SEARCH FOR NEW NEUTRON-RICH NUCLEI PRODUCED BY FAST NEUTRONS AT LAMPF†

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Abstract

The possibility of using fast neutrons to produce new neutron-rich nuclides is investigated. The neutrons were generated by spallation reactions of 800-MeV protons on a Cu beamstop. "Effective cross sections" for the (n,2pn), (n,2p), and (n,3pn) reactions were measured as a function of target A. Results indicate the above cross sections to be large enough to be useful in searches for new nuclides outside of the fission region. Results from the decay studies of neutron-rich ^{200}Pt and ^{197}Ir are presented.

I. Introduction

Nuclides on the neutron-deficient side of stability can be made using a variety of charged particle projectiles, but neutron-rich nuclides outside of the fission region ($75 < A < 170$) are more difficult to produce, therefore less is known about their structure even relatively close to stability. High fluxes of fast neutrons ($E > 20$ MeV) offer the possibility of producing new neutron-rich nuclides using the (n,2pn), (n,2p), and (n,3pn) reactions. As one example, using ^{204}Hg as a target the new nuclides ^{202}Pt and ^{203}Pt could be produced by the (n,2pn) and (n,2p) reactions respectively, and the (n,3pxn) reactions could produce the new nuclides ^{199}Ir, ^{200}Ir, and ^{201}Ir.

The Clinton P. Anderson Meson Physics Facility (LAMPF) will provide a suitable source of high energy neutrons. A beam of 800-MeV protons at currents which will eventually reach 1 ma impenges on a water-cooled Cu beam stop and fast neutrons are generated by spallation. At maximum intensity a flux of about 5×10^{11} n/cm^2·s would be available for neutrons with energy greater than 20 MeV. Beam currents available to us have been limited thus far to 10 μa.

2. Effective Cross Sections

Initial experiments were performed using Hg targets to determine the quantity of (n,2pxn) products of interest to us relative to (n,xn), and (n,pxn) contamination. The ratio of (n,xn) plus (n,pxn) to (n,2pxn) cross sections was about 10^3 so rather clean chemistry is needed in all searches. The production of neutron-rich relative to neutron-deficient products was determined for the (n,2pxn) reaction using ^{45}Sc, ^{51}V, and ^{133}Cs targets. The results are shown in Fig. 1. Obviously strong interference from neutron-deficient nuclides is present and the use of separated targets is essential. The nuclides[1,2] ^{236}Th and ^{84}Hf were discovered using the (p,3p) reaction with 100-MeV protons. Orth[3] has determined that the relative yield of ^{140}Ba and ^{131}Ba from natural Ce targets using both 100-MeV protons and LAMPF beam stop neutrons. If the ^{131}Ba yield is 100 in each case the yield of ^{140}Ba is 0.03 from the ^{142}Ce(n,2pn)^{140}Ba reaction and only 0.00065 from the ^{142}Ce(p,3p)^{140}Ba reaction. It is evident that with neutrons the interference from neutron-deficient nuclides (often the critical factor) is much less severe.

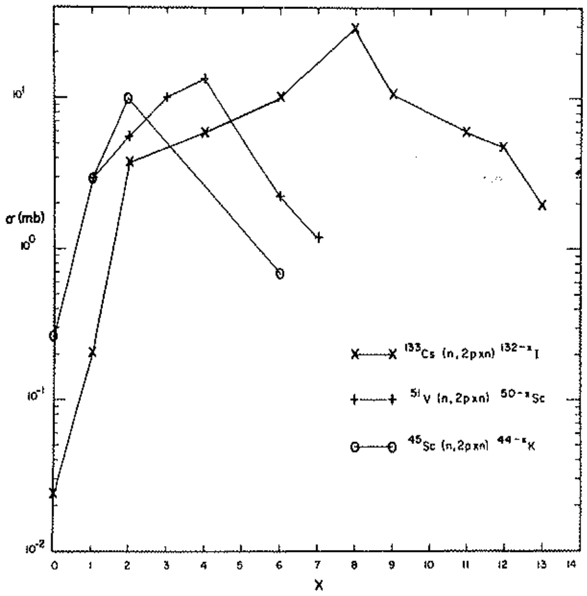

Fig. 1. "Effective" cross sections for (n,2pxn) reactions on various targets.

"Effective cross sections" for the (n,2pn), (n,2p), and (n,2pn) reactions were measured[4] for LAMPF neutrons as a function of target A using for the most part mono-isotopic targets and radiochemical techniques. The (n,α) cross section was also measured for comparison. The cross sections were normalized to an "effective cross section" of 18 ± 5 mb for the ^{12}C(n,2n)^{11}C reaction for neutrons above the reaction threshold of 18.7 MeV. In the neutron spectrum assumed, for neutron energies above 10 MeV, roughly 75, 45, 25, 8, and 2% have energies above 20, 50, 100, 200, and 300 MeV respectively. The results of these measurements are shown in Fig. 2.

Between $A = 40$ and 200 the (n,α), (n,2pn), and (n,2p) cross sections decrease by roughly one order of magnitude and the ratio of (n,α) to (n,2pn) is fairly constant. The ^{31}P(n,3pn)^{28}Mg cross section is fairly large but (n,3pn) decreases drastically above $A = 60$. The (n,2pn) reaction should thus be useful for producing neutron-rich nuclides over the whole periodic table and (n,2p) will certainly be useful for $A < 100$. The (n,3pn) reaction may also be useful for production of new nuclides with $A < 60$.

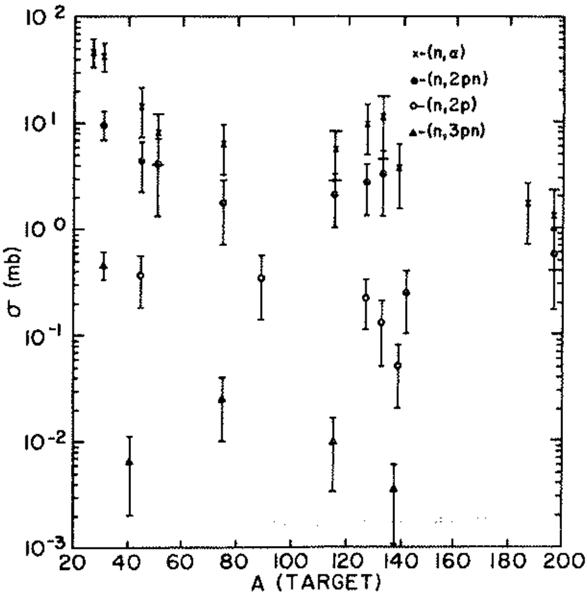

Fig. 2. "Effective cross sections for the (n,2pn), (n,2p), (n,3pn), and (n,α) reactions.

3. Decay Spectroscopy of Neutron-Rich Nuclides

A search was made for the new nuclide ^{202}Pt using the ^{204}Hg(p,3p)^{202}Pt reaction with 100-MeV protons and the ^{204}Hg(n,2pn)^{202}Pt reaction with neutrons generated by a 5 μa, 800-MeV proton beam. A satisfactory fast (10 min.) radiochemical technique for separation of Pt from Hg, Au, and Tl was developed. The search for ^{202}Pt using the (p,3p) reaction was inconclusive due to the high interference from neutron-deficient Pt nuclides. Using the (n,2pn) reaction the ratio of neutron-rich to neutron-deficient products was greatly enhanced, but the available fluxes were too low to produce observable ^{202}Pt. Searches for new nuclides using the (n,2pn) reaction will resume when the LAMPF beam current reaches 100 μa.

3.1 Decay of ^{200}Pt

The decay of the neutron-rich nuclide ^{200}Pt was studied from sources produced by the reaction ^{204}Hg(n,2p3n)^{200}Pt using LAMPF neutrons and also ^{198}Pt(t,p)^{200}Pt. No information is available[5]) on excited states of ^{200}Au except for a 12^- isomer[6]) at approximately 1 MeV. The decay of ^{200}Pt was studied by Roy *et al.*,[7]) but only decay to the ground state was observed. In our experiment Pt was separated radiochemically. A half-life of 12.6 ± 0.3 hrs. was measured for ^{200}Pt which is slightly higher than the value of 11.5 ± 1.0 hrs. obtained by Roy *et al.*[7]) Gamma singles measurements were made with both large volume Ge(Li) and LEPS detectors. A total of 35 γ rays were assigned to ^{200}Pt decay of which 31 were placed in a level scheme for ^{200}Au. Coincidence measurements were performed with two large-volume Ge(Li) detectors, and about 4.5×10^6 events were stored on magnetic tape. The energies, intensities, and placements of the γ rays observed in ^{200}Pt decay are given in Table I.

The γ singles and coincidence data was used to construct the first decay scheme[8]) for ^{200}Pt which is shown in Fig. 3. The percent β^- feeding to levels in ^{200}Au was determined from an equilibrium source of ^{200}Pt and ^{200}Au by comparison of γ intensities of the 227-keV transition depopulating the 304-keV level in ^{200}Au and the 1225-keV transition depopulating the 1593-keV level in ^{200}Hg.

Table I. γ rays from ^{200}Pt decay.

Energy (keV)	Relative intensity[a]	Placement (keV)
25.21±0.06	10.2 ±1.0	unplaced
27.48±0.10	2.93±0.85	104-76
43.67±0.04	59.9 ±3.4	104-60
60.00±0.04	172. ±10.	60-0
76.20±0.05	1000.[a]	76-0
86.40±0.14	2.15±0.86	390-304
97.52±0.09	9.40±1.25	390-293
103.60±0.09	76.7 ±4.1	104-0
135.94±0.15	242. ±14.	240-104
137.68±0.16	17.2 ±2.4	304-166
140.09±0.21	5.3 ±2.3	244-104
146.54±0.17	36.3 ±3.2	390-244
150.61±0.18	18.4 ±2.8	390-240
164.95±0.35[b]	4.7 ±1.5[b]	469-304
166.00±0.20	38.1 ±3.9	166-0
167.37±0.21	27.8 ±3.7	244-76
179.40±0.19	3.49±0.58	240-60
183.38±0.15	4.47±0.60	244.60
189.38±0.40[c]	8.5 ±3.0[c]	293-104
200.00±0.06	50.2 ±3.0	304-104
212.61±0.29	1.29±0.52	unplaced
218.17±0.21	2.48±0.80	unplaced
227.45±0.05	154. ±8.	304-76
232.80±0.08	6.74±0.51	293-60
239.56±0.16	5.92±0.80	240-0
243.71±0.05	186. ±12. 4.1 ±1.2[d]	304-60 244-0
251.46±0.22	4.75±0.82	unplaced
286.69±0.21	2.55±0.52	390-104
292.66±0.06	20.5 ±1.3	293-0
303.70±0.05	12.2 ±0.8	304-0
313.97±0.07	9.47±0.69	390-76
330.28±0.05	81.6 ±4.5	390-60
390.20±0.06	22.4 ±1.3	390-0
408.68±0.22	1.65±0.37	469-60
468.72±0.06	19.4 ±1.1	469-0

[a] Intensity normalized to 1000 for the 76-keV γ ray.
[b] Energy and intensity from spectrum in coincidence with the 244-keV gate.
[c] Energy and intensity from spectrum in coincidence with the 104-keV gate.
[d] Intensity from spectrum in coincidence with the 147-keV gate by comparison with intensity of the 140-, 167-, and 187-keV γ rays.

Due to the lack of information on conversion coefficients for the many intense low-energy transitions emitted in ^{200}Pt decay coupled with the high Z of ^{200}Au, our conclusions concerning J^{π}'s for states in ^{200}Au are limited. On the basis of β and γ feedings some conclusions could be drawn and are indicated in Fig. 3.

A crude description of low-lying levels in ^{200}Au can be made by coupling $d_{3/2}$ or $s_{1/2}$ proton-hole states to $f_{5/2}$, $p_{1/2}$, or $p_{3/2}$ neutron-hole states. There are 16 possible states: two 0^-, five 1^-, five 2^-, three 3^-, and one 4^-. The levels we observe in ^{200}Au would be predominantly of spin 0, 1, and 2 fed by 1st forbidden β^- decay. The above multiplicities are consistent with our observations of 9 levels in ^{200}Au from 0 to 340 keV and the assumption of a minimal number of core-coupled states below 300 keV. A shell-model calculation involving 3 proton holes below $Z = 82$ and 5 neutron holes below $N = 126$ would help to determine whether the low-lying levels are predominantly two-hole states.

3.2 Decay of ^{197}Ir

The decay of neutron-rich ^{197}Ir was studied from sources produced by the reaction

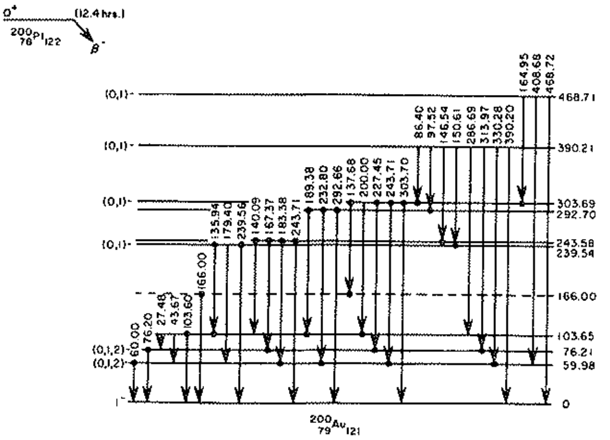

Fig. 3. Decay scheme of ^{200}Pt.

^{198}Pt(p,2p)^{197}Ir using 100-MeV protons at LAMPF. A 10 min radiochemical separation provided satisfactory decontamination from Au and Pt. Measurements of γ singles spectra were made with Ge(Li) and LEPS detectors. Five successive 5 min. spectra were collected for each source in order to distinguish ^{197}Ir γ rays on the basis of half-life. A value of 10 ± 1 min was obtained for the ^{197}Ir half-life in disagreement with the accepted value of 7 min. Preliminary γ singles data is summarized in Table II.

Table II. γ rays from ^{197}Pt decay.

Energy (keV)	Relative Intensity[a]
53.1	88
157.2	40
166.4	120
228.8	24
246.4	84
269.3	132
299.6	244
312.4	44
340.2	48
378.7	377
430.6	611
456.8	371
469.7	1000
496.4	362
527.2	238
533.9	58
539.2	145
542.0	105
563.5	44
581.0	36
708.2	50
715.3	91
738.8	11
791.7	49
809.1	319
815.9	449
849.5	65
873.3	64
939.4	207
947.1	59
1008.0	17
1246.0	20
1343.2	211

[a] Intensity normalized to 1000 for 469.7-keV γ ray.

In analogy with other odd A Ir nuclides, ^{197}Ir should have a $3/2^+$ ground state and a long-lived $11/2^-$ isomeric state. The presence of the $11/2^-$ isomeric state is inferred from observation of the decay of the 80-min. isomer of ^{197}Pt growing in with an approximate 10-min. half-life. It is not clear whether we have observed γ rays from the decay of the $3/2^+$ ground state of ^{197}Ir. Either the ground state half-life is small compared to the time necessary to do the chemical separation or the half-life is about the same as that for the $11/2^-$ isomer. Additional experiments are being planned to enhance the ratio of $3/2^+$ to $11/2^-$ population using production reactions that carry in less angular momentum that 100-MeV protons.

References

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1. C. J. Orth, W. R. Daniels, and B. J. Dropesky, Phys. Rev. C 8, 2364 (1973).
2. T. E. Ward, Y. Y. Chu, and J. B. Cumming, Phys. Rev. C 8, 340 (1973).
3. C. J. Orth (private communication).
4. John C. Hill, D. G. Shirk, R. F. Petry, and K. H. Wang, Phys. Rev. C 12, 1978 (1975).
5. M. J. Martin, Nucl. Data B6 (No. 4), 387 (1971).
6. J. C. Cunnane, R. Hochel, S. W. Yates, and P. J. Daly, Nucl. Phys. A196, 593 (1972).
7. L. P. Roy, J. C. Roy, and J. S. Merritt, Phys. Rev. 105, 1337 (1957).
8. John C. Hill, D. G. Shirk, R. F. Petry, and K. H. Wang, Phys. Rev. C (to be published).