FR8202592

IN2P3
CENTRE D'ÉTUDES NUCLÉAIRES
DE BORDEAUX-GRADIGNAN
LE HAUT-VIGNEAU
33170 GRADIGNAN

CENBG 8207

MECHANISMS OF ALPHA EMITTER PRODUCTION IN ^{12}C INDUCED REACTIONS AT 1 GeV

J.P. Dufour, H. DELAGRANGE, R. Del Moral, A. Fleury
F. Hubert, Y. Llabador, M.B. Mauhourat, K.H. Schmidt
and A. Lleres

XX INTERNATIONAL WINTER MEETING ON NUCLEAR PHYSICS
BORMIO - JANUARY 25-30, 1982

CENBG 8207

MECHANISMS OF ALPHA EMITTER PRODUCTION IN ^{12}C INDUCED REACTIONS AT 1 GeV

J.P. Dufour, H. Delagrange, R. Del Moral, A. Fleury,

F. Hubert, Y. Llabador, M.B. Mauhourat, K.H. Schmidt*

C.E.N.B.G., Le Haut Vigneau - 33170 Gradignan, France

and

A. LLERES

Institut des Sciences Nucléaires - 53, Avenue des Martyrs

38026 Grenoble Cedex, France

Abstract :

We present cross sections, mean projected recoil ranges and angular distributions of radioactive alpha emitters produced in ^{12}C-induced reactions at 1 GeV on targets ranging from Gd to Pb. We use a new technique of on-line electrostatic collection. The wide spectrum of produced isotopes corresponds to nuclei close to the target up to nuclei with as much as 60 nucleons less than the target. The intranuclear cascade calculations can reproduce the main features of nuclei having lost up.

- - -

presented at the XX International Winter Meeting on Nuclear Physics, Bormio (Italy), January 25-30, 1982

* Permanent adress : Gesellschaft für Schwerionenforschung, GSI, Darmstadt (RFA)

to 30 nucleons. The characteristics of produced isotopes with higher mass deficit seem to indicate that a primary interaction is responsible to a large extent of this mass loss, and leads to prefragments with an associated excitation energy greater than 200 MeV, allowing the production of neutron deficient species.

I - Introduction

In heavy ion collisions, the intermediate energy region from 10 MeV/u to 100 MeV/u has a special interest as being the domain of a marked transition behavior in nuclear matter, the milestone between low and high energy reaction mechanisms{1}. This feature can be related to the fact that to this energy domain belong two velocities characteristic of nuclear matter, the sound velocity and the mean Fermi velocity of a nucleon. Within the general concept of participant-spectator introduced in high energy heavy ion physics, our study deals with the properties of the target spectator (TS) oft-defined as "target fragmentation residues"(TFR) {2}. We investigate the production characteristics of such spectators in ^{12}C interactions with medium or heavy mass targets at a bombarding energy of 1 GeV. Due to the actual limitations of our original experimental set-up, we are restricted to the on-line observation of α radioactive species. Nevertheless, usually present TS studies suffer from experimental constraints, i) isotopes detected in off-line γ-spectroscopy, covering a small domain away from the stability line, ii) limited quantity of elements and targets suitable for mass spectrometry. In this context, one of the advantage of on-line α-spectroscopy is the detection of very neutron deficient species particularly in the case of medium and high mass targets. Such an experimental situation is thought to put additional contraints on theoretical models and prepare the optimal conditions for the discovery of new isotopes.

In order to classify and interpret the experimental results obtained for these reactions, two theoretical models quite opposite in their fundamental principles can be introduced as benchmarks, the intranuclear cascade (INC) and the abrasion-ablation (AA) models. They are however both based on a two-step process, reminiscent of the Serber model for high energy p-induced reactions [3]. In the INC framework, during the interaction time, quasi-free collisions occur between the individual nucleons of the projectile and the target nucleons, starting in the overlap region between the projectile and the target [4, 5]. The net result is the ejection of fast light particles associated with a wide spectrum of excitation energy deposited in both projectile and target nuclei. As calculated with the help of the HIC-I code described in Ref [4], the target spectators formed during the initial step of the interaction or "target prefragments" are located about the target with no more than 5 nucleons being ejected in average.These prefragments have an excitation energy ranging from 0 to 600 MeV [6]. In the abrasion-ablation model [7, 8], the projectile punches a clean hole in the target and as a result, the excitation energy is at least equal to the difference between the surface energies of the resulting residue and a spherical nucleus of same volume. The maximum mass deficit corresponding to most central collisions amounts to $\sim$ 50 nucleons ; this situation corresponds to the maximum excitation energy ($\sim$ 300 MeV). The prefragments have in average the target N/Z ratio and are then neutron rich isotopes.

In the case of high energy heavy ion induced reactions on targets of A $\sim$ 100, the two codes predict very similar results. This has been documented by Porile et al. [9] for the reaction ^{12}C + Ag at 25.2 GeV (See Fig. 7 in Ref. [9]).This results from the great proximity, in this region of mass 100, of the $\Gamma_n/\Gamma_p = 1$ line with the stability line (Γ_n and Γ_p are the decay widths for neutron and proton statistical emission respectively). Even if prefragments are formed with high excitation energy in the INC model, their statistical decay leads to isotopes close to the stability line and the same isotopes can be produced by AA prefragments having lost a larger number of nucleons in the AA primary interaction. On the contrary for reactions with heavier targets, the $\Gamma_n/\Gamma_p = 1$ line lies further away from the stable isotopes. The information on the conditions of production for neutron deficient residues can serve as a criterion to estimate the amount of excitation energy deposited in the target-like nucleus, allowing to differenciate between these two theoretical models. There is an experimental evidence for a loss of 23 neutrons and 1 proton from the target in such reactions [10]. The experimental studies of ^{12}C induced reactions (E_{lab} = 1 GeV) on targets of $A \gtrsim 150$ offer then a real possibility to test the validity and define the limits of these theoretical ideas.

II - Experimental procedure and results

Targets ranging from Gd to Pb have been bombarded with the ^{12}C beam of 86 MeV/u, delivered by the synchro-cyclotron at CERN. The typical beam intensity was 10^{10} particles/second. Details of the experimental set-up and operation conditions of the new on-line electrostatic method to collect radioactive alpha emitters can be found in the following references [6, 11, 12]. Several adaptations of this collection principle allow the measurements of cumulative and independent (e.g. the N = 85 isotones) yield cross-sections, mean projected recoil ranges, and angular distributions. As we measure only a limited proportion of all the residues which can be formed, in order to reproduce the overall shape of the residue mass distribution we vary the target element. In these conditions, the various distributions are parametrized as a function of either $\Delta A = A_T - A_R$ or $\Delta Z = Z_T - Z_R$ where T and R stand for target and residue respectively. Part of the results presented at this meeting have been already published [10] and the remaining part must be considered as somewhat preliminary data.

Typical independent yield cross sections with an associated mass loss ΔA lower than 35 nucleons are presented in Fig. 1. A similar maximum (between ^{151}Dy and ^{152}Ho) for all these isotonic distributions is a stricking and interesting experimental result. This maximum production corresponding to quite different mass loss (ΔA = 18 for ^{169}Tm and ΔA = 35 for ^{186}W) can be related to the influence of the Γ_n/Γ_p = 1 line during the extensive decay chain taking place after a primary interaction rather well described in the INC framework [10]. The knowledge of the initial N/Z ratio is unfortunately lost but information can still be gained on the average excitation energy distribution of the prefragments as illustrated in Fig. 2. The ratio of N = 85 independent yield cross-sections between $^{12}C + {}^{182}W$ and $^{12}C + {}^{186}W$ reactions (bottom of Fig. 2) is sensibly greater than one, feature which is reproduced quite nicely by INC calculations. Within this model, prefragments formed in $^{12}C + {}^{182}W$ need about 400 MeV of excitation energy to reach the N = 85 isotones compared to about 460 MeV in the $^{12}C + {}^{186}W$ case. As the excitation energy spectrum (insensible to the target nature) decreases in this energy range, the resulting residue ratio is then greater than unity.

The INC calculations are able to reproduce rather well the isotonic yield distributions with residues no more than 35 nucleons lighter than the target. This conclusion is illustrated in Figs. 2 and 3. In the case of ^{12}C + $^{182,\ 186}W$ reactions (top of Fig. 2) the magnitude of the calculated cross-sections is in good agreement with experimental values. There is only a shift of one Z unit between experimental and calculated distributions. This is extremely satisfactory for such complex calculations performed with a-priori parameters [4, 6]. The lower limit of 1 mb is due to the choice of the initial number of cascades imposed by computer time considerations. The experimental results for the ^{12}C + ^{197}Au reactions are displayed in Fig.3. In the case of the N = 85 isotones (left-inside of Fig. 3) corresponding to mass losses greater than 40 ($42 < \Delta A < 46$), the experimental cross-sections are quite greater than 1 mb but they are not reproduced by INC calculations. The prefragment characteristics predicted by the AA model for a very similar system (^{12}C + ^{208}Pb from R. Legrain [13]) are presented in Fig. 4. The N = 85 isotone maximum production corresponds to ΔA = 45 amu and ΔZ = 12. We may reasonably assume that the evaporation chain originates from a prefragment formed by abrasion and leads to such a final residue only consists of subsequent neutron statistical emission. In such conditions, the target-like prefragment must have lost 30 nucleons in the abrasion interaction (corresponding to A = 178 in ^{12}C + ^{208}Pb theoretical calculations) and possess an excitation energy of 200 MeV to emit the 15 remaining neutrons. This needed excitation energy is predicted in the AA model ; the corresponding impact parameter is $\sim$ 5.6 fm. Even if the energy balance seems correctly predicted, in view of the high level of simplification, this agreement can be accidental. More complete calculations are in order but the incentive to perform such computations has been demonstrated.

In Fig. 5 are presented isotopic and isobaric ratios about ^{151}Dy for various ΔZ losses. The enhancement of both these ratios with increasing ΔZ indicates that isobaric and isotonic distributions are displaced for residues formed further and further away from the target or in other words the production of more and more neutron deficient species is favored. At first sight, this experimental fact can be ascribed to the influence of longer and longer chains of evaporation. But for the larger ΔZ, the needed excitation energy would at least require the total available energy deposited by a highly improbable complete momentum transfer. Furthermore this simple explanation can be completely rejected by looking to the recoil range data as presented latter on. The isomeric ratios or more precisely the ratios between production cross-sections for high spin and low spin isomeric states present also interesting qualitative aspects (Fig. 6). For all three considered isotopes, independent of mass loss, the high spin states are always more populated. The ^{154}Tm case is most striking. The rapid rise of the isomeric ratio in the case of a production close to the target may correspond to the transition from very peripheral collisions to less peripherical interactions. In the very peripherical collisions, only few nucleon-nucleon collisions occur and only relatively small values of angular momentum can be transferred. When the impact parameter diminishes, the overlap region between the two nuclei is then enlarged and this favors angular momentum transfer. This seems effective until the system feels the influence of the projectile orbital momentum as indicated by the net decrease of the ^{154}Tm isomeric ratio with increasing ΔZ. The same fall-down is observed for the two other isotopes nevertheless with less amplitude (This difference has a only chance to be completely understood when the exact spin values will be determined for ^{154}Tm). This pattern at high ΔZ can then be interpreted as a transition from a nucleon-nucleon picture to a more collective interaction of the projectile with the target.

In the AA model this transition is also associated to smaller values of impact parameter. A similar behavior is observed with the mean projected recoil ranges (case of ^{150}Dy in Fig. 7). The experimental ranges are in approximate agreement with INC expectations up to $\Delta A \sim 30$. For mass losses not predicted by this model ($\Delta A >> 30$), the linear momentum transfer continues to raise up to 2.2 GeV/c for ^{150}Dy produced in $^{12}C + ^{208}Pb$. This continuous rise in recoil ranges indicates that for $\Delta A = 30$ near-central collisions have not yet been reached as envisaged in INC calculations.

We observe also residues very close to the target nucleus with atomic numbers greater than the target Z (see Table I) but with almost the target mass. We denote this type of reactions as "charge exchange" reactions.Such a production mode is not reproduced by the INC calculations we used (here density distributions are approximated by only three step functions). Before stating definite conclusions, as these reactions are throught to be very peripheral and then strongly dependent on nuclear density profiles at large radial distances, more elaborated INC calculations must be performed.

Before presenting angular distribution data, we will precise some experimental details necessary to understand their real meaning. On-line angular distributions have been measured with a small moving collection cell under pressure placed in the reaction chamber as a classical gas-detector. Due to the small mean recoil energies of the target fragments (ranging from $\sim$ 2 MeV for $\Delta A = 10$ to $\sim$ 17 MeV for $\Delta A = 60$, Fig. 7), the thickness of the target has a strong influence. A choice has to be made between two extremes : i) a thin target ($\sim$ 100 $\mu g/cm^2$) allowing most of the activity to escape, ii) a thick target (3 mg/cm^2) in which the effective target thickness is proportional to the recoil energy. Due to counting rate considerations we chose this latter option and then measured in fact the quantity $\overline{R}(\theta) \frac{d\sigma}{d\Omega}(\theta)$, $\overline{R}(\theta)$ being the mean recoil range in the target material at a given angle θ. In addition to this effect the thickness of the cell window (Mylar 200 μg/cm^2)prevents the very low energy recoils to enter the collection volume (the resulting low energy threshold is about 2 MeV). The measured activities are then related but not exactly equal, to the angular distribution $\frac{d\sigma}{d\Omega}(\theta)$ in such a way that could be taken into account by theoretical approaches.

The experimental results are presented in Fig. 8 for two targets : ^{181}Ta and ^{208}Pb. With the Ta target the mass loss is ∿ 30 and it seems that only slight differences are observed between the two groups of residues (Dy - Ho) and (Er - Tm). (The exact production of individual isotopes is available, but with quite lower statistics). With the Pb target, differences become more significant in particular for the two rare-earth groups (Dy-Ho) and (Er-Tm). We found interesting and surprising that only a difference of 1 or 2 protons for a same N(85) is correlated with somewhat different transverse momentum transfer. It is of prime importance for the understanding of this effect to remember that the maximum of production in the N-Z plane is observed in a narrow band nearly or on the $\Gamma_n/\Gamma_p = 1$ line. This region plays a special role in the deexcitation path, hindering deeper losses of neutrons and gathering in a close band residual nuclei having eventually different histories. So, when looking at the close nuclei ^{151}Dy, ^{152}Ho, ^{153}Er (N = 85 isotones) located astride the $\Gamma_n/\Gamma_p = 1$ line, we look at some convergent final states of may be very different formation paths. Namely the evaporative precursor nuclei (after the direct interaction) may have different masses, N/Z ratios and excitation energy but nevertheless produce residual nuclei in the same region.

In this framework the less neutron deficient production at wide angles could be associated with the greater losses of mass in the direct quick process. This question is still under analysis.

III - Final remarks

The general conclusion concerning the theoretical model description of the results is that none of them is able to reproduce all our data. More precisely, the INC model is successful for the low losses of mass (ΔA) ranging from 10 to 20, becomes less satisfactory for the ΔA from 20 to 35, and fails for the greater ΔA. On the opposite, the abrasion-ablation model seems to correctly describe the great losses of mass (35 to 60) but does not appear to be successful for explaining the great losses of neutrons involved in the formation of residues having the target Z or more ($\sigma_{^{154}Tm} \simeq 4$ mb in ^{169}Tm target). As a matter of fact for the AA model, the excitation energy transfer is strongly related to the extent of the volume shaked off. Thus, near Z target prefragments have only small excitation energy (less than 50 MeV) and are in this description unable to loss so much more neutrons than protons. As far as we may relate the losses of mass and the recoil energies to the impact parameter b, the two models may be considered valid in the extreme cases: $b \simeq R_1 + R_2$, few nucleons are under interactions (INC), and $b \simeq 0$ a great number of nucleons interact collectively (abrasion-ablation). Our experiments do not show evidence of sharp transitions in the domain of mass residues explored ($0 < \Delta A < 60$) indicating that a smooth mixing of the extreme theoretical approaches is required.

We would like to acknowledge the very efficient collaboration of the CERN-SC staff and in particular of Allardyce and Le Gallic.
Dr R. Legrain has kindly performed for us abrasion-ablation calculations.

References

[1] D.K. Scott, Michigan State University, Cyclotron Laboratory Report n° MSUCL-359 (1981)

[2] A.S. Goldhaber and H.H. Heckman, Ann. Rev. Nucl. Part. Sci. 28, 161 (1978)

[3] R. Serber, Phys. Rev. 72, 1008 (1947)

[4] H.W. Bertini, T.A. Gabriel, R.T. Santoro, O.W. Hermann, N.M. Larson and J.M. Hunt, HIC-1 code package, RSIC Computer code collection, ORNL CCC-249 (1975)

[5] Y. Yariv and Z. Fraenkel, Phys. Rev. C20, 2227 (1979)

[6] M.B. Mauhourat, Thèse 3ième Cycle, Université de Bordeaux I, 1981 (Unpublished)

[7] J. Bowman, W.J. Swiatecki and C.F. Tsang, LBL-2908, 1973 (Unpublished)

[8] D.J. Morrissey, W.R. Marsch, R.J. Otto, W. Loveland and G.T. Seaborg, Phys. Rev. C18, 1267 (1978)

[9] N.T. Porile, G.D. Cole and C.R. Rudy, Phys. Rev. C19, 2288 (1979)

[10] J.P. Dufour H. Delagrange, R. Del Moral, A. Fleury, F. Hubert, Y. Llabador, M.B. Mauhourat, Phys. Lett. B109, 265 (1982)

[11] J.P. Dufour, Thèse es-Sciences Physiques, Université de Bordeaux I, 1981 (Unpublished)

[12] J.P. Dufour, R. Del Moral, A. Fleury, F. Hubert, Y. Llabador, M.B. Mauhourat, R. Bimbot, D. Gardès, M.F. Rivet, Proceedings of the 4th International Conference on Nuclei Far From Stability Helsingor, June 7-13, 1981, Report CERN n° 81-09

[13] R. Legrain (private communication)

Table I Observed charge exchange reactions in 1 GeV ^{12}C-induced reactions. In this type of reactions, residues are formed with an atomic number Z greater than the target Z. The net associated mass loss is small or null.

$Z_R - Z_T$	System	ΔA	σ(mb)
2	$^{12}C + ^{232}Th \rightarrow ^{230}U + X$	- 2	0.3
3	$^{12}C + ^{151}Eu \rightarrow ^{151}Dy + X$	0	2.4
3	$^{12}C + ^{151}Eu \rightarrow ^{150}Dy + X$	- 1	1.1

Figure Caption

Fig. 1 Experimental absolute independent yield cross sections for $N = 85$ isotones as a function of residue atomic number. The solid curves are just to guide the eyes. Each distribution is labelled by the target isotope (From Ref. [10]).

Fig. 2 Theoretical and experimental absolute independent yield cross-sections (as well as their ratio) as a function of the residue atomic number Z for $N = 85$ isotones produced in $^{12}C + {}^{182}W$ and $^{12}C + {}^{186}W$ reactions. The theoretical predictions are represented as a hatched area indicating error limits (from Ref. [10]).

Fig. 3 $N = 85$ isotonic and Pt isotopic yield distributions for the reaction $^{12}C + {}^{197}Au$ (1 GeV). Cumulative yield cross-sections are represented by black squares (■) and independent yield cross-sections by open circles (O).

Fig. 4 Prefragment characteristics predicted by the AA model for the $^{12}C + {}^{208}Pb$ reaction (From R. Legrain [13]. Here are represented, the impact parameter b (in fm) with R_T and R_B respectively the target and projectile radii ($R = r_0 A^{1/3}$, $r_0 = 1.36$ fm), the excitation energy E^* (MeV), the production cross section σ (mb) and the location of these prefragments ($A_{prefragment} - A_{\beta\text{-stability}}$) with respect to stability.

Fig. 5 Isotonic and isobaric ratios as a function of ΔZ ($\Delta Z = Z_{target} - Z_{residue}$) for residues formed about ^{151}Dy in ^{12}C-induced reactions (1 GeV).

Fig. 6 Isomeric ratios for various isotopes as a function of ΔZ

Fig. 7 Theoretical and experimental projected recoil ranges for ^{150}Dy as a function of ΔA. Experimental data are represented as black points with a solid curve drawn through them to guide the eyes. The dashed curve is the INC predictions (From Ref. [10]).

Fig. 8 The evolution of the quantity $\bar{R}(\theta) \frac{d\sigma}{d\Omega}(\theta)$ is shown as a function of the laboratory angle for the two targets ^{181}Ta and ^{208}Pb. In order to emphasize the shape similarities or differences in the distributions experimental cross-sections have been normalised at 24° and 34° for the different isotopes. Each curve corresponds to the weighted mean value for several isotopes. This provide the statistic error bars to be sufficiently reduced and give more confidence to the deviations between the productions of Dy-Ho and Er-Tm at wide angles as observed on lead.

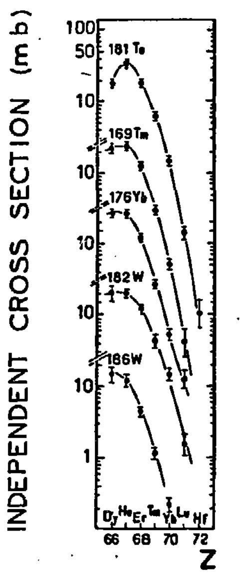

INDEPENDENT CROSS SECTION (mb)
181 Ta
169 Tm
176 Yb
182 W
186 W
Dy Ho Er Tm Yb Lu Hf
Z

Fig. 1

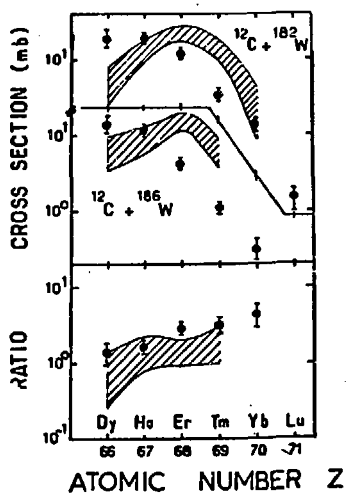

CROSS SECTION (mb)
RATIO
$^{12}C + ^{182}W$
$^{12}C + ^{186}W$
Dy Ho Er Tm Yb Lu
ATOMIC NUMBER Z

Fig. 2

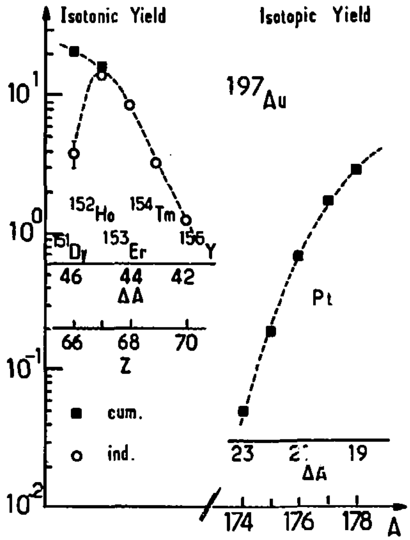

Isotonic Yield
Isotopic Yield
197Au
152Ho
154Tm
151Dy
153Er
156Y
46
44
42
ΔA
66
68
70
Z
cum.
ind.
Pt
23
19
ΔA
174
176
178
A

Fig. 3

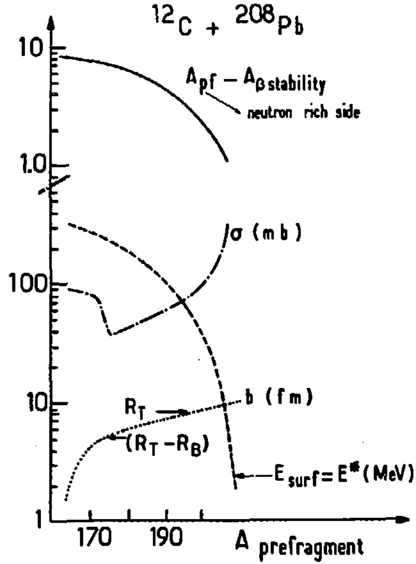

12C + 208Pb
Apf − Aβ stability
neutron rich side
σ (mb)
RT
b (fm)
(RT − RB)
Esurf = E* (MeV)
170
190
A prefragment

Fig. 4

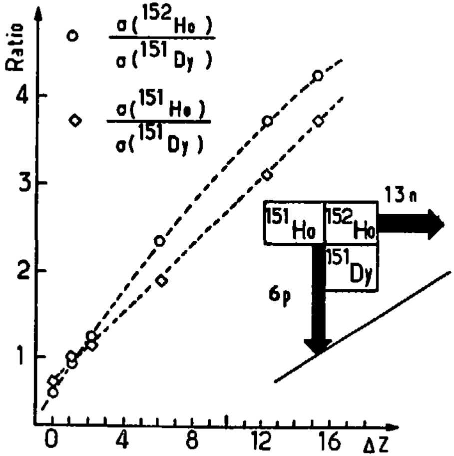

Ratio
σ(152Ho)/σ(151Dy)
σ(151Ho)/σ(151Dy)
151Ho
152Ho
151Dy
13n
6p
ΔZ

Fig. 5

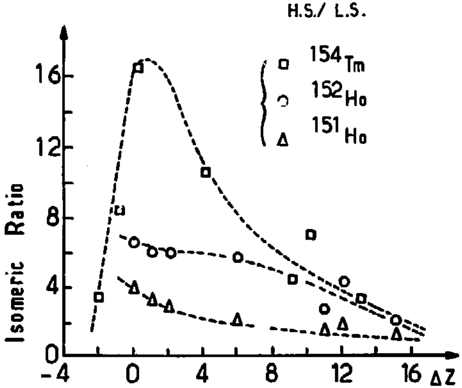
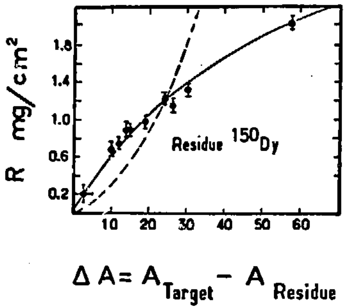
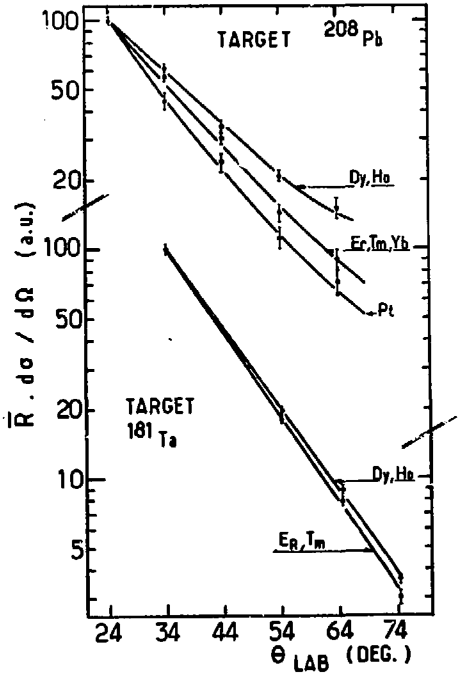

H.S./ L.S.
154Tm
152Ho
151Ho
Isomeric Ratio
ΔZ

Fig. 6



R mg/cm²
1.8
1.4
1.0
0.6
0.2
Residue 150Dy
10
20
30
40
50
60
ΔA = A Target − A Residue

Fig. 7



100
50
20
TARGET 208Pb
Dy,Ho
Er,Tm,Yb
Pt
100
50
20
10
5
TARGET 181Ta
Dy,Ho
ER,Tm
R̄ . dσ / dΩ (a.u.)
24
34
44
54
64
74
θ LAB (DEG.)

Fig. 8