ABSOLUTE CROSS SECTIONS FOR THE ^{64}Zn(^{12}C, X) AND ^{58}Ni(^{12}C, X) REACTIONS

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(Received 30 December 1981)

ABSTRACT — With a He-jet transport system at UNISOR, the absolute cross section for the ^{12}C induced reactions on ^{64}Zn and ^{58}Ni targets from 64 to 93 MeV were obtained from the yields for γ-rays from the decays of the resulting radioactivities.

Strong experimental cross sections are observed with the following outgoing particles: 2pn, α(2p2n), αp, 3pn, αpn and α2pn for ^{64}Zn and 2p, pn, 3pn, αp, αpn and α2pn for ^{58}Ni. Experimental values are compared with theoretical calculations based on a statistical model.

[NUCLEAR REACTIONS ^{64}Zn(^{12}C, X) and ^{58}Ni(^{12}C, X), $E_{^{12}C} = 64.0$ to 93.3 MeV; measured E_γ, I_γ; deduced $\sigma(E)$.]

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(7) UNISOR is a consortium of fourteen institutions and is supported by them and by the US Energy Research and Development Administration.

1 — INTRODUCTION

There is presently considerable research activity centered in the mass region $A = 60\text{-}80$ by in-beam spectroscopy and reaction experiments. Evidence has been found for the coexistence of both spherical and deformed shapes in ^{72}Se and ^{74}Se, refs. [1], [2], and more recently in ^{74,76}Kr where these nuclei exhibit very large ground state deformation with the 0^+_2 level in ^{76}Kr associated with near-spherical shape [3]. In ^{68,70}Ge evidence [4], [5] for the importance of the $g_{9/2}$ orbital is reported at spins 8^+ and this structure seems to occur in ^{72,74}Se also. In odd-A nuclei in this region evidence for the role of the $g_{9/2}$ orbital is also seen [6], [7], [8]. Rotational like bands built on this and other orbitals are seen [6]. In ^{65}Ga the data are best fitted by an asymmetric rotor model [6]. To further test this model in ^{65}Ga more data are needed on the $\Delta I = 1$ transitions in the $g_{9/2}$ and $f_{5/2}$ bands. The odd-odd nuclei in this region have been studied very little but a few high and low spin isomers are now known for example in ^{74}Br, refs. [9], [10]. For the first time levels built on the 4^- isomer in ^{74}Br have been identified and their structure is very rotational [11]. There should be similar isomers in the other odd-odd Br isotope and perhaps in the odd-odd As and Ga isotopes. Information about low spin states and high spin states from high spin isomers can provide valuable data to extend our understanding of the above nuclei. Experimental data on the radioactive decay of isotopes, particularly off the stability line, in this region with an on-line isotope separator would provide valuable and complementary information to these data, including the identification of new isomers. Levels built on such isomers may go unidentified as was first the case in our ^{74}Br work without knowledge of the radioactive decays.

In order to explore the feasibility of the use of the Unisor facility to obtain neutron deficient isotopes in this mass region we investigated the absolute cross sections of the reactions induced by bombardment of ^{64}Zn and ^{58}Ni targets with ^{12}C beams. The experimental results presented here show that neutron deficient isotopes can indeed be produced in sufficient quantity for good experiments with heavy ion beams with energies in the range studied. Strong experimental cross sections were observed for the following outgoing particles: 2pn, α(2p2n), αp, 3pn, αpn, and α2pn for ^{64}Zn and 2p, pn, 3pn, αp, αpn, and α2pn for ^{58}Ni.

There have been various theoretical calculations of the cross sections for heavy ion induced reactions [12]-[15]. There are of course various uncertainties in these calculations as discussed by Robinson et al. [16]. This group has already carried out some measurements of absolute cross sections to test these calculations in this nuclear region up to energies 51 MeV [16]-[18]. Our present results extend these measurements to test the calculations at higher energies. The experimental cross sections obtained in this work are compared with theoretical calculations obtained with the computer code ALICE developed by Blann and Plasil [15].

2 — EXPERIMENTAL PROCEDURE AND RESULTS

Enriched targets of ^{64}Zn of 4.3 mg/cm^2 (enrichment $>99\ \%$) and ^{58}Ni of 3.2 mg/cm^2 (enrichment $>99\ \%$) were bombarded by ^{12}C ions from the Oak Ridge Isochronous Cyclotron with beam energies from 64.0 to 93.3 MeV. The recoiling nuclei were transported with a He-jet system [19] through a teflon tubing of about 20 m length and deposited on a collection tape at UNISOR. After collecting for 144 seconds, the collected activities were moved to a counting chamber and γ-rays were detected with a Ge(Li) detector. Singles γ-ray measurements were performed in the multiscaling mode with 12 planes of each 12 s, in order to extract half-lives of the parent nuclei. The efficiency of the He-jet system was calibrated by a direct catch method, in which the recoil nuclei were collected for 10 min on Mylar film located 5 mm behind the target. After collection, the Mylar film was pulled out from the target chamber and the activities were counted at the same position as used with He-jet system from 6 min to 11 min after bombardment. This procedure was performed for the He-jet system, too. From the comparison of γ-ray intensities, obtained with both methods, of the 594, 604, 743, 1112, 1707, 1780 and 2018 keV transitions from ^{70}As ($T_{1/2}=52.5$ min), the efficiency was determined to be $22 \pm 3\ \%$. In this estimation it was assumed that the efficiency of the direct catch method was 100 %. The absolute efficiency of the Ge(Li) detector used was determined with an IAEA standard source.

Each singles γ-ray spectrum taken in the multiscaling mode was analyzed, and γ-rays were identified by the half-life of the known parent nuclei and relative intensities. Residual nuclei resulting from emitting xn, pxn, 2pxn(αx'n), 3pxn(αpx'n), 2αxn and 2αpxn were surveyed, where x or $x' = 0$ to 3.

Absolute cross sections were estimated with equation $(A - 8)$, as shown in the Appendix, by taking into account β-decay feeding from parent nuclei, if necessary. In the estimation of absolute cross sections, we made the three following asumptions:

1) The Faraday cup is 100 % efficient in catching the cyclotron beam.
2) The charge state for ions captured in the Faraday cup is 6^+.
3) The efficiency of the He-jet system is independent of projectile energy and independent of Z.

Although the charge state of the ^{12}C beam is originally 4^+, passage of ions through the target and the helium atmosphere (pressure of 0.8 atm) ionize them further to a most probably 6^+ charge state. The uncertainty of the energy-dependence of the He-jet system was less than 20 %, which was taken from ref. [20]. Uncertainties of 20 % were thus included in the errors of absolute cross sections.

The experimental cross sections along with the γ-ray energies and metimes used in the analysis are listed in Table I for ^{64}Zn. The beam energies are corrected for the energy losses in the target material. Unidentified γ-rays are listed in Table II, corrected for beam intensities, efficiencies and times.

The feeding corrections from β-decay were deduced to be less than 1 % of the total cross sections for every case. The largest value of F_β that we expect is the case with very small $T_{1/2}$ (p), compared with $T_{1/2}$ (d). Here F_β is the feeding correction factor from β-decay and a function of only the lifetimes of the parent nucleus ($T_{1/2}$ (p)) and of the daughter nucleus ($T_{1/2}$ (d)) (details in the Appendix).

In the present experiment the largest correction factor F_β could be for $^{64}Zn(^{12}C,p3n)^{72}Br$ ($T_{1/2}(p) = 78$ s) and $^{64}Zn(^{12}C,2p2n)^{72}Se$ ($T_{1/2}(d) = 8.4$ d). There F_β is 0.59, but since, even at

90 MeV the absolute value $\sigma_p = 0.26 \pm 0.06$ is very small compared with $\sigma_d = 36 \pm 8$, therefore the β-feeding correction had a negligible influence on σ_d.

3 — DISCUSSION

The experimental absolute cross sections were compared with theoretical calculations obtained with the ALICE program developed by Blann and Plasil [15]. These comparisons are ilustrated in Figs. 1-3 for ^{64}Zn and Figs. 4-5 for ^{58}Ni. In the Figs. 1 and 3, excitation curves for the ^{64}Zn(^{12}C, αp and/or 3p2n)^{71}As and ^{64}Zn(^{12}C, αn and/or 2p3n)^{71}Se reactions show that the cross section for both reactions decreases initially with increasing projectile energy and increases again above an energy of ~ 80 MeV. The first decreasing part is interpreted as due to the αn and αp component, and the increasing part due to the 2p3n and 3p2n reaction channels, respectively. This interpretation is seen to be reasonable by taking

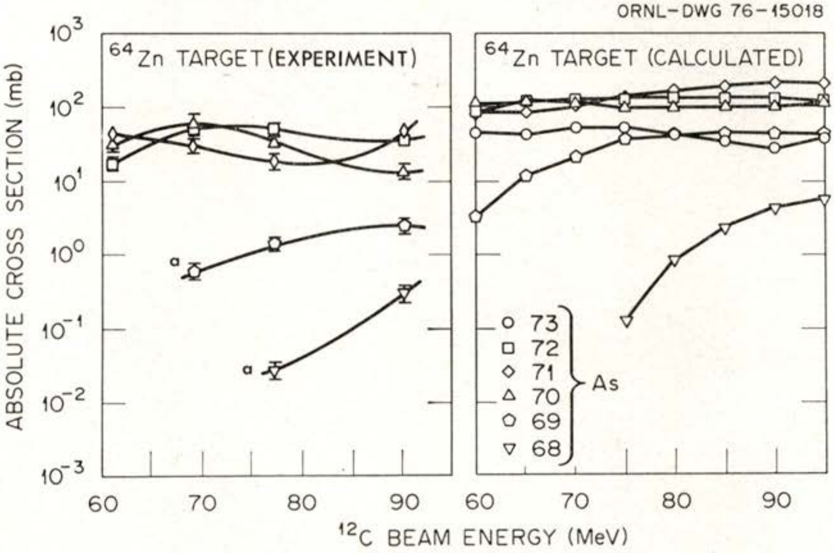

Fig. 1 — Experimental and calculated cross sections for the ^{64}Zn(^{12}C, 3pxn or αpxn)As reactions. The a indicates that the data for αp2n and αp3n channels are not corrected for absolute γ-ray abundances (η), since the ground state feeding is not known.

into account the Q values, $Q(\alpha n) = -9.9$, $Q(2p3n) = -41.9$, $Q(\alpha p) = -7.8$ and $Q(3p2n) = -36.1$ MeV. The theoretically calculated curves for ^{71}As and ^{71}Se of Figs. 1 and 3 also present similar rising for higher energies. However in the ^{71}Se case the experimental cross sections are one order of magnitude smaller than the calculated ones.

The experimental and theoretical values are reasonably close within factors of three to ten for the ^{64}Zn(^{12}C, α and/or 2p2n)^{72}Se, and within factors of two to six for ^{64}Zn(^{12}C,3pn)^{72}As, ^{64}Zn(^{12}C,αp)^{71}As and ^{64}Zn(^{12}C,αpn)^{70}As reactions. For other reactions the general features, but not the absolute values, are reproduced by the theoretical calculations. The agreement for the ^{64}Zn(^{12}C, α2pn)^{69}Ge, and ^{64}Zn(^{12}C, 2αn)^{67}Ge reactions is better than a factor of two but here the experimental data are not corrected for the absolute γ-ray abundances since the ground state feedings are not known. The agreement as shown in Fig. 2 suggests that the ground state feeding is probably negligible.

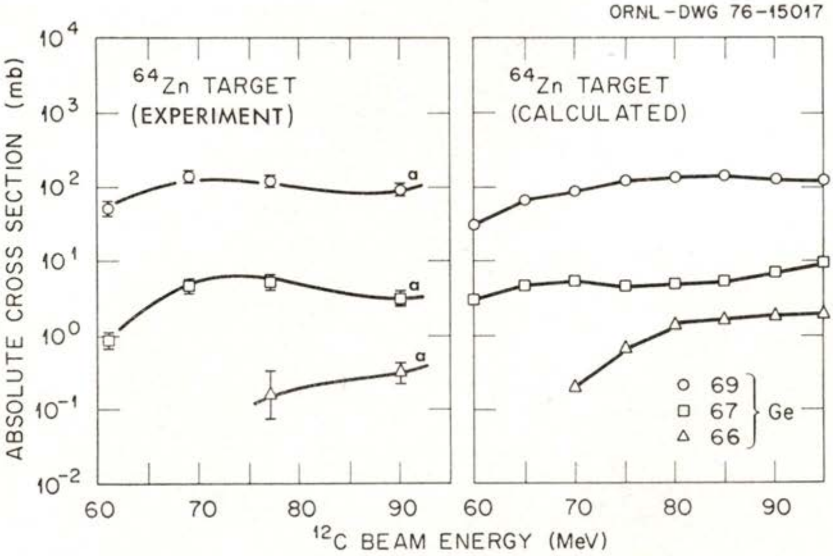

Fig. 2 — Experimental and calculated cross sections for the ^{64}Zn(^{12}C, α2pxn or 2αxn)Ge reactions. The *a* indicates each of these cross sections are uncorrected for the absolute γ-ray abundances (η), (see Discussion in the text).

For the ^{58}Ni(^{12}C, X)Y reactions, the experimental values are: smaller than the calculated ones for ^{68}As by a factor of five to one hundred; for ^{67}Ge from agreement to a factor of 20 lower; in near agreement for ^{66}Ga; a factor of five to ten smaller for ^{65,64}Ga; near agreement for ^{63}Zn; lower by factors of two to ten for ^{61}Zn – as shown in Figs. 4-6. Even though the cross section for production of ^{68}Ge is large, we could not observe ^{68}Ge because of its pure β-decay to the ground state of ^{68}Ga.

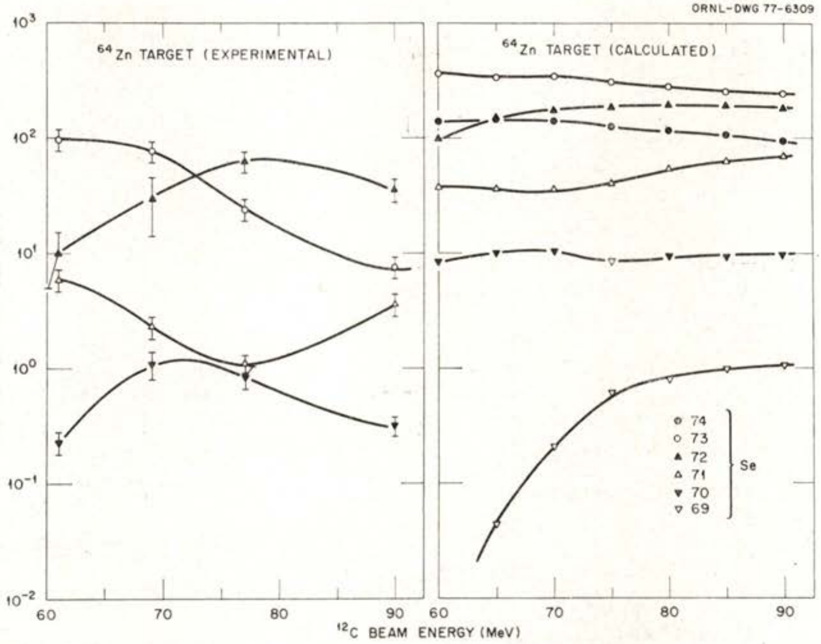

Fig. 3 — Experimental and calculated cross sections for the ^{64}Zn(^{12}C, 2pxn or αxn)Se reactions.

On the other hand, large discrepancies in the absolute values are found in the cases of ^{64}Zn(^{12}C, pxn)Br reactions. The ratios of the theoretical to experimental cross sections at 90 MeV are 2.4×10^3 and 4.5×10^2 for pn and p2n reactions respectively. The data of Robinson et al. [16] for the same compound nucleus, ^{60}Ni + ^{16}O → ^{76}Kr* → Br + pxn, yield an absolute pn cross section

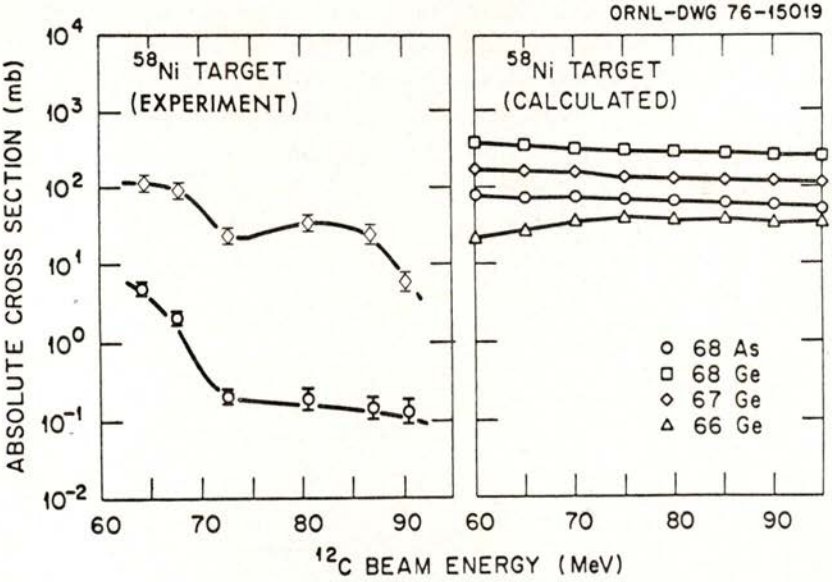

Fig. 4 — Experimental and calculated cross sections for the $^{58}Ni(^{12}C, pn)^{68}As$ and $^{58}Ni(^{12}C, 2pxn)Ge$ reactions.

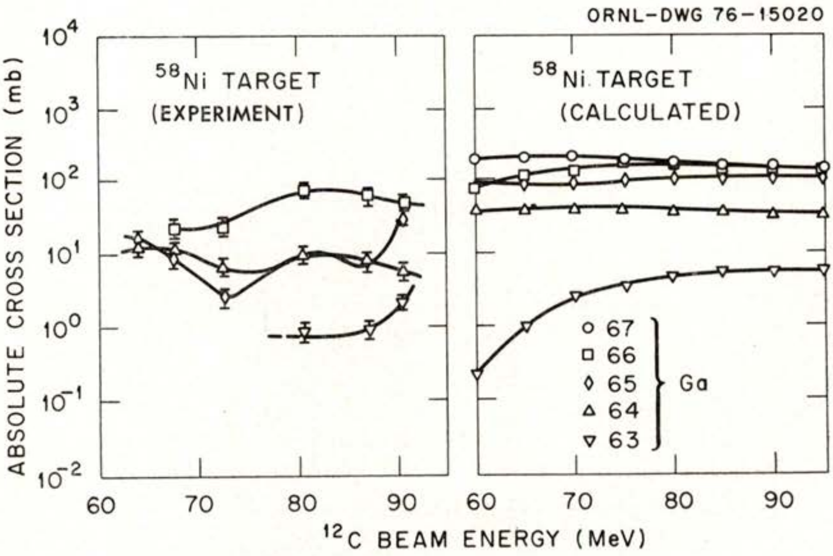

Fig. 5 — Experimental and calculated cross section for the $^{58}Ni(^{12}C, 3pxn$ or $\alpha pxn)Ga$ reactions.

of 95 mb at 46 MeV. The present value is 1.2 mb at 60.7 MeV. If outgoing particles p and n are emitted after formation of the compound nucleus, both reaction cross sections of ^{60}Ni(^{16}O, pn)^{74}Br and ^{64}Zn(^{12}C, pn)^{74}Br should have nearly the same values, like the αp, 2pn and αn cross sections as shown in Fig. 7. The large discrepancies between the experimental and the theoretical values and also with the ^{60}Ni(^{16}O, pn) reaction are thus rather surprising. One source of the discrepancies might be some experimental problem which we failed to take into account. For example, the Br isotopes may have been selectively absorbed by some of the materials used in the experiment. Such absorption can be the primary cause of the discrepancy observed.

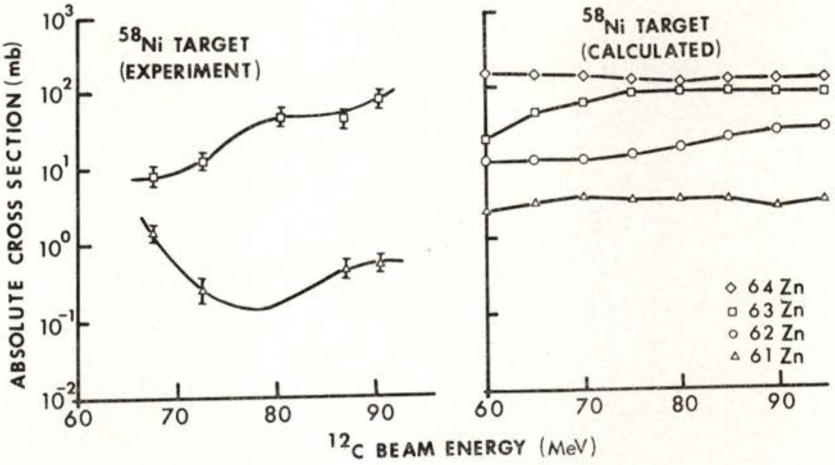

Fig. 6 — Experimental and calculated cross section for the ^{58}Ni(^{12}C, αpxn)Zn reactions.

The strong reactions are ^{64}Zn(^{12}C, 2pn)^{73}Se , 2p2n)^{72}Se , 3pn)^{72}As, αp)^{71}As, αpn)^{70}As, α2pn)^{69}Ge [with moderate cross sections for the production of ^{71}Se and ^{67}Ge] and ^{58}Ni(^{12}C, 2p)^{68}Ge, 3pn)^{66}Ga, 3p2n or αp)^{65}Ga, 3p3n or αpn)^{64}Ga and α2pn)^{63}Zn [with moderate cross sections for the production of ^{68}As and ^{61}Zn and an indication that the cross section for the production of ^{63}Ga may be good at higher energies]. We conclude that neutron deficient isotopes in this mass region can be produced in sufficient quantity for good experiments with heavy ion beams with energies in the range studied.

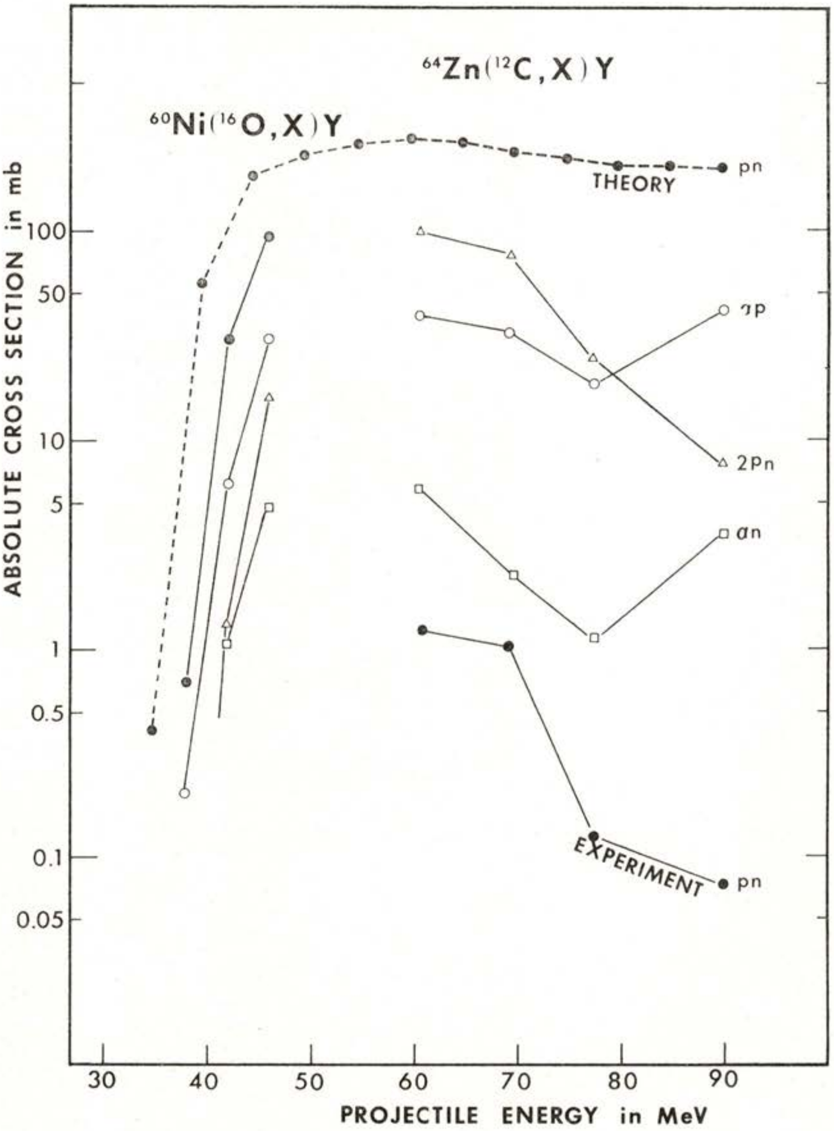

Fig. 7 — Comparison between ^{60}Ni(^{16}O, X)Y [16] and ^{64}Zn(^{12}C, X)Y reaction cross sections.

APPENDIX

In this appendix we derive the equations used for estimation of the absolute cross section. A derivation for the general case, as shown in Fig. 8, in which the isotope is produced both directly and through beta decay from a parent nucleus is presented below.

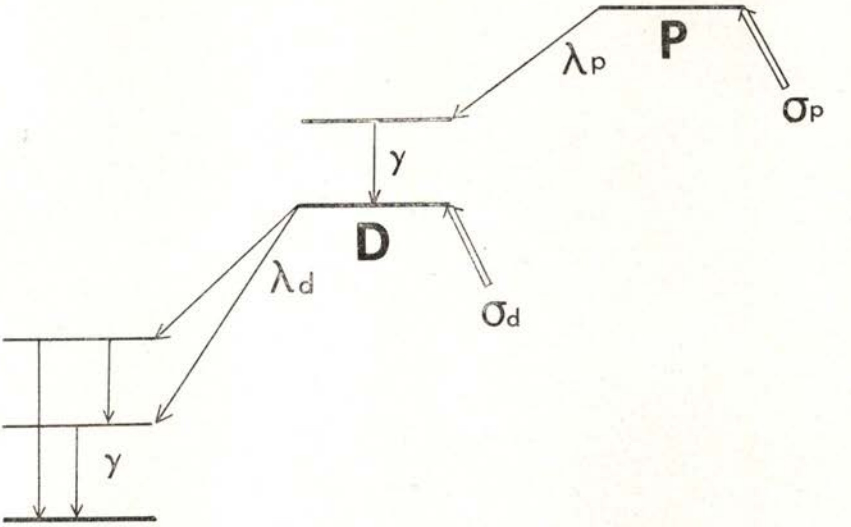

Fig. 8 — General scheme for the derivation of absolute cross sections.

Bombardment

The decay rates of parent and daughter nuclei, P(t) and D(t), at time t are given by

$$\frac{d\,P(t)}{dt} = -\lambda_p P(t) + \sigma_p N n_b \qquad \text{(A-1)}$$

$$\frac{d\,D(t)}{dt} = -\lambda_d D(t) + \sigma_d N n_b + \lambda_p P(t) \qquad \text{(A-2)}$$

where, $\lambda_{p,d}$ are the decay constants and σ the absolute cross sections in which we are interested; n_b is the beam intensity (atom/sec) which is related to the current integrator reading and charge state of the beam; and N is the number of atoms in the target (atom/cm^2). The solutions of the coupled differential equations are

$$P(t) = \frac{\sigma_p N\, n_b}{\lambda_p} \left(1 - e^{-\lambda_p t}\right) \tag{A-3}$$

$$D(t) = \frac{(\sigma_p + \sigma_d) N\, n_b}{\lambda_d} \left(1 - e^{-\lambda_d t}\right) + \frac{\sigma_p N\, n_b}{\lambda_d - \lambda_p} \left(e^{-\lambda_d t} - e^{-\lambda_p t}\right) \tag{A-4}$$

Measurement

A source is collected on the tape for T_b seconds, so the source initially has $P(T_b)$ "P" nuclei and $D(T_b)$ "D" nuclei. The number of nuclei "D" is given by

$$\frac{dD'(t)}{dt} = -\lambda_d D'(t) + \lambda_p P'(t) \tag{A-5}$$

where

$$P'(t) = P(T_b)\; e^{-\lambda_p t} \quad .$$

By using the initial condition at $t = 0$, $D'(0) = D(T_b)$, we find

$$D'(t) = N\, n_b \left\{ \left[\frac{p}{\lambda_d - \lambda_p} \left(1 - e^{-\lambda_p T_b}\right) \right] e^{-\lambda_p t} + \left[\left(1 - e^{-\lambda_d T_b}\right) \left(\frac{\sigma_d}{\lambda_d} - \frac{\lambda_p \sigma_p}{\lambda_d (\lambda_d - \lambda_p)} \right) \right] e^{-\lambda_d t} \right\} \tag{A-6}$$

Therefore, the counting rate R of a detector is

$$R(t) = \eta \varepsilon \omega \lambda_d\; D'(t) \tag{A-7}$$

where $\varepsilon\omega$ is the total efficiency of the system, and η is the γ-ray abundance.

Knowing the number of counts (n) detected in the counting time T_c, we can calculate the cross section,

$$\sigma_d = \frac{n}{\eta \varepsilon \omega\, N\, n_b} \cdot \frac{\lambda_d}{\left(1 - e^{-\lambda_d T_b}\right)\left(1 - e^{-\lambda_d T_c}\right)} - F_\beta \sigma_p \tag{A-8}$$

where, the β-feeding correction factor F_{β} is

$$F_{\beta} = \frac{\lambda_d}{\lambda_d - \lambda_p} \left\{ \frac{\lambda_d}{\lambda_p} \frac{(1 - e^{-\lambda_p T_b})}{(1 - e^{-\lambda_d T_b})} \frac{(1 - e^{-\lambda_p T_c})}{(1 - e^{-\lambda_d T_c})} - \frac{\lambda_p}{\lambda_d} \right\} \qquad \text{(A-9)}$$

Experimental σ_p values are obtained from the same equation (A-8) by putting $F_{\beta} = 0$ and substituting σ_p and λ_p for σ_d and λ_d. Now we can estimate the optimum counting or collection time at UNISOR.

For simplicity; let $\sigma_p = 0$; $T_b = T_c = t$ and the total time of an experiment T, then the total counts are given by

$$n'(t) = n \cdot \frac{T}{t} \propto \frac{(1 - e^{-\lambda_d t})^2}{\lambda_d t} \quad .$$

Fig. 9 shows the relation of n′ *vs* $t/T_{1/2}$. The maximum counts are obtained at $t = 1.8\ T_{1/2}$.

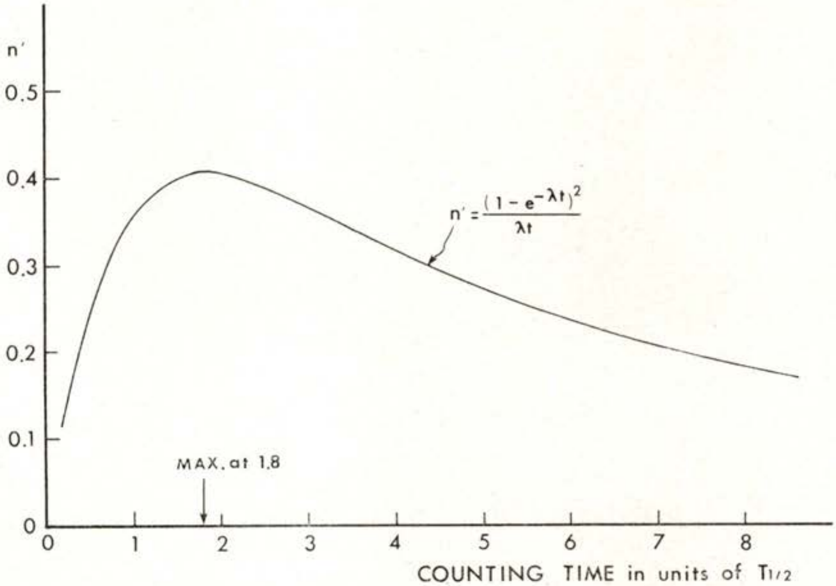

Fig. 9 — The relation of counting time vs. total counts in the isotope separator experiment. The maximum counts are obtained at $t = 1.8\ T_{1/2}$.

TABLE I — Absolute Cross Section for ^{64}Zn(^{12}C, X)Y Reactions. The γ-ray energies and the half-lives used in this analysis are also listed. In some cases the γ-ray abundance, η, is unknown and so enters σ_{ab} as a parameter.

Out-Going Particle	Residual	E_γ (keV)	$T_{1/2}$	$T_{1/2}$ (Parent)	σ_{ab} (mb) Energy (MeV) 60.7	69.3	77.5	90.0
n	^{75}Kr	133, 157	5.5 m					
p	^{75}Br	286.8	1.68 h					
pn	^{74}Br	634.8	25 m (1$^-$) or 42 m (4)*		1.22 ± 0.26	1.03 ± 0.22	0.122 ± 0.054	0.072 ± 0.027
p2n	^{73}Br	64.4, 335.6	3.3 m		0.87 ± 0.18	2.00 ± 0.42	0.86 ± 0.18	0.141 ± 0.030
p3n	^{72}Br	862.3	78 s			0.037 ± 0.008	0.18 ± 0.04	0.26 ± 0.06
2p	^{74}Se		STABLE					
2pn	^{73}Se(9/2+)	67.0	7.2 h		98 ± 21	68 ± 16	24 ± 5	7.6 ± 1.6
	^{73}Se(1/2−)	84.5, 393.4, 1078.6	39 m	3.3 m		50	14	4.8
2p2n	^{72}Se	45.9	8.4 d	78 s	10 ± 5	30 ± 16	63 ± 13	36 ± 8
αn or 2p3n	^{71}Se	147.1, 723.3, 830.8, 870.8, 1095.8	4.9 m		5.9 ± 1.2	2.3 ± 0.5	1.1 ± 0.2	3.6 ± 0.8
α2n	^{70}Se	49.2, 202.6, 376.7, 426.0	41 m		0.23 ± 0.05	1.1 ± 0.3	0.84 ± 0.18	0.32 ± 0.06

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* We took a mean value of 25 m and 42 m, even though the high spin isomer should be more strongly populated. The error assigned overlaps the results if $T_{1/2} = 42$ m is assumed.

TABLE I — (cont'd)

Out-Going Particle	Residual	E_γ (keV)	$T_{1/2}$	$T_{1/2}$ (Parent)	σ_{ab} (mb) Energy (MeV) 60.7	69.3	77.5	90.0
α3n	^{69}Se	98, 66.4	27.3 s					
3p	^{73}As	53.3	80.3 d					
3pn	^{72}As	834.5	26 h	8.4 d	17 ± 4	52 ± 11	51 ± 11	42 ± 9
αp or 3p2n	^{71}As	175.3	62 h	4.9 m	39 ± 8	33 ± 8	18 ± 5	41 ± 9
αpn	^{70}As	595.2, 905.9, 1114.0	52.5 m	41 m	30 ± 6	68 ± 13	39 ± 8	15 ± 3
αp2n	^{69}As	146.0, 232.8	15 m	27.3 s		$0.57 \pm 0.13/\eta$	$1.5 \pm 0.3/\eta$	$2.6 \pm 0.6/\eta$
αp3n	^{68}As	1016.2, 651.5, 761.9, 1778.5	2.7 m				$0.029 \pm 0.015/\eta$	$0.32 \pm 0.06/\eta$
α2p	^{70}Ge		STABLE					
α2pn	^{69}Ge	1106.5	39.2 h	15 m	$54 \pm 12/\eta$	$151 \pm 33/\eta$	$131 \pm 28/\eta$	$96 \pm 20/\eta$
2α	^{68}Ge		288 d	2.7 m				
2αn	^{67}Ge	166.8	19.0 m		$0.93 \pm 0.20/\eta$	$4.9 \pm 1.1/\eta$	$5.6 \pm 1.2/\eta$	$3.4 \pm 0.7/\eta$
2α2n	^{66}Ge	382.0	2.27 h				$0.16 \pm 0.10/\eta$	$0.33 \pm 0.10/\eta$
2α3n	^{65}Ge	649.7	30.9 s					
2αp	^{67}Ga	93.3, 184.6	78.3 h	19.0 m				
2αpn	^{66}Ga	1039.3 833.6	9.4 h	2.27 h				
2αp2n	^{65}Ga	115.0	15.2 m	30.9 s				1.4 ± 0.30

TABLE II — Unidentified γ-rays observed in the ^{64}Zn(^{12}C, X)Y reactions. Raw total counts are divided by efficiencies (ε and ω), beam intensitities (n_b), and times (T_b and T_c).

E_γ	I_γ			
	60.7	69.3	77.5	90.0
74.7	43	35	26	30
121.9	10	7.4	2.4	
143.2	155	43	29	68
180.9	67	64	21	22
358.8	101	98		37
514.7	368	473		
626.6				71
637.8	24	66		
657.9	409	193	95	245
659.1	419	99		209
812.3			66	81
828.1	45	115	81	56
843.4	65			29
925.1	75	18		
937.4	60	44	11	16
962.7			26	44
1073.4		16		35
1179.8	54	173	70	30
1255.1	42		78	
1295.7	62		30	27
1307.6			17	22
1317.4			17	19
1378.6				10
1381.0				27
1382.2	55			13
1443.2	24	52		17
1527.1				23
1535.2				45
1550.6	156	273	157	117
1552.1	101	321	160	
1605.8	77	33	11	
1625.3	48	165	65	
1640.4			37	37
1680.8			27	44
1714				
1767.4		21	40	53
1850.9		82	43	
1923.2		59	31	
1934.6	37			19
1945.8		48	36	
2001.2		8.2	34	48
2014.8			16	23
2033.8		36	14	

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