

similar to the energies corresponding to the first two excited levels in even-mass isotones of $N = 80$. The energy levels of the isotope nuclei ^{136}Ba [23], ^{138}Ce [23], and ^{140}Nd [24] are shown in Fig. 6.

Acknowledgement

We would like to thank our colleagues for clarifying discussions and the crew of the Cyclotron for perform-

ing the irradiations. One of the authors (H.P.M.) thanks the South African Council for Scientific and Industrial Research for financial support in the form of a research fellowship.

23. Nuclear Data Sheets NAS, NRC 61-2-122, NRC 61-3-77.
24. V. V. REMAEV, V. T. GRITSYNA and A. P. KLYUCHAREV, Soviet Phys. JETP **15**, 283 (1962).

Cross Sections of Some (n, p) and (n, α) Reactions Induced by 14.8 MeV Neutrons⁺

By A. KJELBERG*, A. C. PAPPAS and E. STEINNES**, Department of Chemistry, University of Oslo, Blindern, Norway

With 1 figure. (Received July 12, 1965)

Summary

Cross sections for (n, p) and (n, α) reactions induced by 14.8 MeV neutrons in zinc and bromine have been determined by radiochemical methods and using the ^{31}P (n, p) ^{31}Si reaction as monitor. For the previously unreported cross section of ^{79}Br (n, p) $^{79\text{m}}\text{Se}$ a value of 10 ± 3 mb was found.

Zusammenfassung

Wir bestimmten radiochemisch Wirkungsquerschnitte von Zn und Br für (n, p) und (n, α)-Reaktionen mit 14,8 MeV-Neutronen, die Reaktion ^{31}P (n, p) ^{31}Si diente als Monitor. Für den bisher nicht publizierten Wirkungsquerschnitt von ^{79}Br (n, p) $^{79\text{m}}\text{Se}$ fanden wir 10 ± 3 mb.

Résumé

A l'aide des méthodes radiochimiques, nous avons étudié les sections efficaces pour les réactions (n, p) et (n, α) des neutrons de 14,8 MeV avec Zn et Br, la réaction ^{31}P (n, p) ^{31}Si servant de «moniteur». Pour la section efficace de la réaction ^{79}Br (n, p) $^{79\text{m}}\text{Se}$, inconnue jusqu'ici, nous avons trouvé 10 ± 3 mb.

Introduction

With the great number of cross section data now available for nuclear reactions induced by 14 MeV neutrons, one is often struck by the scattering in the values obtained by different authors for the same reaction. This is particularly so for (n, p) and (n, α) reactions, where the reaction products will often be almost completely masked by products of competing (n, 2n) reactions. In such cases the specificity of radiochemical separation methods should generally be superior to direct measurements and facilitate better determinations.

In the present work radiochemical methods have been applied to determine some (n, p) and (n, α) reaction products in zinc and bromine. Parallel to this work has gone a broader study by GRIMELAND, KJELLSBY and VINES [1], using direct counting techniques.

Experimental

Neutrons of energy 14.8 ± 0.2 MeV were produced by the (d, t) reaction using a SAMES J accelerator. The total neutron yield was of the order of 10^9 neutrons per second.

Samples were irradiated in small polyethylene vials. As monitoring reaction was used ^{31}P (n, p) ^{31}Si , with the phosphorous in the form of phosphoric acid. Care was taken to ascertain that sample and flux monitor were exposed to the same neutron flux. A cross section of 85 ± 3 mb, as determined by GRIMELAND et al. [1], was chosen for the monitor reaction in the calculations. Previously reported cross sections for this reaction are 91 ± 9 mb [2], 85.5 ± 7 mb [3], 114 ± 14 mb [4], and 82 ± 10 mb [5].

After chemical separation of the reaction products (see next section) their disintegration rates were determined using an end window Geiger Mueller counter. Corrections for absorption and scattering effects were made according to directions given by PAPPAS [6]. The separated samples gave rather simple decay curves, except for selenium separated from irradiated bromine, where directly formed 3.9 min $^{79\text{m}}\text{Se}$, 57 min $^{81\text{m}}\text{Se}$ and 18 min $^{81\text{g}}\text{Se}$ were present, in addition to $^{81\text{g}}\text{Se}$ formed by decay of $^{81\text{m}}\text{Se}$. In this case the decay was also followed through an aluminium absorber (10 mg/cm^2), which completely stopped the conversion electrons from $^{79\text{m}}\text{Se}$ and $^{81\text{g}}\text{Se}$. Typical decay curves and the resolved components are shown in Fig. 1. For all samples the decay was followed for at least 5 hours. The half-lives found agreed with previously determined values, and no contaminating activities were detected.

⁺ Based on a thesis by E. STEINNES.

* Present address: NP-Division, CERN, Geneva-23, Switzerland.

** Present address: Institute for Atomic Energy, Kjeller, Norway.

1. B. GRIMELAND, E. KJELLSBY and J. VINES, to be published in Physic. Rev.
2. S. G. FOBES, Physic. Rev. **88**, 1309 (1952).
3. J. A. GRUNDL, R. L. HENKEL and B. L. PERKINS, Physic. Rev. **109**, 425 (1958).
4. D. L. ALLAN, Nuclear Physics **24**, 274 (1961).
5. J. KANTELE and D. G. GARDNER, Nuclear Physics **35**, 353 (1962).
6. A. C. PAPPAS, USAEC Report AECU-2806, MIT-LNS-63 (1953).

For the determination of the yield of ^{79m}Se the counting rate of the conversion electrons was used, whereas ^{81m}Se was determined indirectly through the equilibrium counting rate of ^{81g}Se .

The limits of error in the cross sections are calculated from estimated errors in each term used in the calculations, i.e. neutron flux, monitor cross section, chemical yield and measured activity of the samples. Parallels showed a spread well within the limits calculated in this way.

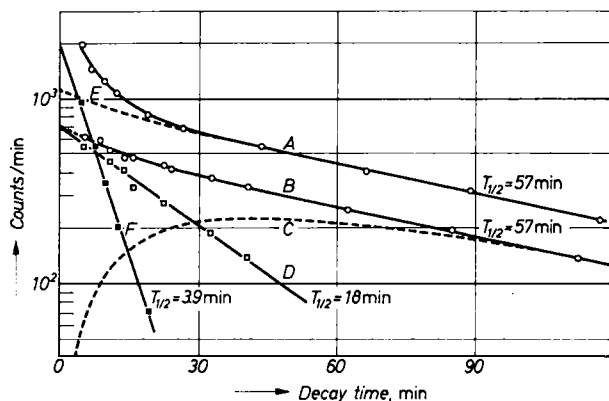


Fig. 1. Decay of selenium isotopes separated from potassium bromide. A. Gross decay curve. B. Decay curve taken through 10 mg/cm² aluminium absorber. C. Growth curve for ^{81g}Se (calculated). D. Decay curve for directly formed ^{81g}Se (with absorber). E. Extrapolated decay curve for ^{81m}Se and ^{81g}Se without absorber. F. Decay curve for ^{79m}Se

Radiochemical Procedures

1. Separation of silicon from phosphoric acid

The procedure was an adaption of a method given by RUDSTAM et al. [7]: To the irradiated phosphoric acid target solution were added Na_2SiF_6 carrier and H_3BO_3 as a complexing agent. SiO_2 was then precipitated with an excess of conc. H_2SO_4 . The precipitate was dried at 110 °C for 10 minutes and mounted for β -counting. After complete decay the precipitate was ignited for 1 hour at 1000 °C and weighed as SiO_2 .

2. Separation of copper from zinc acetate

A procedure given by MEINKE [8] was used in a simplified form: The irradiated target was dissolved in 0.01 N HCl and Cu(II)-carrier was added. Cu(II) was reduced to Cu(I) with NaHSO_3 and CuCNS precipitated by addition of KCNS. The precipitate was weighed as CuCNS after drying at 110 °C for 10 minutes.

3. Separation of selenium from potassium bromide

Irradiated KBr was dissolved in 6 N HCl to which was added As and Se carriers and a known amount of the 120 d ^{75}Se . The solution was oxidized with KClO_3 , and Se was precipitated with NaHSO_3 . The precipitate was filtered off on a membrane filter, dried in a current of air and mounted for β -counting. After decay of the short-lived selenium isotopes, the chemical yields were determined by gamma counting of the recovered amount of ^{75}Se .

4. Separation of arsenic from potassium bromide

After Se had been removed in the manner described previously, 10 ml of magnesium mixture (260 g $\text{MgCl}_2 \cdot 8 \text{H}_2\text{O} + 200 \text{ g NH}_4\text{Cl}$ in 1 l H_2O) was added to the supernatant liquid, and the solution was made slightly alkaline with NH_4OH . After 15 minutes the precipitate was filtered off, dried at 110 °C for 30 minutes and weighed as $\text{Mg}(\text{NH}_4)\text{AsO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$.

Results and Discussion

Present data and comparative literature values are given in Table 1.

Table 1. Summary of cross section values

Reaction	Cross sections in mb		Calculated, [9]
	Present data	Literature data (exp.) (ref. in parenthesis)	
$^{64}\text{Zn}(\text{n}, \text{p})^{64}\text{Cu}$	204 ± 15	386 ± 58 [10], 284 ± 20 [11], 171 ± 18 [4], 182 ± 16 [12], 230 ± 80 [13]	177
$^{76}\text{Br}(\text{n}, \text{p})^{76}\text{Se}$	10 ± 3		24*
$^{76}\text{Br}(\text{n}, \alpha)^{76}\text{As}$	12 ± 2	10.0 ± 1.8 [14], 10.8 ± 2.4 [15], 9.2 ± 2.0 [13], 20 ± 10 [1]	11
$^{81}\text{Br}(\text{n}, \text{p})^{81m}\text{Se}$	16 ± 3	32 ± 8 [16], 26 ± 13 [1]	21*
$^{81}\text{Br}(\text{n}, \text{p})^{81g}\text{Se}$	8.0 ± 1.4	25 ± 5 [16]	
$^{81}\text{Br}(\text{n}, \alpha)^{81g}\text{As}$	3.8 ± 1.0	103 ± 20 [10], 107 ± 20 [16], 6.6 ± 1.4 [13], 14 ± 10 [1], 7 ± 3 [1]	

* The calculated cross section (see later) should apply to the sum of the cross sections for isomers, i. e. for $^{79m}\text{Se} + ^{79g}\text{Se}$ (7×10^4 y, not detected), and for $^{81m}\text{Se} + ^{81g}\text{Se}$.

As shown in Table 1 the results from the present investigations are in good agreement with values from recent work where the reaction products are relatively

7. G. RUDSTAM, P. C. STEVENSON and R. L. FOLGER, *Physic. Rev.* **87**, 358 (1952).

8. W. W. MEINKE, USAEC Report AECD-2738 (1949).

9. B. P. BAYHURST and R. J. PRESTWOOD, *J. Inorg. Nucl. Chem.* **23**, 173 (1961).

10. E. B. PAUL and R. L. CLARKE, *Canad. J. Physics* **31**, 267 (1953).

11. I. L. PREISS and R. W. FINK, *Nuclear Physics* **15**, 326 (1960).

12. F. GABBARD, private communication (1961) to H. NEVERT and H. POLLEHN, EURATOM Report EUR 122. e (1963).

13. E. T. BRAMLITT and R. W. FINK, *Physic. Rev.* **131**, 2649 (1963).

14. H. G. BLOSSER, C. D. GOODMAN and T. H. HANDLEY, *Physic. Rev.* **110**, 531 (1958).

15. A. POULARKIAS and D. G. GARDNER, private communication (1962) to H. NEVERT and H. POLLEHN, EURATOM Report, EUR 122. e (1963).

16. P. STROHAL, N. CINDRO and B. EMAN, *Nuclear Physics* **30**, 49 (1962).

simple to determine, such as for the reactions ^{64}Zn (n, p) ^{64}Cu and ^{79}Br (n, α) ^{76}As . This agreement in the case of the latter reaction supports the low cross section found by us for the reaction ^{81}Br (n, α) ^{78}As , as compared to that found in [10] and [16]. The cross sections measured for the reaction ^{81}Br (n, p) $^{81\text{m}}\text{Se}$ and ^{81}Br (n, p) $^{81\text{g}}\text{Se}$ are considerably lower than the values reported by STROHAL et al. [16].

For the ^{79}Br (n, p) $^{79\text{m}}\text{Se}$ reaction no cross section values have been published previously.

BAYHURST and PRESTWOOD [9] have given empirical equations for estimating (n, p) and (n, α) cross sections at 14 MeV, namely:

$$\sigma_{n, p} (14 \text{ MeV}) = k_1 \pi (0.12 A^{1/3} + 0.21)^2 \exp \left[-31.1 \left(\frac{N-Z}{A} \right) \right]$$

$k_1 = 0.50$ for odd Z - even N , i.e. ($o-e$), nuclei and 0.83 for ($e-e$) or ($e-o$) nuclei.

$$\sigma_{n, \alpha} (14 \text{ MeV}) = k_2 \pi (0.12 A^{1/3} + 0.21)^2 \exp \left[-37.8 \left(\frac{N-Z}{A} \right) \right]$$

$k_2 = 0.50$ for ($o-e$) nuclei, 0.83 for ($e-e$) nuclei. A , N and Z are respectively mass, neutron and proton numbers of the target nuclei.

All but 2 of the about 85 measured cross sections used by BAYHURST and PRESTWOOD [9] for establishing the empirical equations fall within a factor of 2 from the calculated value in the (n, p)-case. In the (n, α)-case 20 of the about 70 values deviate by more than a factor of 2 from the formula value. Of these 20 target nuclei only 3 are of the ($o-e$) type (as is the case for ^{79}Br and ^{81}Br).

Cross sections for the reactions studied in this work, calculated according to the BAYHURST and PRESTWOOD equations, are given in Table 1. It is apparent that our experimental results are in quite good agreement with the calculated values. For the ^{81}Br (n, p) $^{81\text{m}+81\text{g}}\text{Se}$ case, however, the experimental cross section is too high by a factor of 2.

Acknowledgements

The authors are indebted to Dr. B. GRIMELAND, Institute of Physics, University of Oslo for help with the irradiations, and to the Royal Norwegian Council for Scientific and Industrial Research for financial support.

Rapid Radiochemical Separation by Adsorption⁺

By R. S. RAI*, D. R. NETHAWAY**, and A. C. WAHL, Department of Chemistry, Washington University, St. Louis, Missouri

(Received July 27, 1965)

Summary

Conditions are described under which rapid and essentially quantitative adsorption occurs from aqueous solutions for $^{140}\text{Ba}^{++}$ on BaSO_4 (s), $^{90}\text{Sr}^{++}$ or $^{85}\text{Sr}^{++}$ on SrCO_3 (s), and $^{113}\text{Sn}^{\text{IV}}$ on SnS_2 (s) or SnS (s). The presence of U^{VI} in solution does not interfere with the adsorption. These processes, which may involve isotopic exchange, offer convenient and rapid methods for the separation of Cs^+ from Ba^{++} at low concentration, Rb^+ from Sr^{++} at low concentration, and In^{III} from Sn^{IV} at low concentration, and thus the processes are applicable to the separation of short-lived fission products from their immediate descendants.

Zusammenfassung

Wir geben Bedingungen an, unter denen folgende Ionen rasch und fast quantitativ aus wässriger Lösung absorbiert werden: $^{140}\text{Ba}^{++}$ an BaSO_4 (s = fest), $^{90}\text{Sr}^{++}$ oder $^{85}\text{Sr}^{++}$ an SrCO_3 (s) und $^{113}\text{Sn}^{4+}$ an SnS_2 (s) oder SnS (s). Die Anwesenheit von U^{6+} in der Lösung stört nicht. Diese Prozesse, an denen möglicherweise Isotopenaustausch beteiligt ist, bieten bequeme und rasche Trennmöglichkeiten für Cs^+ von Ba^{2+} in geringer Konzentration, entsprechend Rb^+ von Sr^{2+} und In^{3+} von Sn^{4+} in geringer Konzentration, und somit zur Trennung kurzlebiger Spaltprodukte von ihren direkten Folgekernen.

Résumé

Nous décrivons les conditions dans lesquelles on obtient en solution aqueuse une absorption rapide et presque quantitative de l'ion $^{140}\text{Ba}^{++}$ sur BaSO_4 solide, de l'ion $^{90}\text{Sr}^{++}$ ou $^{85}\text{Sr}^{++}$ sur SrCO_3 solide, et de $^{113}\text{Sn}^{4+}$ sur SnS_2 ou SnS solides. L'ion UO_2^{++} n'interfère pas. Ces procédés, qui peuvent mettre en œuvre un mécanisme d'échange isotopique, se prêtent aux séparations rapides $\text{Cs}^+/\text{Ba}^{++}$, $\text{Rb}^+/\text{Sr}^{++}$ et $\text{In}^{3+}/\text{Sn}^{4+}$ à faible concentration, et par conséquent sont applicables à la séparation de produits de fission à vie courte de leurs descendants directs.

⁺ This work was supported by the U. S. Atomic Energy Commission. A portion of this article has been abstracted from the Ph. D. Thesis of D. R. NETHAWAY, Washington University, 1959.

* Present address: Department of Chemistry, Rajasthan University, Jaipur, India.

** Present address: Lawrence Radiation Laboratory, Livermore, California.