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RADII OF RADIOACTIVE NUCLEI

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I. Introduction

The evaluation of nuclear radii from total reaction cross section (σ_R) measurements using secondary radiactive beams has recently been shown to be possible[1] and, at the present, is the unique method for studying nuclear matter radii of unstable nuclei.

At high energies (≈ 800 A·MeV), σ_R was measured for several light (2 < Z < 5) isotopes using a transmission-type technique[1-3]. At intermediate energies (≈ 60 A·MeV), a wider atomic number range (3 < Z < 15) is attained using the associated-γ method[4-6] for σ_R measurements.. Although, for stable nuclei, the results using the associated-γ technique agree with σ_R obtained by attenuation method or from elastic scattering, it could fail for very exotic neutron rich nuclei which decay through neutron emission, leaving the final nucleus in the ground state or at low excitation energy. Thus, for nuclei far from stability, the results of σ_R and nuclear radius obtained by the associated-γ technique should be confirmed by other experiments using different methods.

In this contribution, we present new intermediate energy measurements of σ_R for radioactive nuclei obtained at GANIL, using a new simple direct technique.

II. New Direct Method

Secondary radiactive beams were produced through the projectile fragmentation of a 55 A·MeV ^{48}Ca primary beam on a 350 mg/cm^2 Ta target. Part of the secondary beam produced was transported up to the spectrograph SPEG. At the focal plane, all particles hit a telescope constituted by 3 solid state silicon detectors, respectively: a 50 μm ΔE, a 300 μm x-y position sensitive ΔE and a 6,000 μm E. The telescope was cooled to about -10°C and surronded by an 4π array of 14 NaI(Tℓ) 13.1 cm large and 23.5 cm long γ-detectors. The identification of incident particles is unambiguously given by the time of flight between two micro-channel plates, located respectively just after the production target and just before the telescope, and by the energy loss in the first ΔE detector.

The direct method for obtaining σ_R is very simple. The telescope has the double function of detector/target. As in our preceeding works[4-5], we measure energy-integrated reaction cross section. All incident particles are stopped in the telescope detector/target. Events that correspond to reactions in the detector/target are easily identified, its energy being different from that of elastic scattering (see fig.1). In principle we are not sensitive to reactions with Q=0, or with Q smaller than the energy resolution of the detector system. Nevertheless, all reactions that produce light particles or γ-rays do not give a signal proportional to the final energy (E-Q), because these particles will not be stopped or detected in the telescope.

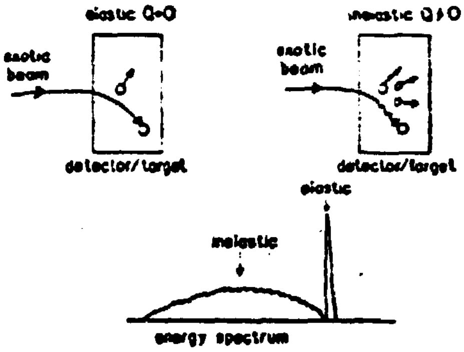

Fig.1. Schema of the direct method. The reaction probability is the number of inelastic events divided by the number of total events.

In order to correct for the slightly different energy of the incident particles, due to the 1% energy acceptance of the beam line, we used the quantity ET^2 (where E is the energy deposed in the telescope and T is the time of flight of incident particles) that is proportional to M, for the calculation of σ_R. The energy resolution obtained for the quantity ET^2 is 0.23%, corresponding for example, to 1.7 MeV for ^{18}N. Fig. 2a shows the spectra ET^2 for ^{18}N incident beam. The reaction probability (P_r) is calculated dividing the number of inelastic events (outside of the sharp elastic peak) by the total number of counts in this spectrum (fig. 2a). Fig. 2b and 2c show the same ET^2 spectra in anti-coincidence and in coincidence with the 4π γ-detectors array. In order to correct for quasi-elastic events in the calculation of the reaction probability, we added to the inelastic events the number of γ-coincidences inside the elastic peak, after substraction of accidentals. This correction represents approximately 2% of the total number of reaction events. The mean energy-integrated reaction cross section is defined by the following equation:

$$\bar{\sigma}_R = \frac{\int_0^{R_{max}} \sigma_R\left(E\right)\frac{dE}{dR}\,dR}{\int_0^{R_{max}} dR} = -\frac{m\,\log\left(1-P_r\right)}{N_A \cdot R_{max}} \qquad (1)$$

where m = 28 is the weight of the Si target, N_A the Avogadro number and R_{max} the range of incident particles, calculated using the tables of Hubert et al.[7].

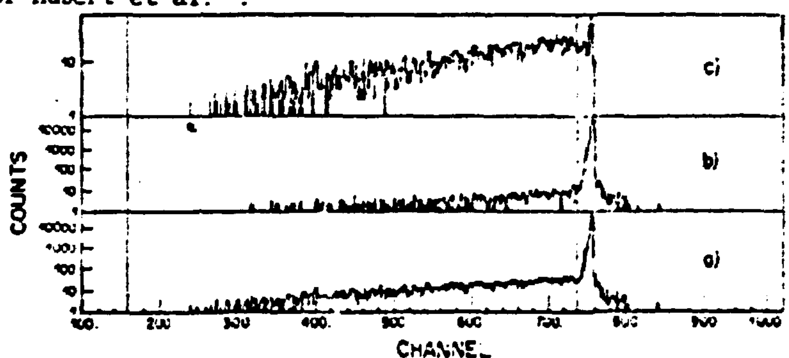

Fig.2. ET^2 spectrum. a) Free detector/target spectrum; b) anticoincidence spectrum with 4π γ-array; c) coincidence spectrum with 4π γ-array. The two vertical lines delimit the region considered as inelastic events.

III. Deducing The Reduced Strong Absorption Radius

In order to get informations on the nuclear properties of the involved exotic nuclei, it is necessary to extract an energy independent parameter. Such is the reduced strong absorption radius, r_o defined by the relationship:

$$\sigma_R(E) = \pi r_o^2 f(E) \tag{2}$$

As has been done in our preceeding paper, we used for the function f(E) the Kox et al. parametrization[3]. This empirical parametrization has been obtained by fitting carefully experimental data measured over a large energy range (30 to 2000 A·MeV) and involving many colliding systems with A_p going from 1 to 40 and A_t from 9 to 209. Thus, we obtain:

$$\sigma_R(E) = \pi r_o^2 \cdot \left[A_p^{1/3} + A_t^{1/3} + a \cdot \frac{A_p^{1/3} \cdot A_t^{1/3}}{A_p^{1/3} + A_t^{1/3}} - C(E)\right]^2 \cdot \left[1 - \frac{V_{cb}}{E_{CM}}\right] \tag{3}$$

where A_p and A_t are the projectile and target mass numbers, a=1.85 is an asymmetry parameter, C(E) is an energy dependent transparency and V_{cb} is the Coulomb barrier. The r_o^2 should be independent of energy, target and projectile, as shown in ref. 8 for stable nuclei. The value of r_o^2 in this case was found to be $r_o^2 = 1.1\ fm^2$. As an example of the meaning of σ_R, the reaction cross section calculated for the system $^{18}O+^{28}Si$ at incident energy 41·A MeV using the relation (3) is presented in fig. 3 as a function of the particle path in the Si target. With respect to the geometrical cross section, defined as the maximum σ_R obtained in this calculation, the transparency and Coulomb corrections are only 0.7% and 2.7% respectively.

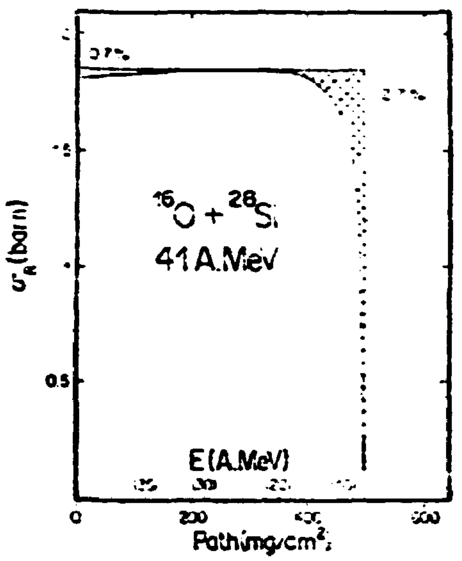

Fig.3. σ_R as a function of the particle path in the Si target, calculated using eq. (3). The marked zones correspond to the effect of transparency (0.7%) and Coulomb correction (2.7%) with respect to the geometrical cross section.

This feature supports the reliability of extracting accurate informations on the geometrical nuclear properties from the energy integrated cross section. In fact, we performed both corrections, assuming for the transparency C(E) the following linear dependence, valid up to about 100 A·MeV:

$$C(E) = 0.31 + 0.014 \frac{E}{A_p} \tag{4}$$

Our results show the r_o^2 as a function of the excess or deficiency of neutrons (N-Z). Neglecting higher order effects and adopting a stopping power approximation:

$$\frac{dE'}{dR} \propto E^{-0.73} \tag{5}$$

we obtain from equations 2, 3, 4 and 5:

$$r_{e}^{2} = \frac{-m \cdot \mathrm{Log}\left[1 - P_{reac}\right]}{\pi R g^{2} \cdot \left[1 - 2.37 \frac{V_{cb}}{E_{cm}} - 0.0147 \frac{E}{A_{p}}\right]} \qquad (6)$$

where:

$$g = A_{p}^{1/3} + A_{t}^{1/3} + 1.85 \frac{A_{p}^{1/3} \cdot A_{t}^{1/3}}{A_{p}^{1/3} + A_{t}^{1/3}} - 0.31 \qquad (7)$$

We show in table 1, the mean value of r_{e}^{2} obtained for all isotopes measured with two magnetic rigidities $B\rho$.

IV. Comparison With Other Methods

In fig. 4, we compare our new r_{e}^{2} results with our results from associated-γ technique[4-5] and with results of associated-γ from Saint Laurent et al.[6] and with results of attenuation technique at 800 A·MeV from Tanihata et al.[1-3] using the same parametrization described in the section III. r_{e}^{2} data are plotted as a function of the isospin T_{z}.

The first conclusion we can infer from fig. 4 is that the values of r_{e}^{2} deduced from different experimental techniques and different energies agree rather well. Nevertheless we observe somewhat larger values of r_{e}^{2} obtained from the new direct method (this work) or attenuation (Tanihata) when compared with results from associated-γ technique for the very neutron rich nuclei (see ^{9}Li, ^{11}Li, ^{12}Be).

For these nuclei, the break-up reaction leading to a nucleus in the ground state or at low excitation energy plus one or several neutrons is expected to increase significantly[5-6]. Thus, this is a severe limitation on the associated γ-ray technique, which in this case will underestimate the reaction cross section and r_{o}^{2}. This problem does not exist in the case of the direct method or with attenuation methods.

Table 1. r_o^2 obtained for all isotopes measured.

A	Z	$r_o^2 (fm^2)$	$\delta r_o^2 (fm^2)$
8	2	1.767	0.276
9	3	1.365	0.024
12	4	1.418	0.062
13	5	1.210	0.012
14	5	1.360	0.026
15	5	1.649	0.152
14	6	1.144	0.003
15	6	1.335	0.016
16	6	1.224	0.012
17	6	1.227	0.033
15	7	1.097	0.036
16	7	1.167	0.021
17	7	1.161	0.010
18	7	1.200	0.013
19	7	1.222	0.017
20	7	1.211	0.048
17	8	1.304	0.168
18	8	1.162	0.030
19	8	1.179	0.019
20	8	1.160	0.014
21	8	1.123	0.022
22	8	1.220	0.040
21	9	1.134	0.025
22	9	1.137	0.020
23	9	1.150	0.020
24	9	1.167	0.039
25	9	1.256	0.103
23	10	1.087	0.061
24	10	1.126	0.030
25	10	1.188	0.036
26	10	1.199	0.041
26	11	1.073	0.059
27	11	1.188	0.039
28	11	1.252	0.054
29	11	1.218	0.056
30	11	1.343	0.013
29	12	1.260	0.089
30	12	1.195	0.056
31	12	1.163	0.077
32	12	1.461	0.110
32	13	1.103	0.085
33	13	1.364	0.066
34	13	1.189	0.096
35	13	1.401	0.127

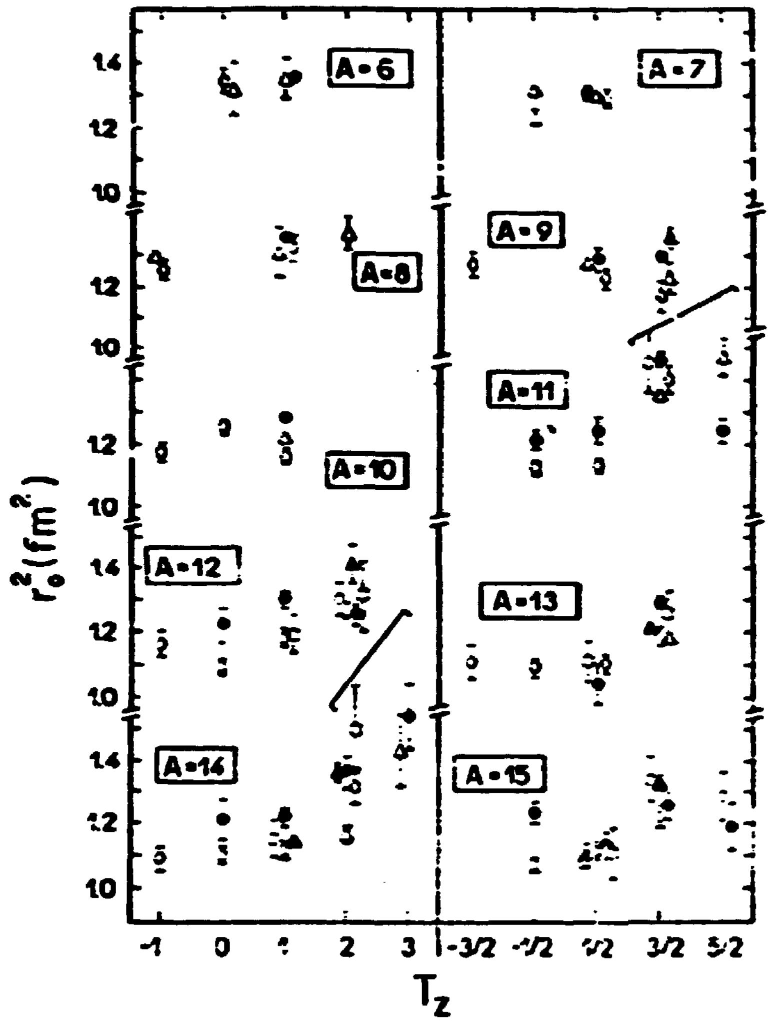

Fig.4. Variation of r_o^2 as a function of isospin: square = our work (associated-γ method) ref. 4, open circle = our work (associated-γ method) ref. 5, close circle = ref. 6, open triangle = Tanihata data ref. 3, close triangle = this work (direct method).

For all the measured isobars, a strong influence of isospin is revealed. We see an increase of r_e^2 when we go to the neutron rich side of any of the measured isobars.

The isospin dependence of nuclear radii has been already observed by Tanihata[3] for A=8 and 12. The predictions of the Hartree-Fock calculations with strong density-dependent Skyrme interaction[8] have given a fair agreement with the data of Tanihata, reproducing the trend of increasing r_e^2 as a function of isospin.

Preliminary Glauber-type calculations of σ_R for A=14, using self consistent nuclear density calculations[9] underestimated the increasing behaviour of r_e^2 with (N-Z). Calculations are being performed for all isobars and for all measured masses.

V. Conclusion

We developed a new simple direct method for the measurement of the reaction cross section (σ_R). We measured σ_R with this method for several exotic nuclei and we deduced the reduced strong absorption radii r_e^2. The r_e^2 obtained in this work agree well with those obtained by other techniques. We observed that, for the very exotic nuclei as ^{9}Li, ^{11}Li and ^{12}Be, there is a disagreement between the data from direct or attenuation technique and the associated-γ method. This is explained by the fact that for these nuclei, break-up reactions leading to a nucleus in the ground state or at low excitation energy plus one or several neutrons is expected to increase.

We observed a strong isospin dependence of the nuclear radii. The radii increase significantly when we go to the neutron rich side of any measured isobar with masses from A=10 up to A=18. For heavier nuclei, the effect is strongly reduced, at least in the isospin range measured.

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