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**Rare Gas Isotope Yields
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of ^{41}K , ^{87}Rb , ^{127}I , ^{133}Cs , and ^{139}La .**

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(Submitted to Radiochimica Acta)

**Rare Gas Isotope Yields
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of ^{41}K , ^{87}Rb , ^{127}I , ^{133}Cs , and ^{139}La .**

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Abstract.

Radiochemical yield measurements have been reported for $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$, $^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$, $^{133}\text{Cs}(\gamma, \pi^+)^{133\text{m},133\text{g}}\text{Xe}$, $^{127}\text{I}(\gamma, \pi^- \text{xn})^{127-x}\text{Xe}$ ($x=0, 2, 4, 5$, and 6), $^{133}\text{Cs}(\gamma, \text{pxn})^{132-x}\text{Xe}$ ($x=1, 3, 5, 7, 9, 10$, and 11), and $^{139}\text{La}(\gamma, 3\text{pxn})^{136-x}\text{Xe}$ ($x=7, 9, 11, 13, 14$, and 15) at bremsstrahlung end-point energies (E_0) of 50 - 1200 MeV. For photopion reactions it has been confirmed that the both yields of (γ, π^-) and (γ, π^+) reactions are independent of target mass (A) and the yield ratios of (γ, π^-) to (γ, π^+) reactions are about 5 over the studied ranges of E_0 and A . The profile of $^{127}\text{I}(\gamma, \pi^- \text{xn})$ yields as a function of x is similar to that of ^{133}Cs but quite different from that of ^{51}V when compared at the same E_0 , suggesting a strong A -dependence. It is also found that the photospallogenic Xe isotope yields from ^{133}Cs and ^{139}La are consistent with the reported mass yield patterns of the other radionuclides produced from the same targets. These results are discussed by referring to the previous literature values and to a cascade-evaporation calculation based on the PICA code by Gabriel and Alsmiller.

Keywords

photopion reaction, photospallation, bremsstrahlung, rare-gas yield, energy and mass dependence.

1. Introduction

Photon is one of unique probes for studying nuclear structure, through 3 types of resonance-interactions; giant resonance, quasi-deuteron resonance, and Δ resonance, which are characteristic to the wave length of incident photons and nuclear size of target. Here only Δ resonance region is concerned. Photons with energies above the pion threshold can be absorbed by a single nucleon inside the target nucleus to produce a Δ isobar. The isobar decays immediately (10^{-24} sec) into a stable nucleon and a pion. The elementary interactions can be written as $\gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+$, $\gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0$, $\gamma + n \rightarrow \Delta^0 \rightarrow p + \pi^-$, and $\gamma + n \rightarrow \Delta^0 \rightarrow n + \pi^0$. After these initial processes, pion and/or nucleon may escape out of the nucleus, or one or both of them would develop a cascade-evaporation process in the same nucleus. Consequently the following reactions can be observed; (γ, π^+) , (γ, π^-) , $(\gamma, \pi^+ \text{xnyp})$, $(\gamma, \pi^- \text{xnyp})$, and (γ, xnyp) . It is expected that the emitted nucleon multiplicities, x and y, are dependent on photon energy and target mass.

Nuclear physicists have been measuring pion and/or nucleon inclusively emitted mainly from light nuclei by using of nuclear physical techniques[1] since 1940's. Recently Arends et al. [2] have reported double-differential cross sections and momentum distributions of π^+ , π^- and proton emitted from Be, C, O, Ti, and Pb targets using tagged photons. They found that the dependence of the energy-integrated differential cross section on the size S of the nucleus, where S is the number of proton or neutron, can be described by $d\sigma/d\Omega \propto S^\alpha$; the exponent α is ~ 0.6 for π^+ and π^- , and ~ 1.15 for proton.

We have been measuring the yields of bremsstrahlung-induced photopion reactions[3,4], photospallation[5-10], photofragmentation[11] and/or photofission[12] from Li to Bi targets by using radiochemical techniques in order to study systematics of photonuclear reactions with respect to energy and target-mass dependences. A bremsstrahlung beam with a continuous energy spectrum ranging from 0 to E_0 has been a unique tool in radiochemical photonuclear reaction studies, due to the absence of high-energy monochromatic photon sources with sufficient beam-intensity. Our efforts[3-12] have, therefore, been concentrated in measurements of product yields at small E_0 intervals with an aid of radiochemical techniques. The measured yields, $Y(E_0)$ in units of μb per equivalent quanta, as a function of E_0 have been

subjected to unfold into cross sections per photon of energy k, $\sigma(k)$, after the method of Tesch [13] with the aid of the LOUHI-82 code[14]. It was found that this method could reveal the new gross features of photonuclear reactions exclusively. Especially radiochemical technique makes identifications of atomic number(Z) possible by isolation of the product nuclides under study unambiguously from many others with different Z produced concomitantly in the target and provides the over-all picture of the competitive reaction channels without the difficulty of the detection threshold encountered in a direct counting method of emitted particles. Also the characteristic features of the target mass dependence of the photon energy(k)-integrated cross sections, $\int_0^{E_0} \sigma(k) dk$, are found to be the same as that of $Y(E_0)$, because of resonant nature of the photonuclear interactions[3,4].

In this paper the photopion and photospallation yields of rare-gas isotopes from $^{41}\text{K}(\gamma, \pi^+)$, ^{41}Ar , $^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$, $^{133}\text{Cs}(\gamma, \pi^+)^{133\text{m}, 133\text{g}}\text{Xe}$, $^{127}\text{I}(\gamma, \pi^- \text{xn})^{127-\text{x}}\text{Xe}$, $^{133}\text{Cs}(\gamma, \text{pxn})^{132-\text{x}}\text{Xe}$, and $^{139}\text{La}(\gamma, 3\text{pxn})^{136-\text{x}}\text{Xe}$ were reported at $E_0=50 - 1200$ MeV in steps of 50-200 MeV or less. Rare gas products from these reactions play crucial roles in the systematic studies and also in many fields of application because of the easiness of rapid chemical isolation from irradiated targets as shown in the present paper. The experimental technique for measurement of rare gas products has been developed in the course of our study of photonuclear reactions. The accumulated data on rare-gas yields in the studied energy region presented in appendix are discussed by referring to the results appeared in the literature and to a cascade-evaporation calculation based on the PICA code by Gabriel and Alsmiller[15,16].

2. Experimental

One disk of K_2CO_3 , two disks of RbCl, KI, CsCl, or LaCl, each with about 640 mg/cm² in thickness and 1 cm in diameter, were placed in a separate quartz tube together with Al or Au beam monitor foils(1cm ϕ) with thickness of 17 and 97 mg/cm², respectively, on top of the first disk and on bottom of the second disk. Irradiations were performed in a water-cooled target holder for 5-10 min with an uncollimated bremsstrahlung beam of maximum end-point energies (E_0) of 50-250 MeV from the 300 MeV electron linac of the Laboratory of Nuclear Science (LNS) of Tohoku University[5]. Irradiations were carried out with an electron beam being passed through an energy-compressing system[17]; the electron energy was limited to be $\pm 1\%$

at full width at half maximum (FWHM). A 0.5 mm thick Pt foil was used as a radiator for bremsstrahlung production. Irradiations at $E_0=250$ to 1000 MeV in steps of 50 MeV and at $E_0=1200$ MeV were performed for 60 to 240 min in air with an electron-free collimated bremsstrahlung from the 1.3 GeV electron synchrotron of the Institute for Nuclear Study (INS), University of Tokyo. The thickness of the Pt converter was 0.05 mm. One or two disks of K_2CO_3 , RbCl, KI, CsCl or LaCl₃, with thickness of about 860 mg/cm² and of diameter 2.5 cm were used as targets together with 290 mg/cm² thick Al beam monitors. The beam intensity was also measured with a Wilson-type thick chamber counter at INS, but in the yield calculation the photon-intensity was obtained from the monitor reactions, $^{27}Al(\gamma, 2pn)^{24}Na$ [18] for $E_0 \geq 100$ MeV, and $^{197}Au(\gamma, n)^{196}Au$ [19, 20] for $E_0 \leq 100$ MeV.

Produced Xe or Kr isotopes were extracted from one of the irradiated disks and collected on charcoal in a Pyrex-glass vacuum system shown in Fig.1. Prior to the end of irradiation, the cold finger (CF) containing 2 g of activated charcoal was gently heated until the section of V4-RP was evacuated down to 1 Pa and then cooled with liquid nitrogen (LN₂). After irradiation, the target disk was immediately placed in a taper-jointed quartz tube (ST) which was then evacuated through V5 and V1 (V2 was also opened for measuring a pressure by Geissler's tube, G). Kr or Xe was extracted from the target disk melted by heating with a gas-oxygen burner under static condition (V5, V3 closed and V4 opened) and adsorbed on the cooled charcoal by digesting for 10-15 min via the cold trap (T2) for removing other volatiles than rare gases. The charcoal was then quickly transferred to an acrylic container of 25 mm i.d. and 35 mm o.d. with a screw-driven cap with a silicon rubber O-ring for gamma-ray measurement. The gas collection yield was determined by comparing with the photopeak counts for relevant nuclides measured in an untreated disk from the same irradiation; 151.2 keV- γ ray of ^{85m}Kr for Kr from Rb, 202.9 keV of ^{127}Xe for Xe from I, and 163.9 keV of ^{131m}Xe or 196.6 keV of ^{129m}Xe for Xe from Cs and La, all of which were not affected by precursor decays. The gamma-ray measurements were performed with high-purity Ge detectors of 1.6-1.7 keV resolution at 1332 keV coupled each with a 4K pulse-height analyzer. The characteristic photopeaks were analyzed with the automatic peak search program by Komura[21]. The peak assignment was based on their γ -ray energy and half-life. The detector efficiency was determined with calibrated ^{152}Eu and ^{182}Ta sources with the same size as the sample. Relevant nuclear data[22] are tabulated in Table 1.

Activity measurement of ^{41}Ar in the irradiated K_2CO_3 target was performed nondestructively.

3. Results and discussion

In Fig.2, three typical examples of the decay curves are shown. The curves are consistent with the half lives of the respective radionuclides. Any losses of the rare gases was not observed in both the containers and the untreated targets during the measurement over 3 months. The photopion and photospallation yields are tabulated in Tables A1-A4 and A5-A6, respectively, in the Appendix. The data from different irradiations are listed separately in the tables. The errors associated with the yield values are those inherited from the counting statistics and decay curve analyses.

In Table A7, the results of PICA calculation for photopion reactions on relevant targets at $E_0=150, 200, 250, 300$, and 400 MeV are tabulated. The details of the calculation are described in the original papers[15,16] and also in Refs.3, 4 and 10.

3.1. Photopion yields

The yield measurements in photopion reactions have been of special interest with regard to behavior of pions and nucleons produced by Δ decay in the target nucleus. Photopion emissions from the nucleus are expected to be dependent on the locations of the initial interactions inside the target nucleus, hence on the size and/or structure of the nucleus, and the energies imparted to the associated particles. So an attention has been directed to target mass- and energy-dependences of the yields of (γ, π^+) , (γ, π^-) , and $(\gamma, \pi^+ xn)$ reactions. The $(\gamma, \pi^+ xn)$ reactions for $x \geq 1$ can not be distinguished from the $(\gamma, \pi^+ n)$ reactions for $x'=0$ in the radiochemical method, and these reactions are classified into photospallation in this paper (e.g., $^{133}Cs(\gamma, \pi^+ xn)^{132-x}Xe$ and $^{139}La(\gamma, 3\pi^+ xn)^{136-x}Xe$ in section 3.2 below). By historical survey of activation method applied to photopion reaction study it was indicated that the investigated targets and products were limited both experimentally and theoretically. In our previous works[3,4] it was found that some of the old data were not consistent with the re-determined ones. As concerned in the present paper, rare gas nuclides produced from these reactions are quite relevant to include in the systematic study, i.e. (γ, π^+) on alkaline targets ^{41}K , ^{87}Rb , and ^{133}Cs , and $(\gamma, \pi^+ xn)$ on ^{127}I and other heavier

targets like ^{139}La .

In radiochemical method, the secondary particle-induced reactions, $(p, x'n)$ and (n, p) , produce the same radionuclides as the primary reactions, $(\gamma, \pi^+ x'n)$ and (γ, π^-) , respectively. The correction for the yields from the secondary reactions was performed on the basis of the excitation functions for these secondary reactions calculated with the ALICE code[23,24], the reported photoproton[25-27] and photoneutron spectra[28,29]. The estimated secondary reaction yields were subtracted from the observed ones by normalizing the yields experimentally obtained below the photopion threshold as already reported in Refs.3 and 4. The secondary yields and the net "measured" photopion reaction yields are shown in the 3rd and 4th columns of the Tables A1-A4, respectively.

3.1.1. Yield curves for (γ, π^+) reactions

$^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$

In Fig. 3, the net yields as a function of E_0 (yield curve) for $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$ are shown by open circles together with the results (closed circle) by Blomqvist et al[30]. Solid curve is drawn to guide the eye. The photopion threshold is indicated by an arrow(Q). The secondary reaction contributions to the observed yields are about 50% at $E_0 \geq 400$ MeV with uncertainty of the contribution of about $\pm 25\%$. This uncertainty is due to ambiguity in the yields below the threshold, and is not included in the net yields because the reproducibility of the observed values at $E_0 \geq Q$ is 20-30%. The repeated measurements are obviously required to obtain more precise results over the whole range of E_0 of interest. However, it is worthy of noting that the magnitudes of the observed yields of $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$ and hence the secondary contributions are quite same as the previously reported ones[3] for $^{51}\text{V}(\gamma, \pi^+)^{51}\text{Ti}$ measured more extensively by the same technique. Also the yields reported by Blomqvist et al.[30] agree with the present measurement.

The values calculated by the PICA code are shown by closed triangles in Fig.3. In the calculation, the incident particle histories of $2 \times 10^6 - 4 \times 10^6$ were followed with the same parameter values as those given by the original authors, except for some alternative sets of cutoff energies for emitted particles. The cutoff energies used in the present calculation were

one-half of the Coulomb barrier for charged particles, and 1 MeV for neutron and π^0 . All calculated values tend to be larger than our measured yields. This point will be discussed below.

$^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$

In Fig.4, the yield curve for $^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$ is shown. The feature of the yield curve is similar to that of $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$ but the measurements are more extensive. The scattering of the data points is much smaller than that of ^{41}Ar data. The secondary contribution from $^{87}\text{Rb}(n, p)^{87}\text{Kr}$ to the observed values was evaluated to be about 10 % at $E_0 > 400$ MeV, which is quite small in comparing with those of about 40-50 % from $^{41}\text{K}(n, p)$ and $^{51}\text{V}(n, p)$ [3] reactions, but close to those of 5-15 % from $^{133}\text{Cs}(n, p)$ (see below) and $^{181}\text{Ta}(n, p)$ [31,32] reactions. The values calculated by the PICA code in the same method as for $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$ reaction are also shown by closed triangles. The calculated value at $E_0 = 200$ MeV is larger by an order of magnitude than the net measured yield, and the differences become smaller with an increase of E_0 , i.e. by a factor of two at $E_0 = 400$ MeV.

$^{133}\text{Cs}(\gamma, \pi^+)^{133m}\text{Xe}$

In Fig.5a, the yield values for $^{133}\text{Cs}(\gamma, \pi^+)^{133m}\text{Xe}$ are shown. Our previous data[4] obtained by counting Xe sample collected on charcoal in a shielded glass ampoule of U-shape were associated with large errors and scattered due to difficulty in γ -ray measurement for ^{133m}Xe and ^{133g}Xe , of which yields are lower by two orders of magnitude than those of other Xe isotopes, especially of 36.4d ^{127}Xe (see Table A5) produced from $(\gamma, p'x'n)$ and/or $(\gamma, \pi^+ x'n)$ reactions. However, an appropriate adjustment of counting time and geometry could reduce the errors in the later measurements. It was found that the all results were consistent, while the number and precision of the measured yield data especially below the Q values are still not enough to estimate the secondary reaction yields accurately. The secondary yield curve for $^{133}\text{Cs}(\gamma, \pi^+)^{133m}\text{Xe}$ was obtained by assuming that the shape of excitation function for $^{133}\text{Cs}(n, p)^{133m}\text{Xe}$ is the same as that for $^{133}\text{Cs}(n, p)^{133g}\text{Xe}$ calculated by the ALICE code, and the secondary contribution at the plateau region was estimated to be 5-10 % of the measured yield.

The yield values for 5.25d ^{133}Xe are regarded to include the contribution from the decay through 2.19d $^{133\text{m}}\text{Xe}$. The correcting for this contribution was difficult due to the lack of decay measurements in the first several days after irradiation during other short lived spallation products dominate. In Fig.5b, the observed yields (not net values) of ^{133}Xe are compared with those of $^{133\text{m}}\text{Xe}$. The difference between the yields of ^{133}Xe and those of $^{133\text{m}}\text{Xe}$ is not significant, especially at lower E_0 . This indicates that the ^{133}Xe yields obtained in this work are mostly due to the decay of $^{133\text{m}}\text{Xe}$. A rough estimate gave the initial yield of ^{133}Xe at the plateau region of $E_0 > 600\text{MeV}$ to be less than 10% of the observed ^{133}Xe , that is, the excited states populated after π^+ emission deexcite to the $3/2^+$ state of ^{133}Xe mostly via $11/2^-$ state of $^{133\text{m}}\text{Xe}$. The PICA calculation for $^{133}\text{Cs}(\gamma, \pi^+)^{133}\text{Xe}$ reaction gives $23 \sim 40 \mu\text{b}/\text{eq.q.}$ at $E_0=200\text{--}400\text{MeV}$ (see Table A7) which are higher than the measured yields of $^{133\text{m}}\text{Xe}$ and/or ^{133}Xe .

Summary of characteristic features of (γ, π^+) yields

All the secondary-corrected yield curves for (γ, π^+) reactions are shown to rise steeply after the threshold and attain to a slightly increasing plateau at $E_0=350\text{--}400\text{MeV}$, indicating that photons responsible for the reactions are mostly of energies lower than 400MeV , but higher than 140MeV (pion threshold) as reported for $^{51}\text{V}(\gamma, \pi^+)^{51}\text{Ti}$ [3]. At $E_0=300\text{MeV}$, the yield values are $12 \pm 8 \mu\text{b}/\text{eq.q.}$ for $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$, $13 \pm 3 \mu\text{b}/\text{eq.q.}$ for $^{51}\text{V}(\gamma, \pi^+)^{51}\text{Ti}$, $10 \pm 4 \mu\text{b}/\text{eq.q.}$ for $^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$ and $8 \pm 5 \mu\text{b}/\text{eq.q.}$ for $^{133}\text{Cs}(\gamma, \pi^+)^{133\text{m}}\text{Xe}$. The values at the plateau region of $E_0=400\text{--}1000\text{MeV}$ are $15\text{--}20 (\pm 30\%) \mu\text{b}/\text{eq.q.}$ for ^{41}Ar , $15\text{--}17 (\pm 15\%) \mu\text{b}/\text{eq.q.}$ for ^{51}Ti , $14\text{--}20 (\pm 20\%) \mu\text{b}/\text{eq.q.}$ for ^{87}Kr and $12\text{--}18 (\pm 30\%) \mu\text{b}/\text{eq.q.}$ for $^{133\text{m}}\text{Xe}$. For $^{133}\text{Cs}(\gamma, \pi^+)^{133}\text{Xe}$, the most of the observed yields were found to be due to the decay of $^{133\text{m}}\text{Xe}$. Our preliminary works indicate that the yields for $^{27}\text{Al}(\gamma, \pi^+)^{27}\text{Mg}$ [31,32] $^{138}\text{Ba}(\gamma, \pi^+)^{138}\text{Cs}$ [33], $^{139}\text{La}(\gamma, \pi^+)^{139}\text{Ba}$ [31] and $^{181}\text{Ta}(\gamma, \pi^+)^{181}\text{Hf}$ [31,32] at these E_0 's are $27(+10, -20)$, 15 ± 10 , 25 ± 10 , and $21 \pm 10 \mu\text{b}/\text{eq.q.}$, respectively, while Blomqvist et al. reported the values of $10.5 \pm 0.5 \mu\text{b}/\text{eq.q.}$ for ^{27}Mg at $E_0=300\text{--}600\text{MeV}$ [34] and of $12.5 \pm 0.5 \mu\text{b}/\text{eq.q.}$ for ^{138}Cs at $E_0=500\text{--}700 \text{MeV}$ [30]. Although the precision is limited up to 50%, it is concluded that the (γ, π^+) yields are independent of target mass(A_t) or the number of target neutron(N_t) over the studied region of $A_t = 41\text{--}181$. By combining the results from ^{41}K ,

^{51}V , ^{65}Cu [24], ^{87}Rb , ^{133}Cs , ^{138}Ba , ^{139}La , and ^{181}Ta targets the averages at $E_0 = 800, 400$, and 250MeV are 19.6 ± 1.4 , 17.0 ± 1.5 , and $8.40 \pm 1.14 \mu\text{b}/\text{eq.q.}$, respectively. The calculation by PICA also gives A_t (or N_t)-independence (Table A7). The average yields calculated from PICA on the same targets described as above are 30.7 ± 3.7 and $21.3 \pm 2.3 \mu\text{b}/\text{eq.q.}$ at $E_0=400$ and 250MeV , respectively. In the previous works[3,4] it was found that the peak energy of the calculated excitation function, $\sigma(k)$, of $^{51}\text{V}(\gamma, \pi^+)^{51}\text{Ti}$ was required to add 60MeV to fit the measured one. However, this kind of adjustment in k or E_0 can not account for the high estimation of the yields by PICA.

3.1.2. Yield curves for (γ, π^+xn) reactions

$$^{127}\text{I}(\gamma, \pi^+xn)^{127-x}\text{Xe}$$

In Fig.6, the yield curves for $^{127}\text{I}(\gamma, \pi^+xn)$ reactions as a function of E_0 are shown together with our previous data obtained by counting Xe collected on charcoal in a shielded glass tube of U-shape[35]. The yield values obtained in this work are consistent with the previous ones and are not distinguished in Fig.6. The apparent range of scattering of the observed data points is within 30-50 % for the (γ, π^+xn) reactions of $x=2\text{--}6$, but as large as 50-100 % for the (γ, π^+) reaction. The contributions of the secondary yields to the observed ones at $E_0=800 \text{MeV}$ were estimated to be 8 %, 25 %, 8 %, 13 %, and 6 % for ^{127}Xe , ^{126}Xe , ^{125}Xe , ^{124}Xe , and ^{123}Xe , respectively. The net "measured" yields show E_0 -variations similar to those of (γ, π^+) reactions, also indicating that the productions of these isotopes are due to resonance at photon energies around 300MeV . But it is notable that the yield values of (γ, π^+xn) reactions for $x=0\text{--}6$ at the plateau regions are around $100 \mu\text{b}/\text{eq.q.}$, in contrast to the (γ, π^+) ones of $10\text{--}20 \mu\text{b}/\text{eq.q.}$ Also noted is that a regular variation of the yield values with respect to an increase of the number of the emitted neutrons(x) is apparent as observed in those of $^{133}\text{Cs}(\gamma, \pi^+xn)$ for x up to 9. This point (mass yield variation) will be discussed below.

The calculated values from PICA are also shown by closed triangles in Fig.6. The calculation for $^{127}\text{I}(\gamma, \pi^+)$ reaction appears to reproduce the shape of the measured yield curve and the values within the scattering of the data points, as far as one concerns the results shown in

Fig.6a. The calculated values for $(\gamma, \pi^- 2n)$, $(\gamma, \pi^- 4n)$, $(\gamma, \pi^- 5n)$, and $(\gamma, \pi^- 6n)$ reactions shown in Figs.6b-e are systematically larger by factors of 1.5-4.0 than the measured yields at $E_0=200$ -400 MeV.

Mass yield curves of $(\gamma, \pi^- xn)$ reactions

In Fig.7, the mass yield curves for $^{127}\text{I}(\gamma, \pi^- xn)^{127-x}\text{Xe}$, the net yields as a function of the number of the emitted neutrons(x) at $E_0=250$ (circles), 400(squares), and 800(triangles) MeV are compared with the corresponding ones from ^{51}V [3] and ^{133}Cs [4] targets. The attached errors are the range of scattering in the yields. The curves are drawn to guide the eye. As in the case of ^{133}Cs (dotted curves), the ^{127}I results(solid curves) at $E_0=400$ and 800 MeV are very close to each other, though slight deviations appear at $x \geq 4$. It is found that the $^{127-x}\text{Xe}$ yields from ^{127}I are also close to the $^{133-x}\text{Ba}$ from ^{133}Cs at the respective x of ≥ 1 at the same E_0 , but quite different from those of ^{51-x}Cr from ^{51}V . The products yields from of $^{51}\text{V}(\gamma, \pi^- xn)$ reactions decrease rapidly with increase of x from 0 to 3, but the corresponding yields from ^{133}Cs and ^{127}I increase to the highest yields at $x=2-3$ ($\sim 300 \mu\text{b}/\text{eq.q.}$ at $E_0=400$ and 800 MeV) and decrease to almost the same yields at $x=0$ with an increase of x to 6 (in the cases of $E_0=400$ and 800 MeV). For an example, the $(\gamma, \pi^- 3n)$ yields of ^{133}Cs and ^{127}I appear to be two orders of magnitude higher than the corresponding ones of ^{51}V . This mass-dependent feature of $(\gamma, \pi^- xn)$ reactions suggests that the photon energies transferred into the targets are A_1 -dependent, but it appears that the excitation energies are not proportional to S , the number of the target nucleons.

In contrast to the A_1 -dependence of the $(\gamma, \pi^- xn)$ yields for $x \geq 1$, the yield values for the (γ, π^-) reactions on the ^{127}I and ^{51}V targets are almost equal (87 ± 3 vs. $93 \pm 3 \mu\text{b}/\text{eq.q.}$ at $E_0=400$ -1000 MeV and 35 ± 7 vs. $65 \pm 20 \mu\text{b}/\text{eq.q.}$ at 250 MeV). For ^{133}Cs target, the yield values from this type of reaction were available only for an isomer $^{133\text{m}}\text{Ba}$ ($\sim 60 \mu\text{b}/\text{eq.q.}$ at $E_0=400$ -1000 MeV and $\sim 40 \mu\text{b}/\text{eq.q.}$ at $E_0=250$ MeV), but not for the 10.7y ground state isomer $^{133\text{g}}\text{Ba}$ [4]. However, the production ratio of $^{133\text{g}}\text{Ba}/^{133\text{m}}\text{Ba}$ is expected not to be higher than 2, as estimated from the systematic variation of cross sections for $^{131\text{m}}, ^{129\text{m}}\text{Ba}$ and for $^{131\text{g}}, ^{129\text{g}}, ^{128\text{g}}, ^{127\text{g}}, ^{126\text{g}}, ^{124\text{g}}\text{Ba}$ from $(\gamma, \pi^- xn)$ reactions(Fig.3 in Ref.4). This means that the $^{133\text{m}}\text{Ba}$ yields are also close to the ^{127}Xe

and ^{51}Cr yields from $^{127}\text{I}(\gamma, \pi^-)$ and $^{51}\text{V}(\gamma, \pi^-)$ reactions, respectively. The yield values of ^{139}Ce from $^{139}\text{La}(\gamma, \pi^-)$ reaction obtained by Sarkar[31] are 85 ± 20 and $49 \pm 10 \mu\text{b}/\text{eq.q.}$ at $E_0=400$ -1000 MeV and 250 MeV, respectively. It is then concluded that the (γ, π^-) yields from $A_1=51$ and $A_1=127$ -139 are the same in magnitude and the average values over the three targets(^{51}V , ^{127}I and ^{139}La) are 93 ± 13 , 80 ± 13 , and $52 \pm 8 \mu\text{b}/\text{eq.q.}$ at $E_0=800$, 400, and 250 MeV. Combined with the conclusion of the A_1 -independence of (γ, π^-) yields deduced in subsection 3.1.1, the yield ratio of (γ, π^-) to (γ, π^+) is evaluated to be 5-6 at $E_0 \geq 250$ MeV over the studied region of A_1 .

The PICA calculation results the A_1 -independence of the (γ, π^+) and (γ, π^-) yields, too, but the yield ratios are 1.8 ± 0.4 and 2.2 ± 0.4 at $E_0 = 400$ and 250 MeV, respectively. The yield ratios from PICA are rather close to the N/Z of the targets as expected from the initial elementary processes of $\gamma p \rightarrow n\pi^+$ and $\gamma n \rightarrow p\pi^-$. While the PICA calculation for the $^{127}\text{I}(\gamma, \pi^-)^{127}\text{Xe}$ yield of $42 \pm 12 \mu\text{b}/\text{eq.q.}$ at $E_0=250$ MeV is consistent with the weighted mean of $34.8 \pm 6.5 \mu\text{b}/\text{eq.q.}$ from the four measured yields(Table A4), these numbers appear slightly smaller than $52 \pm 8 \mu\text{b}/\text{eq.q.}$ from the averaged of the three targets as noted above. The corresponding average of the calculated ones is $47 \pm 7 \mu\text{b}/\text{eq.q.}$ At $E_0=400$ MeV, the measured value for ^{127}Xe is $128 \pm 28 \mu\text{b}/\text{eq.q.}$, but the smoothed yield curve(Fig.6a) suggests a value of $90 \pm 40 \mu\text{b}/\text{eq.q.}$ that is closer to the averaged value of $80 \pm 13 \mu\text{b}/\text{eq.q.}$ The corresponding average of PICA is $56 \pm 8 \mu\text{b}/\text{eq.q.}$ It is, therefore, concluded that the PICA calculation tends to underestimate the (γ, π^-) yield by about 30%. This underestimate for the (γ, π^-) yields together with the overestimate for the (γ, π^+) ones (subsection 3.1.1) caused the low yield ratio of $Y(\gamma, \pi^-)/Y(\gamma, \pi^+) \sim 2$ in PICA. The high values of the observed yield ratio may suggest a new implication for the nuclear structure that is not included in the theoretical ground of the PICA code.

In Fig.8, the mass yield curves for $^{127}\text{I}(\gamma, \pi^- xn)$ reactions at $E_0=250$ and 400 MeV are shown by open symbols and compared with the calculated values(closed symbols). The calculated values for the $(\gamma, \pi^- xn)$ reactions for $x \geq 1$ especially at $E_0=250$ MeV show an even-odd effect; higher for the even mass(odd x) products than for the odd mass (even x) products, except at $x=6$ where the calculated result is irregularly high (see also Fig.7 in Ref.4). The zig-zag feature is

more evident at lower E_0 , and also notable for ^{51}V and ^{133}Cs , as pointed out previously[4]. Different sets of cut off energies for charged particles and neutrons do not change the feature. By neglecting these even-odd variations in the calculated values, it may be concluded that the PICA calculation reproduces the mass yield shapes very well, but the yield values are systematically larger by factors of 1.5-4.0 than the measured ones both at $E_0=400$ and 250MeV, as noted in the yield curves above, in contrast to the case of the (γ, π) yield. It may be recalled again that the energy shift of 30MeV is required to fit the peak energies of the calculated excitation functions, $\sigma(k)$, to those of the observed ones for $(\gamma, \pi + xn)$ reactions on ^{51}V and ^{133}Cs , but the discrepancy in the magnitudes of $\sigma(k)$ and/or $Y(E_0)$ can not be explained by the energy shift.

3.2. Photospallation yields

While both hadron- and bremsstrahlung-induced spallations at intermediate energies have been studied for more than three decades to obtain insight into reaction mechanism, recent renewed interest in the incineration of long-lived radioactive-wastes from atomic power plants and many other applications have found that more systematized measurements of spallation yields are required for grounding the theoretical and/or empirical predictions. In the previous papers[5-8], we presented an example of this kind of effort, that is, the yield measurements of bremsstrahlung-induced spallations of ^{51}V , ^{59}Co , $^{63,65}\text{Cu}$, $^{85,87}\text{Rb}$, $^{84,86,87,88}\text{Sr}$, ^{89}Y , ^{127}I , ^{133}Cs , ^{139}La , and ^{197}Au were reported for the same energy range as in the present work. Rudstam's empirical formula[36] and the PICA calculation were examined based on these data[9,10]. However, some preliminary yield data[8] on spallogenic Xe isotopes from ^{133}Cs were available in the examination of the empirical formula[9]. For the comparative study with the calculation[10], only those data from ^{133}Cs and ^{139}La spallations measured at $E_0=400$ MeV were presented in a graphical form by quoting the present study.

In Tables A5 and A6 in Appendix, the yield values obtained in this work are presented together with the previous ones and identified as either independent(I) or cumulative(C). The number of the yield measurements of $^{131\text{m}}, ^{129\text{m}}, ^{127}, ^{125}, ^{123}, ^{122}, ^{121}\text{Xe}$ from $^{133}\text{Cs}(\gamma, \text{pxn})$ reactions over E_0 -range of 50-1000 MeV have increased to 27-32, including multiple ones at the same E_0 , from 10-

16 of the previously reported ones. Included also in the Table A5 are those values associated with large errors due to uncertainties of the gas collection yields which were sometimes caused by difficulty in the $^{131\text{m}}\text{Xe}$ and/or $^{129\text{m}}\text{Xe}$ measurements on the chemically untreated targets dominated by 6.47d ^{132}Cs from $^{133}\text{Cs}(\gamma, n)$ reaction but included in the final errors for a conservative consideration. The increased number of the measurement allows a conclusion statistically improved for the E_0 -variation of the yields, which are well consistent in systematic changes of shape and magnitude with those of the remaining spallogenic products of ^{133}Cs reported previously[5,8]. For $^{139}\text{La}(\gamma, 3\text{pxn})^{136\text{--}x}\text{Xe}$, the yield measurements are not extensive compared with those of $^{133}\text{Cs}(\gamma, \text{pxn})^{132\text{--}x}\text{Xe}$, and an unambiguous E_0 -variation over 250-1000 MeV of the 6 product nuclides, $^{129\text{m}}\text{Xe}(x=7)$, $^{127}\text{Xe}(x=9)$, $^{125}\text{Xe}(x=11)$, $^{123}\text{Xe}(x=13)$, $^{122}\text{Xe}(x=14)$ and $^{121}\text{Xe}(x=15)$, were obtained. For photospallation, the secondary contributions were not observable, indicating that the secondary particles are not energetic enough to induce those reactions.

The new data for Xe yields both from ^{133}Cs and ^{139}La at several selected E_0 's were included to analyze Rudstam's five-parameter CDMD formula, which was modified to include the corrections of isobaric precursor-decays using iterative non-linear least squares fits as reported in the previous paper[9]. The results of corrections for the precursor-decays to the cumulative yields are presented in italics in tables A5 and A6, and the isotopic distributions for ^{133}Cs and ^{139}La spallations at $E_0=800$ MeV are exemplified in Fig.9. The symbols are the observed values corrected for the precursor decays and labeled with the same symbol for the product isotopes of the same Z . The solid curves are the empirical results from the non-linear least squares fit to the observed values. The conclusions on the parameter values obtained from the fittings and on the implications on spallation mechanisms were not changed those from the previous ones[9], and the present results were found to corroborate the previous conclusions.

The dashed curves in Fig.9 are the results from the PICA calculation at $E_0=800$ MeV. The PICA code can be applied only to the photon energy range of 40-350 or 400MeV responsible for Levinger's quasi-deuteron mechanism and single pion-photoproduction and to the target nuclei of $A \geq 12$. The code is provided with cross sections for photon energies with vanishing values up to 660MeV after the resonance peak at about 300MeV. A detailed comparison of the calculation with the observed ones in the previous work[10] was, therefore, limited to those at $E_0=400$ MeV, and a good agreement in features of isotopic distribution and magnitude was shown

for lighter targets such as ^{51}V , ^{59}Co , and ^{89}Y but not for heavier ^{127}I , ^{133}Cs , ^{139}La , and ^{197}Au . The PICA results for ^{139}La , for an example, at $E_0 = 400\text{MeV}$ were asymmetric in isotopic distributions for $(\gamma, 0-4 \text{ or } 5\text{pxn})$ reactions and rather closer in magnitude to those observed at $E_0 \geq 700\text{MeV}$. The calculation at $E_0 > 400\text{MeV}$ was thence tried here to see apparent reproducibility of the observed results at those E_0 's, though it appears to have less physical meanings. It is now found that a good agreement is obtainable at $E_0 = 800\text{MeV}$ for ^{133}Cs target as exemplified in Fig.9, provided that the PICA results are shifted lower in nucleon multiplicity($x+y$) by 1-2 units. For ^{139}La , the locations of the isotopic distributions are reproducible, but the magnitudes of the calculated values at peak regions are slightly higher (by a factor of up to 2) than the observation at high proton multiplicity(larger y) in a manner to yield smaller slope of the mass yield curve. Because of asymmetric nature of the isotopic distributions of $(\gamma, 0-2\text{pxn})$ reaction on both targets, large deviations at the neutron-rich isotopes ($x=0-5$) are unavoidable. The calculation was performed also at $E_0 = 600$ and 1000MeV for the two targets and the reproducibilities were found to be similar to those at $E_0 = 800\text{MeV}$. The same trial on ^{59}Co and ^{89}Y indicated that the feature of the reproduction for ^{89}Y is so good as for ^{133}Cs , but that a slight underestimate was resulted at larger y for ^{59}Co in a manner to yield larger slope of the mass yield curve. In our previous work[9,10] the parameters $\hat{\sigma}$ and P of the Rudstam's 5-parameter formula were deduced from both the empirical results and the PICA results. The parameters $\hat{\sigma}$ and P are the total inelastic cross section and the slope of the mass yield curve that determine the magnitude and shape of the mass distribution, respectively, and depend on both irradiation energy E_0 and target mass A , while the remaining 3 parameters, R , S and T , that define the charge distribution, are independent of E_0 .

The PICA results on P were well consistent with the empirical ones for ^{51}V , ^{59}Co and ^{89}Y , but smaller for ^{127}I - ^{197}Au . However, the E_0 -variation of P suggested to agree with the empirical (observed) ones at higher E_0 when extrapolated(see Fig.5 in Ref.10). On the other hand, the PICA $\hat{\sigma}$'s were discrepant from the empirical ones more at lower A , and at higher E_0 (Fig.3 in Ref.10). This means that the P value affects substantially the shape of the mass distribution, and results a better agreement with the observed ones for the heavier targets such as ^{133}Cs and ^{139}La at $E_0 = 600-1000\text{MeV}$ than at $E_0 \leq 400\text{MeV}$, as found in this work, while the deviations of the PICA results at ^{59}Co and ^{89}Y are slightly enhanced. The present results suggest that the PICA code can

be used for an approximate estimation of the photospallation yields even at $E_0 = 400-1000\text{MeV}$, but a better prediction is available from the empirical ones deduced in the previous work[9]. Also implied is that the PICA analysis is very promising for studying further photonuclear reaction mechanism at these energies, when the code is modified accordingly.

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Figure captions

Fig.1. Schematic diagram of a glass vacuum system for extraction and collection of rare gases.

The glass line is of 15mm ϕ Pyrex tubes and sectioned by taper-joints. The extraction and collection of rare gases are carried out under static condition under <1Pa. RP: oil rotary pump. T1: cold trap for oil mist from RP. T2: cold trap for volatile active elements. Liquid nitrogen is filled just to the bottom of the trap T2. CF: cold finger of 25mm i.d. containing activated charcoal. ST: taper-jointed quartz tube of 30mm $\times$ 200mm for melting the target. G: Geissler's tube. V1,2,3,4,5, and 6: glass cocks.

Fig.2. Examples of decay curves of rare gas isotopes. Open circles show rare gases collected in a plastic container. Closed circles show rare gases in an untreated target. (a) ^{127}Xe from ^{127}I . Solid lines correspond to the decay with a half life of 36.41d. (b) $^{85\text{m}}\text{Kr}$ from ^{87}Rb . Solid lines show a half life of 4.480h. (c) ^{41}Ar from K. Solid line presents a half life of 1.827h.

Fig.3. Yield variation of $^{41}\text{K}(\gamma, \pi^+)^{41}\text{Ar}$ as a function of E_0 . Open circles denote the values from this work and closed circles denote Blomqvist's work[30]. The values calculated by the PICA code are also shown by closed triangles. Arrow on E_0 axis indicates the Q value for the (γ, π^+) reaction.

Fig.4. Yield variation of $^{87}\text{Rb}(\gamma, \pi^+)^{87}\text{Kr}$ as function of E_0 . For others see the caption of Fig.3.

Fig.5. Yield variation of $^{133}\text{Cs}(\gamma, \pi^+)^{133}\text{Xe}$ as function of E_0 . (a) the net yields of $^{133\text{m}}\text{Xe}$. Open circles and closed ones show this work and our previous work[4], respectively. (b) the observed yields of $^{133\text{g}}\text{Xe}$, not corrected for $^{133\text{m}}\text{Xe}$ decay and the contribution of the secondary reaction. For others see the caption of Fig.3.

Fig.6 Yield variation of $^{127}\text{I}(\gamma, \pi^- \text{xn})^{127-\text{x}}\text{Xe}$, $\text{x}=0,2,4,5$, and 6 as function of E_0 . For other informations see the caption of Fig.3.

Fig.7 Mass yield curves of $(\gamma, \pi^- \text{xn})$ reaction on ^{51}V (shadowed symbols connencted by dotted curves), ^{127}I (open symbols connencted by solid curves), and ^{133}Cs (hatched symbols connencted by dotted curves) at $E_0=250$ (circles), 400 (squares), and 800 (triangles) MeV.

Fig.8 Measured and calculated mass yield curves of $^{127}\text{I}(\gamma, \pi^- \text{xn})^{127-\text{x}}\text{Xe}$ reaction.

Fig.9. Isotopic distributions for (a) ^{132}Cs and (b) ^{139}La at $E_0=800\text{MeV}$. The symbols are the precursor-corrected yield values. The solid curves are the results of non-linear least squares fit

to Rudstam's semi-empirical formula. The dotted curves show the PICA results (see the text for assumptions).

Table 1. Relevant nuclear data for yield measurements.

Nuclide	Half life	γ -ray energy measured [keV]	Fractional abundance [%]
^{133m} Xe	2.19 d	233.2	10.3
^{133g} Xe	5.245 d	81.0	37.0
^{131m} Xe	11.9 d	163.9	1.96
^{129m} Xe	8.89 d	196.6	4.59
¹²⁷ Xe	36.41 d	202.9	68
¹²⁵ Xe	16.9 h	188.4	54.9
¹²³ Xe	2.08 h	178.0	14.9
¹²² Xe	30.1 h	350.0	7.8
¹²¹ Xe	40.1 m	252.7	17.6
⁸⁷ Kr	1.272 h	402.6	49.6
^{85m} Kr	4.480 h	151.8	75.1
⁴¹ Ar	1.827 h	1293.6	99.16
²⁴ Na	15.02 h	1368.6	100
¹⁹⁶ Au	6.18 d	355.7	86.9

Appendix.

The photopion yields are tabulated in Tables A1 to A4, and the photospallation yields are in Tables A5 and A6.

For photopion reaction the values calculated with the PICA code are listed in Table A7.

Table A1. Measured yields($\mu\text{b}/\text{eq.q.}$) of ^{41}Ar from photopion reaction of ^{41}K .

E_0 [MeV]	observed yield	estimated secondary yield	net photopion yield
1200	28.2 (15)	14.0	14.2 (15)
	40.3 (21)	14.0	26.3 (21)
1000	32.5 (14)	13.4	19.1 (14)
	33.2 (23)	13.4	19.8 (23)
950	32.1 (23)	12.8	19.3 (23)
	19.7 (19)	12.8	6.9 (19)
850	5.21 (77)	12.2	-
750	23.5 (13)	12.2	11.3 (13)
	32.4 (22)	12.2	20.2 (22)
	29.2 (21)	12.2	16.9 (21)
	30.6 (24)	12.2	18.3 (24)
700	25.2 (17)	11.9	13.3 (17)
650	39.4 (28)	11.6	27.8 (28)
550	26.5 (18)	10.9	15.6 (18)
	36.4 (21)	10.9	25.5 (21)
500	19 (2)	10.5	9 (2)
450	27.1 (21)	10.0	17.1 (21)
	24 (3)	10.0	14 (3)
375	30.0 (34)	9.24	20.7 (34)
	19 (3)	9.24	10 (3)
350	17 (3)	8.94	8 (3)
	15 (4)	8.94	6 (4)
320	31 (8)	8.50	23 (8)
	14 (2)	8.54	5 (2)
	16 (3)	8.54	7 (3)
275	19 (2)	7.88	11 (2)
	22 (5)	7.83	14 (5)
250	13 (6)	7.47	5 (6)
	17 (5)	7.47	9 (5)
	16.5 (20)	7.47	9.1 (20)
	16 (3)	7.47	9 (3)
220	5.5 (8)	6.93	-
	8.0 (11)	6.93	1 (1)
80	3.9 (2)	3.22	-
66	4.37 (22)	2.67	-
	3.31 (15)	2.67	-
50	3.44 (13)	1.93	-
	1.47 (5)	1.93	-

The numbers in parentheses are experimental errors to the last digit(s); for example, 28.2 ± 1.5 is expressed as 28.2(15).

Table A2. Measured yields($\mu\text{b}/\text{eq.q.}$) ^{87}Kr from photopion reaction of ^{87}Rb .

E_0 [MeV]	observed yield	estimated secondary yield	net photopion yield
1200	17.9 (15)	1.85	16.0 (15)
1000	21.9 (15)	1.79	20.2 (15)
1000	21.3 (8)	1.79	19.5 (8)
950	17 (2)	1.76	15 (2)
900	18.8 (32)	1.76	17.0 (32)
800	22.0 (25)	1.67	20.4 (25)
750	14.9 (29)	1.63	13.2 (29)
750	17.2 (19)	1.63	15.6 (19)
700	16.7 (7)	1.59	15.1 (7)
650	18.4 (32)	1.55	16.8 (32)
600	14.2 (12)	1.51	12.7 (12)
550	16.8 (20)	1.46	15.4 (20)
500	21.6 (50)	1.41	20.2 (50)
500	15.5 (17)	1.41	14.1 (17)
450	13 (2)	1.35	12 (2)
400	13.1 (20)	1.28	11.8 (20)
375	9.3 (46)	1.25	8.1 (46)
365	12 (21)	1.23	10.7 (21)
320	8.42 (1230)	1.16	7.26 (1230)
320	9.65 (1180)	1.16	8.49 (1180)
320	7.8 (19)	1.16	6.6 (19)
315	8.98 (208)	1.15	7.83 (208)
275	5.05 (96)	1.08	3.97 (96)
275	9.0 (14)	1.08	7.9 (14)
250	1.88 (167)	1.03	0.847 (167)
250	9.0 (12)	1.03	7.9 (12)
250	12 (4)	1.03	11 (4)
220	3.48 (19)	0.96	2.52 (19)
220	2.48 (13)	0.96	1.52 (13)
162	0.369 (133)	0.81	-
150	0.453 (199)	0.77	-
90	0.472 (220)	0.54	-
80	0.442 (292)	0.49	-
68	0.399 (42)	0.43	-
66	0.328 (21)	0.42	-
50	0.375 (16)	0.31	-
50	0.34 (2)	0.31	-

The numbers in parentheses are experimental errors to the last digit(s); for example, 17.9 ± 1.5 is expressed as 17.9(15).

Table A3. Measured yields($\mu\text{b}/\text{eq.q.}$) of $^{133\text{m},133\text{g}}\text{Xe}$ from photopion reaction of ^{133}Cs .

E_0 [MeV]	$^{133\text{m}}\text{Xe}$			$^{133\text{g}}\text{Xe}^{++}$		
	observed yield	estimated secondary yield	net photopion yield	observed yield	estimated secondary yield	net photopion yield
1200	5.75 (109)	1.10	4.66 (109)	9.56 (80)	-	-
1000	16.2 (30)	1.09	15.1 (30)	24.8 (187)	-	-
	17.5 (97)+	1.09	16.4 (97)	24.2 (46)+	-	-
950	15.9 (27)	1.08	14.8 (27)	24.1 (21)	-	-
900		1.06		30.6 (54)	-	-
	14 (10)+	1.06	12.9 (10)	47 (43)+	-	-
850		1.04		22.1 (38)	-	-
800	41.0 (274)	1.03	39.9 (274)	86.0 (566)	-	-
	13.1 (100)	1.03	12.1 (100)	17.8 (11)+	-	-
750	15.3 (48)	1.01	14.3 (48)	33.0 (89)	-	-
	26.3 (72)	1.01	25.3 (72)	24.3 (26)	-	-
700	8.67 (167)	0.99	7.68 (167)	19.5 (13)	-	-
	11 (6)+	0.99	10 (6)	39 (23)+	-	-
650	13.3 (45)	0.96	12.3 (45)	11.4 (29)	-	-
600		0.94		18.8 (165)	-	-
550	8.43 (324)	0.91	7.52 (324)	21.6 (57)	-	-
500	9.79 (278)	0.89	8.91 (278)	16.2 (12)	-	-
	18 (27)+	0.89	17 (27)	32 (26)+	-	-
450		0.81		15.0 (75)	-	-
	21 (7)	0.85	20 (7)	18.1 (21)	-	-
400		0.82		16.0 (127)	-	-
375	3.3 (73)	0.80	2.5 (73)	1.4 (14)	-	-
350		0.78		12.9 (22)	-	-
300		0.73		10.9 (14)+	-	-
275	5.6 (72)	0.71	4.9 (72)	5.51 (491)	-	-
250	3.7 (19)	0.68	3.02 (19)	4.58 (200)	-	-
		0.68		< 20.3	-	-
	16 (12)	0.68	16 (12)	7.88 (307)	-	-
				9.70 (589)	-	-
220	0.836 (114)	0.64	0.198 (114)	2.40 (16)	-	-
	0.731 (174)	0.64	0.093 (174)	2.09 (18)	-	-
180	1.12 (26)	0.58	0.54 (26)	1.27 (16)	-	-
150	0.939 (608)	0.52	0.415 (608)	0.903 (507)	-	-
90	0.378 (243)	0.38		0.365 (234)	-	-
80	0.29 (97)	0.34		0.222 (102)	-	-
		0.34		0.351 (36)	-	-
		0.34		0.26 (23)	-	-

+ Our previous data (Ref.4).

++ not corrected for $^{133\text{m}}\text{Xe}$ decay (see the text).

The numbers in parentheses are experimental errors to the last digit(s); for example, 5.75 ± 1.09 is expressed as 5.75(109).

Table A4. Measured yields($\mu\text{b}/\text{eq.q.}$) of Xe isotopes from photopion reaction of ^{127}I .

E_0 [MeV]	^{127}Xe			^{125}Xe		
	observed yield	estimated secondary yield	net photopion yield	observed yield	estimated secondary yield	net photopion yield
1200	98.6 (43)	9.20	89.4 (43)	345 (14)	52.0	293 (14)
1000	146 (28)	7.52	138 (28)	570 (17)	48.4	522 (17)
	106 (21)	7.52	98 (21)	323 (64)	48.4	275 (64)
				372 (24)	48.4	324 (24)
				327 (73)	48.4	278 (73)
900	79.7 (81)	7.31	72.4 (81)	321 (30)	46.4	275 (30)
	74.0 (14)	7.31	66.7 (8)	348 (22)	46.4	302 (22)
	108 (8)	7.31	101 (8)	376 (15)	46.4	330 (15)
850	92.1 (52)	7.20	84.9 (52)	372 (20)	45.2	326 (20)
800	139 (25)	7.08	131 (25)	344 (10)	44.0	300 (10)
	126 (22)	7.08	119 (22)	423 (50)	44.0	379 (50)
750	116 (24)	6.95	109 (24)	480 (97)	42.8	437 (97)
700	85.3 (52)	6.82	78.5 (52)	452 (27)	41.4	410 (27)
				258 (18)	41.4	217 (18)
650	123 (11)	6.67	117 (11)	302 (26)	39.8	262 (26)
600	139 (68)	6.51	132 (68)	251 (11)	38.1	213 (11)
	98.0 (26)	6.51	91.5 (26)	331 (26)	38.1	293 (26)
		6.51		280 (130)	38.1	242 (130)
550	78.4 (54)	6.34	72.1 (54)	290 (19)	36.3	254 (19)
500	128 (29)	6.14	122 (29)	308 (36)	34.2	274 (36)
	60.2 (79)	6.14	54.1 (79)	302 (30)	34.2	267 (30)
		6.14		212 (39)	34.2	178 (39)
	102 (24)	6.14	95.9 (24)	376 (49)	34.2	342 (49)
450	71.4 (165)	5.93	65.5 (165)	321 (74)	31.9	289 (74)
400	134 (28)	5.70	128 (28)	270 (96)	29.2	241 (96)
				257 (20)	29.2	228 (20)
				249 (13)	29.2	220 (13)
375	72.3 (111)	5.57	66.7 (111)	316 (44)	27.8	288 (44)
365	152 (65)	5.51	146 (65)	211 (11)	27.2	184 (11)
350	54.8 (109)	5.25	49.6 (109)	234 (45)	26.2	208 (45)
320	66.9 (154)	5.25	61.7 (154)	248 (45)	24.2	224 (45)
	70.3 (221)	5.25	65.1 (221)	257 (69)	24.2	233 (69)
	39.5 (40)	5.25	34.2 (40)	229 (21)	24.2	205 (21)
315	111 (57)	5.21	106 (57)	192 (13)	23.9	168 (13)
300				261 (47)	22.8	238 (47)
275	78.1 (479)	4.94	73.2 (479)	209 (11)	20.9	188 (11)
	38.4 (77)	4.94	33.5 (77)	124 (24)	20.9	103 (24)

Table A4. (continued)

E ₀ [MeV]	¹²⁷ Xe			¹²⁵ Xe		
	observed yield	estimated secondary yield	net photopion yield	observed yield	estimated secondary yield	net photopion yield
250	31.8 (158)	4.75	27.0 (158)	99 (49)	18.8	80.2 (49)
	37.4 (169)	4.75	32.6 (169)	145 (65)	18.8	127 (65)
	35.7 (84)	4.75	31.0 (84)	132 (28)	18.8	113 (28)
	79.7 (208)	4.75	74.9 (208)	265 (62)	18.8	246 (62)
220	22.1 (12)	4.49	17.6 (12)	78.4 (42)	16.2	62.3 (42)
	19.3 (8)	4.49	14.9 (8)	59.7 (22)	16.2	43.5 (22)
195	22.4 (16)	4.24	18.2 (16)	40 (28)	13.8	26.2 (28)
180	24.1 (121)	4.08	20.0 (121)	22.7 (113)	12.3	10.4 (113)
150	6.89 (169)	3.71	3.18 (169)	10.8 (26)	9.15	-
90				6.46 (144)	2.98	-
80	3.01 (151)	2.44	-	2.08 (104)	2.13	-
	2.3 (6)	2.44	-	1.90 (49)	2.13	-
	2.5 (5)	2.44	-	1.10 (18)	2.13	-

The numbers in parentheses are experimental errors to the last digit(s); for example, 98.6 ± 4.3 is expressed as 98.6(43).

Table A4. (continued)

E ₀ [MeV]	¹²³ Xe			¹²² Xe		
	observed yield	estimated secondary yield	net photopion yield	observed yield	estimated secondary yield	net photopion yield
1200	280 (12)	27.0	253 (12)	201 (9)	92.0	109 (9)
1000	445 (13)	24.0	421 (13)	364 (16)	77.1	287 (16)
	250 (50)	24.0	226 (50)	195 (39)	77.1	118 (39)
	254 (16)	24.0	230 (16)	154 (12)	77.1	76.9 (12)
	244 (18)	24.0	220 (18)			
900	248 (24)	22.2	226 (24)	204 (47)	69.3	135 (47)
	218 (16)	22.2	196 (16)			
	278 (10)	22.2	256 (10)	225 (10)	69.3	156 (10)
850	297 (17)	21.2	276 (17)	220 (31)	65.2	155 (31)
800	282 (9)	20.1	261 (9)	172 (6)	61.0	111 (6)
	284 (33)	20.1	264 (33)	340 (140)	61.0	279 (140)
750	381 (77)	19.0	362 (77)	309 (64)	56.7	252 (64)
700	378 (24)	17.9	360 (24)	271 (18)	52.2	219 (18)
	195 (18)	17.9	177 (18)			
650	220 (20)	16.7	204 (20)	246 (36)	47.6	198 (36)
600	220 (8)	15.4	205 (8)	128 (30)	42.9	84.7 (30)
	241 (19)	15.4	226 (19)	240 (110)	42.9	197 (110)
	185 (23)	15.4	170 (23)			
550	242 (16)	14.0	228 (16)	185 (13)	38.0	147 (13)
500	238 (28)	12.6	225 (28)	163 (31)	33.0	130 (31)
	257 (26)	12.6	244 (26)	212 (24)	33.0	179 (24)
	188 (21)	12.6	175 (21)			
	276 (35)	12.6	263 (35)			
450	244 (56)	11.1	232 (56)	180 (44)	27.9	152 (44)
400	207 (8)	9.45	197 (8)	140 (19)	22.8	117 (19)
	151 (20)	9.45	142 (20)			
	198 (11)	9.45	189 (11)	153 (10)	22.8	130 (10)
375	206 (32)	8.62	197 (32)	210 (30)	20.2	190 (30)
365	168 (8)	8.28	159 (8)	107 (30)	19.2	87.8 (30)
350	193 (38)	7.77	185 (38)	130 (29)	18.0	110 (29)
320	176 (31)	6.72	169 (31)	220 (60)	15.0	210 (60)
	222 (61)	6.72	215 (61)	44 (33)	15.0	29 (33)
	207 (20)	6.72	200 (20)	120 (20)	15.0	100 (20)
315	146 (9)	6.55	139 (9)	94.8 (264)	14.2	26.4 (264)
300	181 (31)	6.02	175 (31)			
275	126 (10)	5.14	121 (10)	82.8 (25)	10.4	72.4 (25)
	89.8 (173)	5.14	84.7 (173)	56.0 (120)	10.4	45.6 (120)

Table A4. (continued)

E _e [MeV]	¹²³ Xe			¹²² Xe		
	observed yield	estimated secondary yield	net photopion yield	observed yield	estimated secondary yield	net photopion yield
250	43.7 (216)	4.26	39.5 (216)	22.6 (112)	8.21	14.4 (112)
	79.3 (373)	4.26	75.1 (373)	141 (72)	8.21	133 (72)
	82.8 (186)	4.26	78.5 (186)	35 (6)	8.20	27 (6)
	134 (31)	4.26	130 (31)	92 (54)	8.20	84 (54)
220	21.0 (12)	3.24	17.8 (12)	6.19 (64)	5.79	0.405 (64)
	16.8 (7)	3.24	13.5 (7)	4.20 (35)	5.79	-
195	3.25 (27)	2.43	0.82 (27)	1.85 (30)	4.02	-
180	3.41 (171)	1.98	1.43 (171)	1.62 (83)	3.09	-
150	1.64 (39)	1.17	-	1.78 (24)	1.58	-
90						
80	0.0440 (326)	0.0846	-	0.116 (240)	0.051	-
	< 0.074	0.0846	-	0.878 (281)	0.051	-
	0.074 (49)	0.0846	-	0.31 (15)	0.051	-

Table A4. (continued)

E _e [MeV]	¹²² Xe		
	observed yield	estimated secondary yield	net photopion yield
1200	85.1 (35)	11.0	74.1 (35)
1000	153 (6)	9.40	144 (6)
	72.2 (143)	9.40	62.8 (143)
900	88.6 (7)	9.40	79.2 (7)
	74.4 (73)	8.28	66.1 (73)
	87.4 (38)	8.28	79.1 (38)
850	90.3 (51)	7.69	82.6 (51)
800	137 (9)	7.10	130 (9)
	119 (21)	7.10	112 (21)
750	118 (24)	6.50	111 (24)
700	97.8 (88)	5.90	91.9 (88)
650	65.1 (62)	5.28	59.9 (62)
600	80.8 (80)	4.66	76.2 (80)
	72.9 (88)	4.66	68.2 (88)
550	79.8 (52)	4.03	75.8 (52)
500	79.1 (101)	3.40	75.7 (101)
	72.2 (74)	3.40	68.8 (74)
	72 (15)	3.40	68.6 (15)
450	76.3 (177)	2.79	73.5 (177)
400	74.5 (90)	2.18	72.3 (90)
	61.3 (40)	2.18	59.1 (40)
375	80.6 (118)	1.89	78.7 (118)
365	52.3 (73)	1.78	50.5 (73)
350	53.3 (106)	1.61	51.6 (106)
320	44.5 (90)	1.29	43.2 (90)
	56.0 (158)	1.29	54.7 (158)
	67.7 (75)	1.29	66.4 (75)
315	43.8 (50)	1.24	42.6 (50)
300	78.0 (20)	1.09	76.9 (20)
275	28.1 (34)	0.85	27.2 (34)
	16.1 (32)	0.85	15.3 (32)

Table A4. (continued)

E ₀ [MeV]	¹²¹ Xe		
	observed yield	estimated secondary yield	net photopion yield
250	4.33 (214)	0.64	3.6909 (214)
	13.4 (71)	0.64	2.14 (71)
	9.0 (29)	0.64	8.4 (29)
220	0.550 (49)	0.417	0.133 (49)
	0.391 (21)	0.417	-
195	0.214 (420)	0.268	-
180	0.283 (144)	0.194	-
150	0.0521 (359)	0.0856	-
90			-
80	0.0495 (598)	0.00036	-
	0.045 (75)	0.00036	-

Table A5. Measured yields (mb/eq.q.) of Xe isotopes from photospallation of ¹³³Cs.

E ₀ [MeV]	^{131m} Xe(*I)	^{129m} Xe(I)	¹²⁷ Xe(C)	¹²⁵ Xe(C)	¹²³ Xe(C)	¹²² Xe(C)	¹²¹ Xe(C)
1000	1.39(40)	1.71(49)	2.76(79)	2.86(82)	1.60(46)	1.32(38)	0.56(16)
	1.26(10)*	1.35(5)*	2.25(6)*	2.42(6)*	1.45(4)*	1.04(3)*	0.42(1)*
	1.16(16)*	2.05(34)*	4.14(7)*	2.87(3)*			
900			2.57(73)	2.12(68)	1.35(36)	0.98(33)	0.47(11)
	1.32(18)	1.64(22)	2.83(38)	3.11(41)	1.86(25)	1.29(18)	0.54(7)
			4.39(12)*	2.93(9)*	1.35(5)*		
850	1.94(92)*	1.51(13)*	3.60(2)*	2.73(14)*	0.88(8)*	0.66(22)*	0.22(8)*
			2.67(76)	2.28(73)	1.21(42)	0.96(33)	0.42(8)
800	2.07(18)	2.78(22)	4.43(43)	4.76(37)	3.39(26)	2.27(18)	0.95(7)
	1.04(89)	1.12(60)	1.89(101)	1.68(90)	1.26(67)	0.81(43)	0.45(24)
	1.12(5)*	1.29(4)*	2.17(6)*	2.34(7)*	1.41(5)*	1.04(3)*	0.42(1)*
700			2.58(67)	2.32(66)	1.16(34)	0.94(31)	0.39(8)
650			4.22(18)*	3.08(14)*	1.26(6)*		
	1.80(39)*	1.34(13)*	2.98(24)*	2.23(9)*	1.10(89)*	0.70(5)*	0.29(7)*
			2.06(60)*	2.24(42)*	1.07(25)*	0.88(22)*	0.31(5)*
600	2.07(24)	2.46(28)	3.98(45)	3.92(45)	2.82(32)	2.13(25)	0.80(9)
	0.93(79)	1.17(86)	2.02(114)	1.84(104)	1.19(67)	0.89(51)	0.23(13)
	0.83(15)*	1.28(25)*	2.85(3)*	2.12(36)*			
500			2.25(60)	2.03(79)	1.07(37)	0.90(42)	0.35(12)
	0.95(55)	1.10(63)	1.83(106)	2.02(117)	1.21(70)	0.88(51)	0.37(21)
	1.75(118)*	1.39(18)*	3.57(5)*	2.57(7)*	0.44(3)*		0.12(2)*
450			1.94(51)	1.98(81)	1.01(42)	0.81(37)	0.28(10)
	1.46(25)	1.73(28)	2.90(45)	2.92(46)	1.87(29)	1.34(25)	0.51(8)
	0.76(50)	1.05(69)	1.30(86)	1.31(86)	0.72(47)	0.52(34)	0.21(14)
400			3.16(22)*	1.98(14)*	0.88(6)*		
	0.20(50)*	1.63(174)*	3.12(5)*	2.09(7)*	2.8(6)*	1.50(50)*	0.53(9)*
			1.68(56)	1.64(73)	0.82(31)	0.63(23)	0.24(9)

Table A5. (Continued).

E_0 [MeV]	$^{131m}\text{Xe}(*\text{I})$	$^{129m}\text{Xe}(\text{I})$	$^{127}\text{Xe}(\text{C})$	$^{125}\text{Xe}(\text{C})$	$^{123}\text{Xe}(\text{C})$	$^{122}\text{Xe}(\text{C})$	$^{121}\text{Xe}(\text{C})$
365	1.13(63)	0.96(53)	1.58(87)	1.39(76)	0.81(45)	0.58(32)	0.24(13)
320	1.22(29)	1.31(29)	2.06(46)	1.86(41)	1.10(25)	0.98(30)	0.29(7)
	1.65(45)	1.54(40)	2.37(60)	2.31(58)	1.50(38)	0.84(2)	0.36(10)
	1.03(14)	1.13(15)	2.07(27)	1.94(25)	0.93(13)	0.68(8)	
315	2.34(259)	0.70(15)	1.41(17)	1.06(13)	0.61(7)	0.43(6)	0.17(2)
300			2.74(24)*	1.48(13)*	0.51(4)*		
	0.91(8)*	0.82(4)*	1.36(5)*	1.44(4)*	0.72(2)*	0.52(2)*	0.17(2)*
			1.10(48)*	1.05(30)*	0.47(12)*	0.45(10)*	0.13(4)*
275	0.80(40)	0.76(38)	1.09(54)	1.10(55)	0.57(29)	0.31(16)	0.096(5)
250	0.91(30)	0.80(26)	1.05(34)	0.86(28)	0.42(14)	0.24(8)	
	1.22(35)	1.07(30)	1.60(43)	1.36(37)	0.70(19)	0.30(10)	0.13(4)
220	0.39(5)*	0.35(4)*	0.81(9)*	0.68(8)*	0.20(2)*	0.09(1)*	0.030(4)*
			0.81(24)*	0.53(11)*	0.17(4)*	0.08(3)*	0.03(1)*
180	1.05(7)	0.76(5)	0.90(6)	0.60(4)	0.17(1)	0.064(4)	0.015(1)
150	0.70(33)	0.46(22)	0.48(22)	0.25(12)	0.05(2)	0.010(5)	0.0008(4)
149	0.81(5)*	0.51(3)*	0.57(3)*	0.31(2)*	0.054(3)*	0.011(1)*	0.0008(1)*
			0.53(7)*	0.28(4)*	0.050(7)*	0.010(2)*	0.0006(2)*
90	0.54(19)	0.23(8)	0.11(4)	0.003(1)			
80	0.67(6)	0.20(2)	0.072(6)	0.00015(2)			

I: independent, *I: precursor contribution was neglected, C: cumulative.

Yield values in italics are corrected precursor-decay.

+: our previous work (Ref.8).

The numbers in parentheses are experimental errors to the last digit(s); for example, 1.39 ± 0.40 is expressed as 1.39(40).Table A6. Measured yields (mb/eq.q.) of Xe isotopes from Photospallation of ^{139}La .

E_0 [MeV]	$^{129m}\text{Xe}(\text{I})$	$^{127}\text{Xe}(\text{C})$	$^{125}\text{Xe}(\text{C})$	$^{123}\text{Xe}(\text{C})$	$^{122}\text{Xe}(\text{C})$	$^{121}\text{Xe}(\text{C})$
1000	0.97(45)	0.62(28)	1.08(49)	0.74(33)	0.57(26)	^a 0.23(10)
		0.58(8)	0.94(15)	0.88(15)	0.58(14)	
800	0.86(42)		1.28(62)	0.95(46)	0.70(34)	^a 0.29(14)
			0.92(15)	0.78(17)	0.62(15)	
600	0.62(7)		1.11(3)	0.79(2)	0.42(10)	0.24(1)
500		0.59(3)	1.05(4)	0.70(3)	0.51(3)	0.23(1)
		0.52(8)	0.72(13)	0.51(7)	0.35(7)	0.18(4)
400		0.53(2)	0.85(3)	0.54(2)	0.29(3)	^a 0.17(1)
		0.32(4)	0.52(10)	0.41(6)		
365	0.52(16)		0.62(9)	0.39(5)	0.27(4)	0.097(14)
315			0.46(7)	0.26(4)		0.0585(9)
275		0.20(2)	0.26(2)	0.13(1)	0.11(20)	0.025(4)
250	0.13(2)		0.11(2)	0.057(9)	0.024(4)	^a 0.006(1)
			0.08(3)	0.038(13)	0.020(6)	

I: independent, C: cumulative.

Yield values in italics are corrected for precursor decay.

n: yields not corrected for precursor contribution.

The numbers in parentheses are experimental errors to the last digit(s); for example, 0.97 ± 0.45 is expressed as 0.97(45).

Table A7. Results of PICA calculation for photopion reactions.

Target	Product	150MeV	200MeV	250MeV	300MeV	400MeV
⁴¹ K	⁴¹ Ar	0.	10.7(38)	17.5(62)	16.3(62)	22.1(61)
	⁴¹ Ca	0.	20.1(52)	28.4(79)	41.8(60)	42.4(85)
⁸⁷ Rb	⁸⁷ Kr	0.	16.5(67)	19.9(63)	22.3(84)	27.9(99)
	⁸⁷ Sr	0.	55.0(123)	19.9(63)	79.5(159)	97.6(184)
¹³³ Cs	¹³³ Xe	0.	23.3(88)	39.7(120)	17.9(68)	59.0(129)
	¹³³ Ba	0.	36.6(61)	43.3(125)	41.0(103)	50.5(119)
¹²⁷ I	¹²⁷ Te	0.	19.5(80)	28.3(100)	41.4(125)	33.0(117)
	¹²⁷ Xe	0.	16.3(728)	42.4(122)	52.7(141)	61.9(160)
	¹²⁶ Xe	0.	104.(18)	209.(27)	169.(25)	260.(330)
	¹²⁵ Xe	0.	91.2(176)	212.(27)	233.(30)	346.(38)
	¹²⁴ Xe	0.	87.9(169)	265.(31)	275.(32)	338.(37)
	¹²³ Xe	0.	26.1(92)	127.(21)	252.(31)	326.(37)
	¹²² Xe	0.	3.26(326)	91.9(182)	169.(25)	223.(30)
	¹²¹ Xe	0.	0.	60.0(146)	94.1(189)	132.(23)
	¹²⁰ Xe	0.	0.	10.6(61)	33.9(113)	41.2(130)
	¹¹⁹ Xe	0.	0.	0.	7.53(532)	4.12(412)

The numbers in parentheses are statistical errors to the last digit(s); for example, 10.6 ± 6.1 is expressed as 10.6(61).

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5(a)

Fig.5(b)

Fig.6(a)

Fig.6(b)

Fig.6(c)

Fig.6(d)

Fig.6(e)

Fig.7

Fig.8

Fig.9