(E), based on the results of Kox et al.[10]:

$$C(E) = 0.14 + 0.015\ E/A \qquad (5)$$

One finally obtains at first order :

$$P_{reac} = \pi r_0^2\ D^2\ (1 - 2.37 \frac{B_c}{E_{c.m.}} - 0.0190 \frac{E/A}{D}) \qquad (6)$$

where

$$D = A_1^{1/3} + A_2^{1/3} + aA_1^{1/3}\ A_2^{1/3}\ (A_1^{1/3} + A_2^{1/3}) - 0.14\ \text{fm} \qquad (7)$$

takes into account the normal A-dependence of the cross-section and the reduced radius r_0 is expected to be independent of energy and of the system. Kox et al.[10] obtained a value of r_0 = 1.05 fm. The values obtained in the present measurements are shown on figure 2.

The comparison of the measurements done at the two $B\rho$ values, therefore at two energies for each nucleus, provides a check of the validity of the energy dependence (4). The two values of r^2_0 agree within error bars. A strong variation of r_0^2 on neutron excess is observed. Note that r_0^2 should not depend on the atomic number because the expected A-dependence is already taken into account explicitely (equations (2) and (4)). Possible sources or experimental artifact were carefully checked . No correction was found to depend significantly on the nuclear species. For example, the correction due to γ-multiplicity varies by 2 % from ^{15}N to ^{19}N.

Such a strong dependence is surprising. A long range tail of the nuclear matter distribution may produce such an effect. This could be due to increasing deformation as a function of neutron excess, as was suggested by Tanihata et al.[3,4] in order to explain the unexpected large radius observed for ^{11}Li. Our data show this trend for all atomic numbers and it is not likely that such a structure effect will show up independently of the proton number. Hence it seems more probable that a long range tail would be due to an increase of the diffuseness or a neutron halo.

In order to have a quantitative estimate of such effects, we have calculated these reaction cross sections following a simplified Glauber approach. The attenuation of the incident flux is calculated from the probability for a collision between a nucleon of the target and a nucleon of the projectile[11]. The nuclei are supposed to move on a classical trajectory calculated in a realistic Coulomb + nuclear potential. The total nucleon-nucleon cross section was taken from the literature[12]. The matter distribution of the nuclei was that of the droplet model[13].

The results of these calculations are as follows :

- the energy and mass dependence of eq.(4) is very well reproduced by the calculations. Indeed, the r_0 value extracted from calculated σ_R at different energies (and therefore for different nucleon-nucleon cross sections) and various nuclei are very constant, i.e. $r_0 = 1.05 \pm 0.02$ fm. This also excludes a bias due to an improper geometry in eq.(4).

- Higher reaction cross sections can be obtained by allowing a deformation of the nuclei or, equivalently, an increase of the diffuseness of the mass distribution. In order to obtain the 15 % increase of r_0 observed for $N-Z = 6$, it is necessary to use a quadrupole deformation $\beta = 0.7$ or a diffuseness of $a = 0.7$ instead of the standard value $a \doteq 0.55$ fm. However, Hartree-Fock calculations[13] for C and O predict a very small increase of the root-mean-square radius, which is in contradiction with such a strong increase of the diffuseness or such a strong deformation.

In conclusion, we have measured the reaction cross-section for neutron rich-light nuclei on Si. The reduced strong absorption radius increases rapidly with neutron excess. A striking feature of the present data is that this unexpected increase does not depend on the atomic number, but only on neutron excess.

FIGURE CAPTIONS

1) A schematic view of the experimental set up for the detection of the associated radiation around the Si-telescope that serves as target. The six detector array is mainly sensitive to γ rays and, with less efficiency, to neutrons, whereas the smaller NaI detector behind the telescope will register, too, charged particles produced in the forward angle cone with high enough energy to leave the last Si-detector.

2) The square of the reduced strong absorption radius r_0^2 as a function of neutron excess for various atomic numbers.

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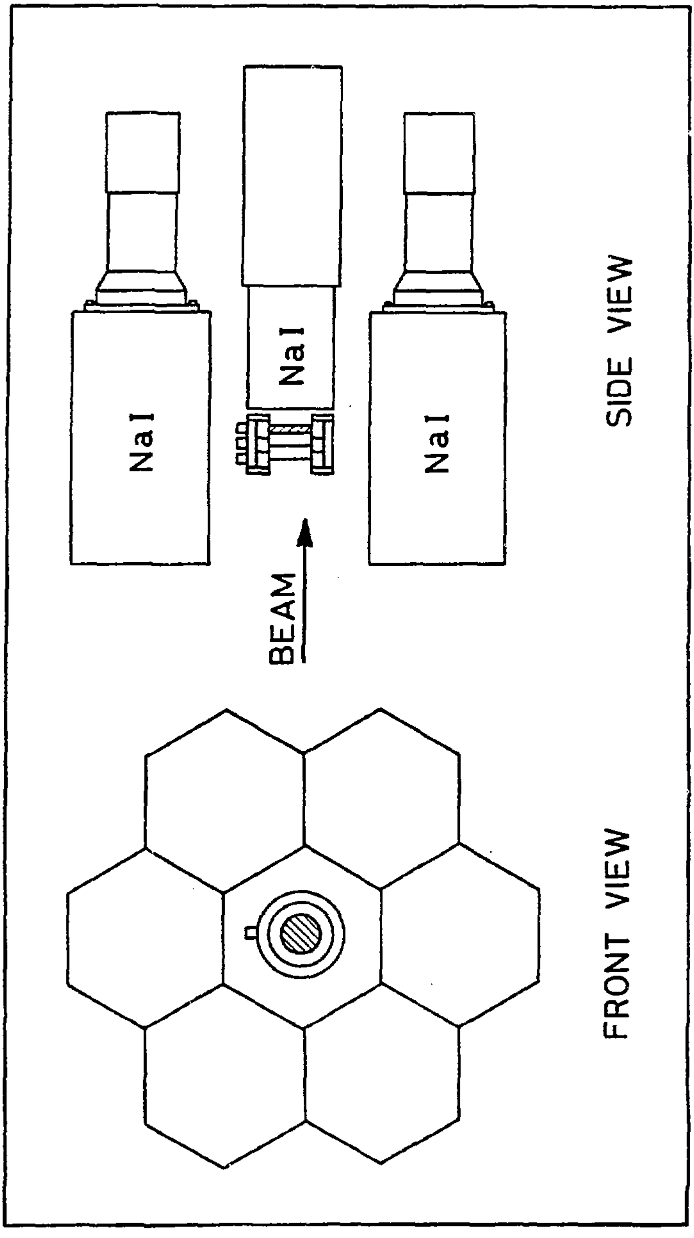
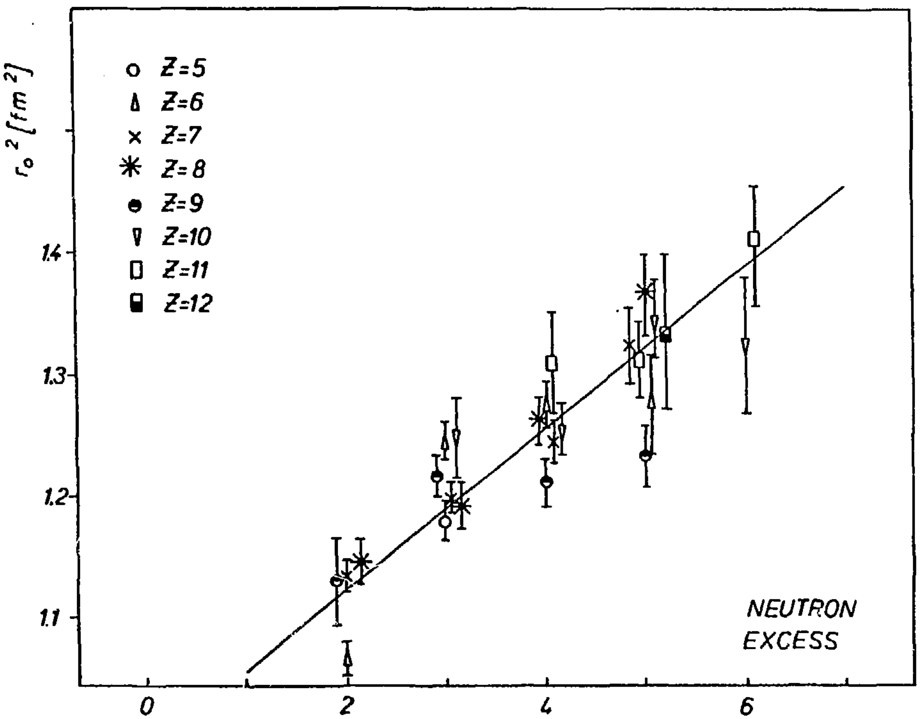


Figure 1


Z=5
Z=6
Z=7
Z=8
Z=9
Z=10
Z=11
Z=12
r_o^2 [fm^2]
1.4
1.3
1.2
1.1
0
2
4
6
NEUTRON
EXCESS

Fi... 2