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Evidence for Products of Rapid Neutron Capture on the Surfaces of Peculiar A Stars

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Observations indicate the presence of the unstable element promethium, as well as of certain products of rapid neutron capture in peculiar A stars. An analysis of these features indicates the possible presence of the heaviest elements (from the hypothetical island of stability around $Z=114$) in the surfaces of these stars. Observational results concerning some specific abundance correlations (e.g. between promethium, uranium, and plutonium in the same star) are desirable to prove the hypothesis.

INTRODUCTION

Rapid neutron capture (the *r*-process) is generally believed to constitute the most important mechanism in the production of the heaviest chemical elements in nature. The process is usually found in explosive stellar events, and a recent study (Schramm and Fowler 1971) showed that it can yield nuclides with mass numbers up to ~ 300. After the termination of the *r*-process, these superheavy nuclei undergo beta decay toward the hypothetical island of stability in the vicinity of atomic number $Z = 114$. The prediction of such an island by numerous workers in the field of nuclear theory (see e.g. Nilsson *et al.* 1969, where references to earlier papers may be found) have led to much experimental work both on producing such nuclei, and on a search for their possible occurrence in nature, yet the results still remain dubious. It is the aim of this paper to point that indirect evidence for the presence of superheavy nuclei in nature may be obtained from the spectra of peculiar A stars. This seems to be a promising way of looking for these nuclei, in addition to the already known ways of looking in meteorites (Dakowski 1969, Anders and Heymann 1969), lunar material (Bhandari *et al.* 1971), and cosmic radiation (Price *et al.* 1971).

The problem is of importance not only for nuclear physics but also for theories of stellar evolution. We still lack observational evidence in favour of the *r*-process in individual celestial bodies. We note in this context that Merrill's announcement (1952) on the detection of technetium in S stars is regarded today as a proof of the operation of the slow neutron-capture process in stars. The observation of promethium in the Ap star HR 465 by M. Aller and Cowley (1970) is probably of similar importance with respect to the *r*-process.

THE HEAVIEST ELEMENTS AND PROMETHIUM IN Ap STARS

The most important results concerning abundances of elements with $Z \geqq 76$ in the peculiar A stars are summarized in Table 1. We restricted

TABLE 1

Observational evidence for the heaviest elements in Ap stars

Element	Results
$_{76}$Os	Lines of Os I identified in five stars, Os II—in four stars, and suspected in one (Brandi and Jaschek 1970). Os II found in 73 Dra (Guthrie 1969b, Jaschek and Malaroda 1970).
$_{78}$Pt	Pt II lines found in 73 Dra (Jaschek and Malaroda 1970) and in five other Ap stars (Brandi and Jaschek 1970). Pt II lines found by Dworetsky (1969) in nine Ap stars of the Hg group.
$_{79}$Au	Au I suspected in 73 Dra (Jaschek and Malaroda 1970) and in HD 25354 and HD 71866 (Brandi and Jaschek 1970).
$_{80}$Hg	Wavelengths of the Hg 3894 line in the Ap stars of the main group are systematically larger than the wavelengths in Mn stars and for terrestrial samples of mercury (Guthrie 1971).
$_{82}$Pb	Determined in α^2 CVn (Burbidge and Burbidge 1955).
$_{90}$Th	Th II lines suspected in 73 Dra (Guthrie 1969b).
$_{92}$U	U II lines in 73 Dra suspected by Guthrie (1969b) and found by Jaschek and Malaroda (1970). U II lines found in HD 2543, HD 42616, and the λ3860 line found only in HD 15144, HD 137909 and HD 216533 (Brandi and Jaschek 1970). Suspected in α^2 CVn.

ourselves mainly to new results published since a review paper by Guthrie (1969a), to which the reader is referred for earlier references. It is important to stress the fact that the presence of uranium (and possibly also, of thorium) indicates that the matter we observe is enriched by *r*-process products. The isotopic shifts of the lines of Pt II in HR 4072 (Dworetsky 1969) and of the Hg II 3984 line in several Ap stars (Guthrie 1971, where references to original observational papers may be found) indicate that the mean atomic masses of platinum and of mercury in the peculiar A stars are larger by some units than for terrestrial samples. The mercury in HD 192913 seems to consist only of the heaviest isotope, ^{204}Hg, that may be produced exclusively in the *r*-process.

The results of the search for Pm II lines in HR 465 were summarized recently by M. Aller (1971). From a total of 153 laboratory lines, 110 lines were found in the stellar spectrum, while many of the remaining 43 were also apparent on the tracings. Though these lines appear in a very crowded region of the spectrum, it is difficult to imagine that all 110 were identified by chance coincidence in wavelength. Aller stated that only 69.5 lines (including blends) of the reported identifications would be expected from chance coincidences. Let us therefore assume, for the time being, that this identification points to the real occurrence of promethium in HR 465.

The presence of promethium seems to be related to the *r*-process in a more complicated way than is the presence of technetium to the *s*-process. The main difference stems from the extremely short half-lives of the promethium isotopes. Its two most long-lived isotopes, with mass numbers 145 and 146, have half-lives of 17.7 and 5.55 yr, respectively. In addition, they are neutron-deficient and cannot be produced in neutron capture. The longest-lived promethium isotope that can be produced in neutron capture is ^{147}Pm, with a half-life of 2.62 yr. But even if sufficient amounts of this nuclide were produced in a single process, its abundance would drop by a factor of 3.24×10^{-12} in 100 yr, and by a factor of 10^{-115} in 10^3 yr. It is thus almost impossible to regard the observed Pm lines as resulting from directly produced promethium. This argument applies not only against the *r*-process but also against the *s*-process origin in which promethium may be produced continually but its half-life renders it unobservable in practice.

If we do not wish to invent special ad hoc mechanisms that might be responsible for the origin of promethium, we have at our disposal one quite natural mechanism which seems to have been over-looked by astrophysicists though it was proposed some years ago by Selinov (1958) to account for some anomalies in cosmic abundances: spontaneous fission. Today the physicists have at

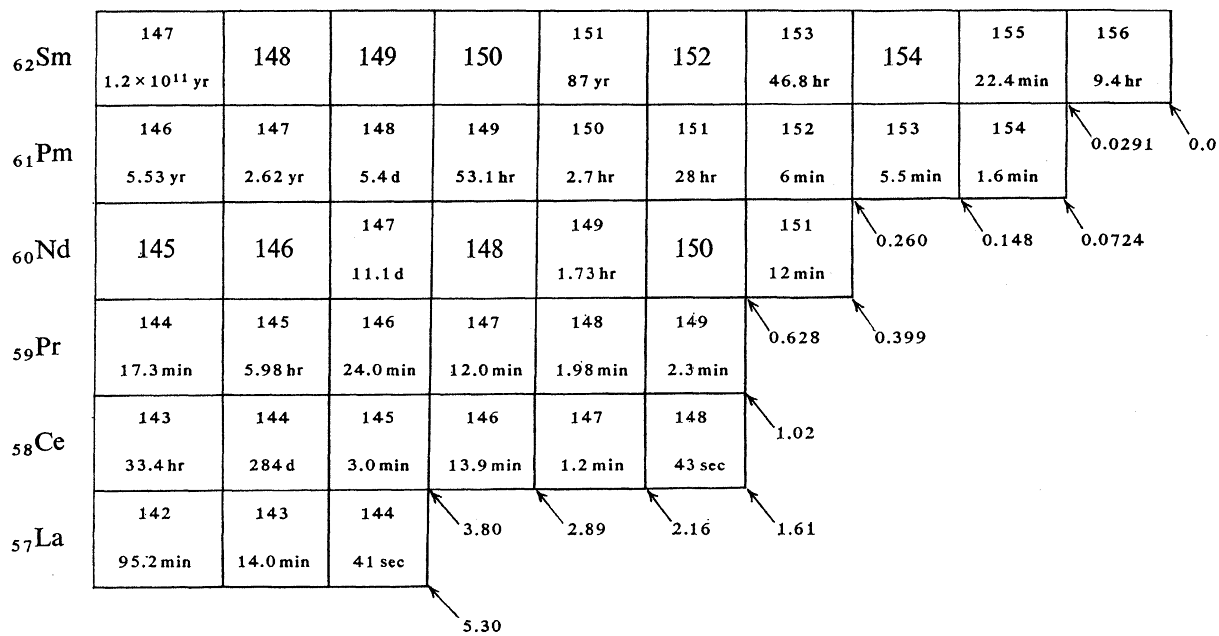

FIG. 1. Fragment chart of nuclides.

their disposal a steady promethium source in reactors. In Figure 1 the fragment of a chart of nuclides is shown, with the promethium isotopes that may be produced in the fission of a heavy nucleus. ^{147}Pm, ^{149}Pm and ^{151}Pm are the three longest-lived promethium isotopes that appear in the isobaric decay chains of fission products. In order to characterize the production of promethium in the fission of ^{235}U by thermal neutrons, we give the isobaric chain yield from a recent chart of the nuclides (Seelmann–Eggebert *et al.* 1968): 2.16 per cent for $A = 147$, 1.02 per cent for $A = 149$, and 0.399 per cent for $A = 151$. An analysis of the product yield curves for the fission of various nuclei by Wahl (1965) indicates a constancy in position on the mass-number axis of the heavy-mass peak in the mass distribution. This is explained by the 50-proton and/or 82-neutron shell effects. This extra-stable region includes the mass numbers $135 \leqq A \leqq 150$, which are of primordial importance for the production of promethium. In the region of superheavy nuclei the mass distribution changes inasmuch as the light-mass peak is shifted towards the heavy-mass peak. As they both nearly coincide in the elements in the vicinity of $Z \approx 110$, symmetric fission occurs and the yield of the isobars with $A = 147$, 149, and 151 is nearly twice the yield in the region of $Z = 92$. The symmetric fission of superheavy elements was proposed by Dakowski (1969) as an explanation of the anomalies in isotopic composition of xenon and krypton in meteorites. The same factor may, perhaps, enhance the abundance of promethium in at least one Ap star.

If promethium may be regarded thus as a fission product of the superheavy products of a previous *r*-process, then we may use the estimates of Schramm and Fowler (1971) to obtain the promethium abundance. They obtained altogether an abundance of 0.556 or 0.179 (on the Si = 10^6 scale) for the eight long-lived superheavy nuclei with $T_{1/2} \geqq 10^3$ yr and $Z \geqq 110$. The first abundance value was obtained for a nuclear parameter $\kappa = 1.79$, according to the mass law of Myers and Swiatecki (1966); the second was for $\kappa = 2.3$ (Seeger 1967). The range of κ between these two extreme values is quite reasonable and sufficient for calculations of the *r*-process. We applied the results of abundance calculations of superheavy nuclei,

TABLE 2

Abundance of ^{147}Pm from the spontaneous fission of the superheavy nuclei

Time (in yr) after the *r*-process event	Abundance on Si = 10^6 scale for the nuclear parameter κ	
	$\kappa = 1.79$	$\kappa = 2.3$
10	1.45×10^{-5}	3.92×10^{-6}
10^2	1.49×10^{-5}	4.04×10^{-6}
10^3	9.40×10^{-6}	2.71×10^{-6}
10^4	1.84×10^{-6}	7.03×10^{-7}
10^5	8.90×10^{-7}	2.86×10^{-8}
10^6	2.06×10^{-10}	6.40×10^{-11}
10^7	3.58×10^{-11}	9.78×10^{-12}
10^8	1.92×10^{-11}	5.24×10^{-12}
10^9	3.75×10^{-14}	1.02×10^{-14}

If these abundances are to be applied to matter which has been ejected by a supernova, they should be multiplied, together with the abundances derived by Schramm and Fowler (1971), and those for other *r*-process elements, by a common factor, much higher than unity, and characterizing the enrichment of the ejected matter in heavy elements.

which are given in Table 1 in the paper by Schramm and Fowler (1971), to estimates of the abundance of ^{147}Pm for various time intervals after the *r*-process. For time intervals $t \gg 10^2$ yr, the whole promethium abundance results just from this fission; with a fission yield of Pm of 0.05 (which is not overestimated for symmetric fission), and the rather conservative estimates of half-lives as given by Schramm and Fowler (1971), we arrive at the values given in Table 2. Though these seem to be quite small, undetectable values, they are to be considered as some average values for cosmic matter which has passed the stage of rapid neutron capture. They must be raised by some orders of magnitude, however, if we deal with matter ejected by a supernova in which such a capture had just occurred. This question is closely related to the problem of the origin of the abundance anomalies in Ap stars.

ABUNDANCE ANOMALIES AND THE VAN DEN HEUVEL–GUTHRIE THEORY

Let us assume here, with a majority of authors, that the abundance anomalies exhibited in the spectra of the peculiar A stars are real. Now, the membership of peculiar A stars in clusters and visual binaries with normal main sequence members make it difficult to assume that these stars were formed from interstellar matter of some strange composition. It seems to be more justified to assume that the anomalies are restricted to the surface layers. A suggestion proposed by Fowler *et al.* (1965) and elaborated in detail by Van den Heuvel (1967) and by Guthrie (1968) seems to account well for the surface abundance anomalies. This proposal suggests that the present Ap stars are the original secondaries of close binary systems in which the original, more massive, primaries have evolved and exploded as supernovae. Some of the material was lost into space, some part of it was transferred to the surface of the secondary star. The transfer of material enriched by the explosion in heavy elements changed the composition of the surface of the secondary component. In addition, surface nuclear reactions were possible. Guthrie applied his modified version of the Van den Heuvel theory to a detailed explanation of the observed anomalies of heavy and light elements in Ap stars (Guthrie 1969a, 1970, 1971). With an initial separation of the binary system of the order of 10 a.u., and with an ejected mass of $10\,M_\odot$, the secondary component of the system receives a total of about $10^{-6}\,M_\odot$, with a much higher percentage of *r*-process nuclides than in the average cosmic matter. The abundances of superheavy nuclides in this matter may thus be higher by some orders of magnitude than the values obtained by Schramm and Fowler, and the same applies to the promethium abundance. All these anomalies, however, should be characteristic only of the surface layers.

Provided the supernova-origin theory of the heavy elements holds, the peculiar A stars seem to be the most suitable objects for a search after the heaviest elements. Note that the most recent estimates of the total half-lives of superheavy elements (Łukasiak *et al.* 1971) yield values higher by one or two orders of magnitude than those used by Schramm and Fowler (1971), and this stretches the time scale for promethium observability in the surfaces of the Ap stars.

It has been suggested (Kuchowicz 1970a, b) that a search for transuranium elements should be made in the spectra of those Ap stars in which uranium has already been found, as in 73 Dra. Estimates of plutonium abundance show that even 10^7 yr after the *r*-process the U/Pu ratio is of the order of unity which makes a detection of plutonium in stellar spectra not altogether hopeless. A search for further transuranium elements is rendered more difficult by their diminishing half-lives, yet the abundance of promethium in the spectra of Ap stars may be an indication of the possible presence of elements from the stability island around $Z = 114$. In order to obtain some conclusive results concerning the synthesis of these elements one should try to find the lines of lighter transuranium elements (plutonium, neptunium, curium) both in HR 465, and in those Ap stars in which uranium has already been identified. Abundance correlations between various *r*-process products should provide some kind of transuranium chronology of the Ap stars. They may be applied also to test the validity of Guthrie's version of the Van den Heuvel theory of the origin of Ap stars. It should also prove interesting to find whether promethium is observed in those stars in which heavy elements produced in the *r*-process were identified.

It is at present difficult to give quantitative arguments in favour of the proposed theory of promethium origin. Yet another feature of the peculiar A stars, usually connected with direct production of the respective elements in the *r*-process, may be mentioned: the overabundances of rare-earth elements. Many of them, especially La, Ce, Pr, Nd, Sm, are just high-yield fission products, like promethium. Perhaps the overabundances of these elements may be due at least in part to spontaneous fission of transuranium elements? Since we have to do with stable final products, the contribution of the so-called fission-gap nuclei (between the two stability islands around uranium and around $Z = 114$) is here of importance, too. Schramm and Fowler (1971) have emphasized this aspect with respect to the universal abundance curve; it seems to be still more important in case of the surface layers of Ap stars, with their much higher percentage of the *r*-process products.

For a testing of the *r*-process theory it should prove extremely useful to try to estimate the exact wavelengths of the heavy-element lines in Ap stars, in order to be able to speculate on the *r*-process contributions to these abundances. It would further be necessary to determine in the laboratory the exact wavelengths for various promethium isotopes, and to compare these values with the stellar ones in order to rule out any possible contribution from the longest-lived isotope (^{145}Pm), which has nothing in common with the *r*-process.

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