for $OCSe^{80}$ was determined at Brookhaven National Laboratory and the sign in the apparatus for circular polarization at MIT. Final Zeeman measurements on $OCSe^{79}$ were made with a Columbia University spectrometer using an MIT Zeeman cell and magnet. Certain preliminary measurements were carried out at Brookhaven. The remainder of the measurements were done at Columbia.

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# "Nonmesonic" Bound *V*-Particle Decay*

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A theoretical treatment is presented of the apparent relative stability of $V$ particles in nuclear matter in terms of the process of bound $V$-particle nonmesonic decay. Mean lives for nonmesonic decay of $V$ particles imbedded in nuclear fragments such as He, Li, $\cdots$O, are estimated as $\approx 10^{-11}-10^{-12}$ sec. A very brief discussion is given of the bearing of such relatively long mean lives on possible mechanisms of $V$-particle production.

## INTRODUCTION

RECENTLY, cosmic-ray evidence has suggested the existence of unstable nuclear fragments ($Z\geqq 2$) emitted in high-energy events.[1] These fragments are observed to come to rest in emulsions in about $10^{-12}$ sec and then to decay with a visible energy release of 50–150 Mev. Since the mean life for the emission of a nucleon from a nuclear fragment having an excitation energy $\approx 100$ Mev is $\approx 10^{-20}$ sec, it has been assumed[2] that all the "excitation energy" in such a fragment is concentrated on a single nucleon, i.e., that one of the nucleons in the fragment is a $V$ particle; it is further assumed that this $V$ particle (considered as an elementary fermion) is still bound to the other nucleons in the fragment by "nuclear forces" about as strong as those acting among the nucleons themselves. It is the purpose of the present note to relate the mean life for the decay (mesonic or nonmesonic) of such a "$V$-particle nuclear fragment" to the mean life for the mesonic decay of a free (unbound) $V$ particle (free $V\rightarrow p+\pi^- +35$–$40$ Mev, in about $10^{-10}$ sec).[3] In fact, the $V$ particle bound in such a fragment may decay without the emission of a $\pi$ meson, the appropriate energy and momentum balance being insured by the appearance of an ejected nucleon and a recoiling, in general excited, residual fragment. It is reasonable to suppose that this nonmesonic decay of a "$V$-particle nuclear fragment" is a process formally analogous to the nonradiative deexcitation of a nucleus in an ordinary excited state (internal conversion); the general basis of the analogy may be considered by postulating an appropriate Hamiltonian density $H$ for the system of nucleons, $V$ particles, and $\pi$ mesons. We take

$$H=H(\psi_n)+H(\psi_V)+H(\varphi_\alpha)+H_{\text{prod}}(\psi_n,\psi_V,\varphi_\alpha,\cdots)+\frac{g}{2\kappa_n}(\psi_n{}^*\boldsymbol{\sigma}\tau_\alpha\psi_n)\cdot\nabla\varphi_\alpha+\frac{g}{2\kappa_V}(\psi_V{}^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_\alpha+\left\{\frac{\eta}{\kappa_n+\kappa_V}(\psi_n{}^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_\alpha+\text{h.c.}\right\},\quad(1)$$

where

$\psi_n,\ \psi_V,\ \varphi_\alpha=$ quantized field amplitudes for the nucleon, $V$ particle, and $\pi$-meson fields, respectively;

$H(\psi_n),\ H(\psi_V),\ H(\varphi_\alpha)=$ Hamiltonian densities for isolated nucleon, $V$ particle, and $\pi$-meson fields, respectively;

$\kappa_n,\ \kappa_V=$ inverse Compton wavelengths of the nucleon and $V$ particle;

$g=$ coupling constant between nucleon and $\pi$-meson fields;

$\eta=$ coupling constant among nucleon, $V$ particle, and $\pi$-meson fields ($\eta\ll g$ to account for the relatively long mean life of a free $V$ particle against decay into a nucleon and $\pi$ meson);

$H_{\text{prod}}(\psi_n,\psi_V,\varphi_\alpha,\cdots)=$ relatively large interaction term describing $V$-particle production in nucleon-nucleon and/or $\pi$-meson nucleon collisions, and contributing a major part of the $V$-particle nucleon

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[1] M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953); Tidman, Davis, Herz, and Tennent, Phil. Mag. **44**, 350 (1953); J. Crussard and D. Morellet, Compt. rend. **236**, 64 (1953); Freier, Anderson, and Naugle, preprint, Phys. Rev. (to be published).
[2] See M. Danysz and J. Pniewski, Phil. Mag. **44**, 348 (1953).
[3] Latest mean-life estimates in W. L. Alford and R. B. Leighton, Phys. Rev. **90**, 622 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953); J. G. Wilson and C. C. Butler, Phil. Mag. **43**, 993 (1953); Bridge, Peyrou, Rossi, and Safford, Phys. Rev. **91**, 362 (1953).

"nuclear force." On our assumption, however, $H_{\text{prod}}$ is necessarily of such a form that it cannot contribute appreciably to either free $V$-particle mesonic, or bound $V$-particle nonmesonic (or mesonic) decay, i.e., $H_{\text{prod}}$ cannot be expressed in any approximation as:

$$\text{constant}\times\{(\psi_n^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_\alpha+\text{h.c.}\}$$

or as

$$\text{constant}\times\{(\psi_n^*\boldsymbol{\sigma}\psi_n)\cdot(\psi_n^*\boldsymbol{\sigma}\psi_V)+\text{h.c.}\},$$

with the constants $\gtrless\eta$. It is to be noted that gradient coupling has been assumed for the (pseudoscalar) $\pi$-meson field, the here relatively small, nucleon-velocity dependent terms also present in this interaction being neglected. The assumption of direct ($\beta\gamma_5$) coupling with use of the equivalence theorem[4] leads in the nonrelativistic approximation to the Hamiltonian density of Eq. (1) together with additional interaction terms ($\sim\varphi_\alpha^2$); these latter interaction terms, however, do not alter any of the general conclusions obtained below. It should also be emphasized that if it is ever definitely established that $V$ particles are copiously produced in the reactions:

$$\text{nucleon}+\text{nucleon}\rightarrow\text{nucleon}+V, \tag{2a}$$

or

$$\pi\text{ meson}+\text{nucleon}\rightarrow\pi\text{ meson}+V, \tag{2b}$$

it will follow that $V$ particles cannot exist in nuclear fragments for times as long as $10^{-12}$ sec. For the inverse of these production reactions (with "reabsorption" by the nucleons of the fragment of any $\pi$ mesons produced, e.g., $V\rightarrow\text{nucleon}+\pi+\bar{\pi}$; etc.) can now correspond to the nonmesonic bound $V$-particle decay; this decay will occur with a mean life $\ll 10^{-12}$ sec if the coupling constants in the processes of Eq. (2) are adjusted to describe copious $V$-particle production. On the other hand, e.g., copious "pair" production of $V$ particles via reactions of the type

$$\text{nucleon}+\text{nucleon}\rightarrow V+V, \tag{3a}$$

or

$$\pi\text{ meson}+\text{nucleon}\rightarrow V+\text{"heavy" meson} \tag{3b}$$

is not inconsistent with the relatively long mean life of bound $V$ particles within nuclear matter.[5] At the moment, some experimental data[6] presents evidence against copious "pair" production of $V$ particles via reactions (3a) or (3b) so that the here-adopted interpretation[2] of the behavior of the unstable nuclear fragments remains in doubt. However, very recent Brookhaven cosmotron work[6a] indicates $V$-particle production via reaction (3b).

[4] Brueckner, Gell-Mann, and Goldberger, Phys. Rev. **90**, 476 (1953); L. L. Foldy, Phys. Rev. **84**, 168 (1951); F. J. Dyson, Phys. Rev. **73**, 929 (1948).

[5] Compare A. Pais' analysis [Phys. Rev. **86**, 663 (1952)] of the relative stability of the free $V$ particle for mesonic decay which also rules out production reactions (2a) and (2b) but permits production reactions (3a) and (3b). We must assume (as does Pais) that for the "heavy" meson in question, the reactions: nucleon+nucleon→nucleon+nucleon+"heavy" meson, or, $\pi$ meson +nucleon→"heavy meson"+nucleon, are very improbable.

[6] Leighton, Wanlass, and Anderson, Phys. Rev. **89**, 148 (1953); Fretter, May, and Nakada, Phys. Rev. **89**, 168 (1953).

## CALCULATION OF PROBABILITY OF NONMESONIC BOUND V DECAY

We now assume, that the $\pi$-meson field amplitude may be written as:

$$\varphi_\alpha=\varphi_{\alpha;\,\text{quantized}}+\varphi_{\alpha;\,\text{static}}, \tag{4}$$

where

$$(\nabla^2-\kappa_\pi^2)\varphi_{\alpha;\,\text{static}}=4\pi\frac{g}{2\kappa_n}\nabla\cdot(\psi_n^*\sigma\tau_\alpha\psi_n) \tag{5}$$

or

$$\varphi_{\alpha;\,\text{static}}(\mathbf{r})=-\frac{g}{2\kappa_n}\nabla_r\cdot\int\psi_n^*(x')\boldsymbol{\sigma}'\tau_\alpha'\psi_n(x')Y(\mathbf{r}-\mathbf{r}')dx';$$

$$\text{with } x'\equiv\mathbf{r}',s',\tau';\ Y(\mathbf{r})\equiv e^{-\kappa_\pi r}/r; \tag{6}$$

and

$$\varphi_{\alpha;\,\text{quantized}}(\mathbf{r})=\sum_{\mathbf{q}}\left[\frac{2\pi\hbar c}{(q^2+\kappa_\pi^2)^{\frac{1}{2}}}\right]^{\frac{1}{2}}\times\Omega^{-\frac{1}{2}}\{a_\alpha(\mathbf{q})e^{-i\mathbf{q}\cdot\mathbf{r}}+\text{h.c.}\} \tag{7}$$

with $\kappa_\pi$ = inverse Compton wavelength of $\pi$ meson; $\mathbf{q}$ = wave-number of meson in quantized field; $a_\alpha(\mathbf{q})$ = destruction operator for mesons of wave-number $\mathbf{q}$; and $\Omega$ = hohlraum volume. The interaction term in Eq. (1) which leads to the nonmesonic decay of a $V$ particle is then:

$$H^{\text{inter}}=\frac{\eta}{\kappa_n+\kappa_V}(\psi_n^*\boldsymbol{\sigma}\tau_\alpha\psi_V)\cdot\nabla\varphi_{\alpha;\,\text{static}}, \tag{8}$$

with $\varphi_{\alpha;\,\text{static}}$ given by Eq. (6). Passing from the quantized-field representation of the nucleons to the corresponding configuration space representation, $\varphi_{\alpha;\,\text{static}}$ is given by

$$\varphi_{\alpha;\,\text{static}}(\mathbf{r})=-\frac{g}{2\kappa_n}\nabla_r\cdot\int\sum_{j=1}^{A-1}\Psi_f^*(x_1,\cdots,x_j,\cdots x_{A-1})\times\boldsymbol{\sigma}_j\tau_{\alpha;j}Y(\mathbf{r}-\mathbf{r}_j)\Psi_i(x_1,\cdots,x_j,\cdots x_{A-1})\times dx_1\cdots dx_j\cdots dx_{A-1}, \tag{9}$$

where $\Psi_i$, $\Psi_f$ are configuration space wave functions of the initial and final states of the $A-1$ "other" nucleons in the nuclear fragment. The interaction Hamiltonian matrix element for the nonmesonic decay of the bound $V$ particle therefore becomes (setting $\kappa_n=\kappa_V=\kappa$):

$$\mathcal{H}_{fi}^{\text{inter}}=-\frac{\eta g}{(2\kappa)^2}\int\cdots dx_j\cdots\int dx_A\times\sum_{j=1}^{A-1}(\mathcal{B}\Psi_f(\cdots x_j\cdots)\psi_n(x_A))^*[\boldsymbol{\tau}_A\cdot\boldsymbol{\tau}_j\boldsymbol{\sigma}_A\cdot\nabla_A\boldsymbol{\sigma}_j\cdot\nabla_A\times Y(\mathbf{r}_A-\mathbf{r}_j)]\psi_V(x_A)\Psi_i(\cdots x_j\cdots)$$

$$=\int\cdots dx_j\cdots\Psi_f^*\mathfrak{A}\Psi_i, \tag{10a}$$

[6a] By Fowler, Shutt, Thorndike and Whittemore, Phys. Rev. **91**, 1287 (1953).

with

$$\mathfrak{A}\equiv-\frac{\eta g}{(2\kappa)^2}\int dx_A \sum_{j=1}^{A-1}\psi_n^*(x_A)\times\mathfrak{B}[\boldsymbol{\tau}_A\cdot\boldsymbol{\tau}_j\boldsymbol{\sigma}_A\cdot\nabla_A\boldsymbol{\sigma}_j\cdot\nabla_A Y(\mathbf{r}_A-\mathbf{r}_j)]\psi_V(x_A). \quad (10b)$$

In Eqs. (10a) and (10b) the antisymmetrization operator $\mathfrak{B}$ has been inserted to account for the Pauli exclusion principle between the nucleon into which the $V$ particle transforms itself and the other nucleons in the residual fragment;[7] $\psi_V(x_A)$, $\psi_n(x_A)$ indicate the initial $V$ particle and the corresponding final nucleon wave functions in configuration space.

Equation (10a) exhibits the analogy between the nonmesonic decay of a nuclear fragment containing a bound $V$ particle and the radiationless (nonphotonic) decay of an ordinary excited nucleus (internal conversion); in the latter case $\Psi_i$, $\Psi_f$ are initial and final state orbital electronic wave functions of the atom ($\Psi_f$ contains an electron orbital corresponding to an electron ejected from the atom), $\psi_V(x)$, $\psi_n(x)$ are initial and final nucleon orbitals for the nucleon making the transition from the ordinary excited to the non-excited nuclear state ($\mathfrak{B}$, the antisymmetrization operator, is absent), $[\eta g/(2\kappa)^2]\boldsymbol{\tau}_A\cdot\boldsymbol{\tau}_j\boldsymbol{\sigma}_A\cdot\nabla_A\boldsymbol{\sigma}_j\cdot\nabla_A Y(\mathbf{r}_A-\mathbf{r}_j)$ is replaced by $e^2/|\mathbf{r}-\mathbf{r}_j|$.

In terms of $\mathfrak{H}_{fi}^{\text{inter}}$, the reciprocal mean life for nonmesonic decay is given in lowest order as:

$$\frac{1}{\tau_{\text{bound; nonmesonic}}}=\frac{2\pi}{\hbar}\sum_{\epsilon_f,\mathbf{k}_n,s_n,\tau_n}\left|\int\cdots dx_j\cdots\Psi_f^*\mathfrak{A}\Psi_i\right|^2\times\delta\left(\left[\frac{\hbar^2k_n^2}{2M_n}+M_nc^2+\epsilon_f+(A-1)M_nc^2\right]-\left[\epsilon_V+M_Vc^2+\epsilon_i+(A-1)M_nc^2\right]\right). \quad (11)$$

Further, we may suppose that for most of the states $f$ of the residual fragment for which $\int\cdots dx_j\cdots\Psi_f^*\mathfrak{A}\Psi_i$ is appreciable, the corresponding energy eigenvalues $\epsilon_f$, $\epsilon_i$ satisfy $|\epsilon_f-\epsilon_i|\ll(M_V-M_n)c^2+\epsilon_V$, i.e., for most of the states $f$ in nonmesonic bound $V$-particle decay, one nucleon carries off most of the available energy (see the experimental data in reference 1). Then $\hbar^2k_n^2/2M_n\approx(M_V-M_n)c^2+\epsilon_V\approx(M_V-M_n)c^2$, and, applying the closure procedure (with respect to the $\Psi_f$):

$$\frac{1}{\tau_{\text{bound; nonmesonic}}}=\frac{2\pi}{\hbar}\int\frac{d\omega_n}{4\pi}\sum_{s_n,\tau_n}\times\left(\int\cdots dx_j\cdots\Psi_i^*\mathfrak{A}^\dagger\mathfrak{A}\Psi_i\right)\frac{4\pi k_nM_n\Omega}{\hbar^28\pi^3}, \quad (12)$$

with

$$\hbar k_n\approx[2M_n(M_V-M_n)]^{\frac{1}{2}}c\approx4\hbar\kappa_\pi.$$

We may now, for the sake of simplicity and without altering the order of magnitude of the result, replace the antisymmetrization operator $\mathfrak{B}$ in Eqs. (10a) and (10b) by unity. Then $\mathfrak{A}$ may be written:

$$\mathfrak{A}\approx-\frac{\eta g}{(2\kappa)^2}\int d\rho ds_Ad\tau_A\sum_{j=1}^{A-1}\Omega^{-\frac{1}{2}}\exp[-i\mathbf{k}_n\cdot(\mathbf{r}_j+\boldsymbol{\rho})]\times v^*(s_n,\tau_n;s_A,\tau_A)[\boldsymbol{\tau}_A\cdot\boldsymbol{\tau}_j\boldsymbol{\sigma}_A\cdot\nabla_\rho\boldsymbol{\sigma}_j\cdot\nabla_\rho Y(\rho)]\times u(\epsilon_V;\mathbf{r}_j+\boldsymbol{\rho})v(s_V,\tau_V;s_A,\tau_A), \quad (13)$$

where, in addition, a plane wave approximation is used for $\psi_n(x_A)$ and $\psi_V(x_A)$ is factorized into its space and spin, charge parts. Since $u(\epsilon_V;\mathbf{r}_j+\boldsymbol{\rho})$ is slowly varying over spatial regions $\approx k_n^{-1}\approx(4\kappa_\pi)^{-1}$, we may effectively drop the dependence of $u(\epsilon_V)$ on $\boldsymbol{\rho}\equiv\mathbf{r}_A-\mathbf{r}_j$. The integration over $\boldsymbol{\rho}$ is then immediate if it is noted that $\nabla_\rho\nabla_\rho$ is Hermitian and so can be taken to act on

$$\exp[-i\mathbf{k}_n\cdot(\mathbf{r}_j+\boldsymbol{\rho})];$$

we obtain:

$$\mathfrak{A}\approx\int ds_Ad\tau_Av^*(s_n,\tau_n;s_A,\tau_A)\mathfrak{D}v(s_V,\tau_V;s_A,\tau_A), \quad (14a)$$

where

$$\mathfrak{D}\equiv\frac{\eta g}{(2\kappa)^2}\frac{4\pi}{k_n^2+\kappa_\pi^2}\sum_{j=1}^{A-1}\Omega^{-\frac{1}{2}}\exp(-i\mathbf{k}_n\cdot\mathbf{r}_j)\times u(\epsilon_V;\mathbf{r}_j)\boldsymbol{\tau}_A\cdot\boldsymbol{\tau}_j\boldsymbol{\sigma}_A\cdot\mathbf{k}_n\boldsymbol{\sigma}_j\cdot\mathbf{k}_n. \quad (14b)$$

Using Eqs. (12), (14a), and (14b), we find[7a] that

$$1/\tau_{\text{bound; nonmesonic}}=(1/\tau_0)\int\frac{d\omega_n}{4\pi}\sum_{j,l}\int\cdots dx_j\cdots dx_l\cdots\times\Psi_i^*(\cdots x_j\cdots x_l\cdots)\exp(-i\mathbf{k}_n\cdot\mathbf{r}_{jl})\kappa_\pi^{-3}\times u^*(\epsilon_V;\mathbf{r}_l)u(\epsilon_V;\mathbf{r}_j)\tfrac{1}{3}\boldsymbol{\tau}_j\cdot\boldsymbol{\tau}_l\boldsymbol{\sigma}_j\cdot\boldsymbol{\sigma}_l\times\Psi_i(\cdots x_j\cdots x_l\cdots), \quad (15)$$

where

$$1/\tau_0=\pi(k_n/\kappa_\pi)(1+\kappa_\pi^2/k_n^2)^{-2}(M_\pi/M_n)^3\times(\eta^2/\hbar c)(g^2/\hbar c)(M_\pi c^2/\hbar).$$

The terms in Eq. (15) with $j=l$ give the major contribution to the reciprocal mean life.[8] Setting $j=l$ and defining

$$\rho(\mathbf{r}_1)\equiv\int d\tau_1ds_1dx_2\cdots dx_{A-1}|\Psi_i(x_1,\cdots,x_{A-1})|^2,$$

[7] The mode of action of the operator $\mathfrak{B}$ may be described via the usual permutation operators.

[7a] Remembering that with the (charge-independent) $H$ of Eq. (1), the expectation value of any linear function of $\boldsymbol{\tau}_A$ is zero in the initial $V$-containing nuclear fragment.

[8] The terms in $1/\tau_{\text{bound; nonmesonic}}$ for $j\neq l$ are $\approx(A-2)10^{-2}$ $\times$terms in $1/\tau_{\text{bound; nonmesonic}}$ for $j=l$, and so are unimportant for the $A$ of practical interest. The small factor $10^{-2}$ follows from the destructive interference entailed by having $k_n\langle r_{jl}\rangle\approx k_n/\kappa_\pi\approx4\gg1$.

we obtain:

$$1/\tau_{\text{bound; nonmesonic}} = (1/\tau_0)(A-1)3 \times \int d\mathbf{r}_1 \kappa_\pi^{-3} |u(\epsilon_V; \mathbf{r}_1)|^2 \rho(\mathbf{r}_1). \quad (16a)$$

Now,

$$\rho(\mathbf{r}_1) = (A-1)^{-1}\{n(s_{\frac{1}{2}})\rho(s_{\frac{1}{2}}; \mathbf{r}_1) + n(p_{\frac{3}{2}})\rho(p_{\frac{3}{2}}; \mathbf{r}_1) + n(p_{\frac{1}{2}})\rho(p_{\frac{1}{2}}; \mathbf{r}_1) + \cdots\},$$

where $n(s_{\frac{1}{2}})$ gives the number of nucleons in the lowest $s_{\frac{1}{2}}$ orbital, etc., ($n(s_{\frac{1}{2}})=4$ for $A-1 \geqq 4$, etc.), and $\rho(s_{\frac{1}{2}}; \mathbf{r}_1)$ is the space density at $\mathbf{r}_1$ caused by a nucleon in the $s_{\frac{1}{2}}$ orbital, etc. We take oscillator functions for the orbitals, i.e., $\rho(s_{\frac{1}{2}}; \mathbf{r}_1) = (\pi^{\frac{1}{2}}\alpha)^{-3} \exp(-r_1^2/\alpha^2)$, $\rho(p; \mathbf{r}_1) = \frac{2}{3}(\pi^{\frac{1}{2}}\alpha)^{-3} \times (r_1/\alpha)^2 \exp(-r_1^2/\alpha^2)$, etc.; we also take $|u(\epsilon_V; \mathbf{r}_1)|^2 = \rho(s_{\frac{1}{2}}; \mathbf{r}_1)$ (no Pauli exclusion operative between $V$ particle and nucleon). We then obtain

$$1/\tau_{\text{bound; nonmesonic}} = (1/\tau_0)3(2^{\frac{1}{2}}\pi^{\frac{1}{2}}\kappa_\pi\alpha)^{-3} \times \{n(s_{\frac{1}{2}}) + \tfrac{1}{2}[n(p_{\frac{3}{2}}) + n(p_{\frac{1}{2}})] + \cdots\}. \quad (16b)$$

Equation (16b) can be used for all nuclear fragments with $A-1 \leqq 16$ (e.g., for $A-1=16$; $n(s_{\frac{1}{2}})=4$, $n(p_{\frac{3}{2}})=8$, $n(p_{\frac{1}{2}})=4$). For $A-1>16$, a term of the form

$$\left\{\int \rho(s_{\frac{1}{2}}, \mathbf{r}_1)\rho(d_{\frac{5}{2}}, \mathbf{r}_1)d\mathbf{r}_1 \div \int [\rho(s_{\frac{1}{2}}, \mathbf{r}_1)]^2 d\mathbf{r}_1\right\} n(d_{\frac{5}{2}})$$

must be inserted into Eq. (16b); the ("overlap") coefficient of $n(d_{\frac{5}{2}})$ will be less than $\frac{1}{2}$, etc., and it is thus seen that for large $A-1$, $1/\tau_{\text{nonmesonic}}$ ceases to increase with increasing $A$.

The mean life for the mesonic decay of a free $V$ particle may now also be calculated via the term in the interaction Hamiltonian density [Eq. (1)]:

$$\frac{\eta}{\kappa_V + \kappa_n}(\psi_n{}^* \boldsymbol{\sigma} \tau_\alpha \psi_V) \cdot \nabla \varphi_{\alpha;\,\text{quantized}},$$

where $\varphi_{\alpha;\,\text{quantized}}$ is given in Eq. (7). One finds:

$$1/\tau_{\text{free; mesonic}} = (q/\kappa_\pi)^2[q/(q^2+\kappa_\pi^2)^{\frac{1}{2}}] \times (M_n/M_n + M_\pi)(M_\pi/M_n)^2 \times (\eta^2/\hbar c)(M_\pi c^2/\hbar) \approx 10^{10}\ \text{sec}^{-1}, \quad (17)$$

where

$$\left[\hbar^2 q^2 \Big/ 2\left(\frac{M_\pi M_n}{M_\pi + M_n}\right)\right] = (M_V - M_n - M_\pi)c^2, \quad \text{i.e.,} \quad q \approx (5/7)\kappa_\pi.$$

Thus, from Eqs. (16b) and (17),

$$\frac{1/\tau_{\text{bound; nonmesonic}}}{1/\tau_{\text{free; mesonic}}} \approx (4/3)(g^2/\hbar c)(\kappa_\pi\alpha)^{-3} \times \{n(s_{\frac{1}{2}}) + \tfrac{1}{2}[n(p_{\frac{3}{2}}) + n(p_{\frac{1}{2}})] + \cdots\} \approx 5\{n(s_{\frac{1}{2}}) + \tfrac{1}{2}[n(p_{\frac{3}{2}}) + n(p_{\frac{1}{2}})] + \cdots\}, \quad (18)$$

where we have taken $g^2/\hbar c \approx 10$ and $\alpha \approx 2\times 10^{-13}$ cm. It is obvious that the factor "5" in Eq. (18) may actually lie between, say, 5/10 and 50, since it is proportional to the rather uncertain numerical value of $g^2/\alpha^3$. Whatever the exact numerical value of this factor, however, the relative stability of $V$ particles within nuclear matter is demonstrated on our model.

## DISCUSSION

The observed mean life, $\tau_{\text{observed}}$ of nuclear fragments (of a given $A$) containing a $V$ particle may now be related to the mean life for the mesonic decay of a free $V$ particle, $\tau_{\text{free; mesonic}}$, and to the nonmesonic mean life of a bound $V$ particle, $\tau_{\text{bound; nonmesonic}}$, by the expression:

$$1/\tau_{\text{observed}} = 1/\tau_{\text{bound; mesonic}} + 1/\tau_{\text{bound; nonmesonic}} \approx 1/\tau_{\text{free; mesonic}} + 1/\tau_{\text{bound; nonmesonic}} \approx 10^{11} - 10^{12}\ \text{sec}^{-1}, \quad (19)$$

the numerical values [from Eqs. (17), (18)] applying for $A-1 \leqq 16$. From Eqs. (18), (19), we can also relate the number of such nuclear fragments which decay with the emission of a $\pi$ meson to the number in which all the "excitation energy" is imparted to nucleons. We have:

$$\frac{\text{number decaying with emission of } \pi \text{ meson}}{\text{number decaying without emission of } \pi \text{ meson}} = \left(\frac{1/\tau_{\text{bound; mesonic}}}{1/\tau_{\text{bound; nonmesonic}}}\right) \cdot P \approx \left(\frac{1/\tau_{\text{free; mesonic}}}{1/\tau_{\text{bound; nonmesonic}}}\right) \cdot P \approx \tfrac{1}{5}\{n(s_{\frac{1}{2}}) + \tfrac{1}{2}[n(p_{\frac{3}{2}}) + n(p_{\frac{1}{2}})] + \cdots\}^{-1} \cdot P, \quad (20)$$

where $P$ is the probability of a (real) $\pi$ meson emitted by the $V$ particle within the fragment, actually emerging. ($P$ varies between 1 and $\approx (A-1)^{-\frac{1}{3}}$ according to the magnitude of the ratio: effective mean free path for $\pi$-meson absorption within nuclear matter $\div$ effective linear dimensions of fragment.) Therefore, when enough of these nuclear fragments are detected and classified according to atomic mass number, their observed mean lives and the nature of their decay products will offer a test of the present theory. So far, one example of a nuclear fragment decaying with the actual emission of a $\pi$ meson[9] and three examples of nonmesonic

[9] Of course, even in such a decay of the fragment, the kinetic energy of the emitted $\pi$ meson and associated nucleon need not be exactly the $Q$ of the decay of a free $V$, as a consequence of the existence of $V$ and nucleon binding energies, and since energy-momentum exchange may transpire between the emitted $\pi$ and associated nucleon, and the rest of the nucleons in the fragment, as the former leave the fragment. Such energy-momentum interchanges are equivalent in our electromagnetic analogy to a radiative de-excitation of a nucleus with the emitted photon suffering a change of energy in leaving the atom in virtue, e.g., of a Compton or Raman scattering against one of the atomic electrons.

nuclear fragment decay have been observed.[1] The existence of a $\pi$ meson in the decay products rules out the possibility (at least in one of these events) that the nuclear fragments are $\pi$-mesonic atoms—on the other hand, e.g., $K$-mesonic atoms are obviously not necessarily inconsistent with such observations. As a consequence, a more conclusive test to distinguish between the $\pi$-mesonic (or $K$-mesonic) atom hypothesis and the $V$-particle-in-a-nuclear-fragment hypothesis would involve the appearance or non-appearance of "$V$ deuterons" among the unstable fragments produced in high energy events. Phenomenologically, "$V$ deuterons" would ionize and scatter like deuterons, stop, and decay with the release of $\approx 175$ Mev. A "$V$ deuteron" on the mesonic atom picture would consist of a meson in a Bohr orbit about a di-proton; the latter, however, is a nuclearly unstable structure and so could not exist as a unit for a time $\approx 10^{-12}-10^{-10}$ sec. On the $V$-particle hypothesis, however, a "$V$ deuteron" would be a nuclearly stable structure of a proton bound to a neutral $V$ and would have a mean life $\approx 10^{-10}$ sec with a branching ratio of roughly one to one[10] for the two possible eventual decay schemes,

$$\text{"}V\text{ deuteron"}\begin{array}{l}\rightarrow p+n+\approx 175\text{ Mev}\\ \rightarrow p+p+\pi^{-}+\approx 35\text{ Mev}\end{array}$$

$$(\text{or, } p+n+\pi^0+\approx 35\text{ Mev}).$$

Thus a "$V$ deuteron" which comes to rest in a photographic emulsion would be seen to give rise either to a three-pronged star containing a $\pi$ meson with $\approx 35$ Mev kinetic energy shared among the three prongs, or to a one-pronged star with the visible particle having a kinetic energy of $\approx 175/2$ Mev. (The one-pronged star associated with the decay into $p+n+\pi^0$ would involve a visible particle with a rather small kinetic energy.)

In those events in which a $\pi$ meson is not observed as a decay product, it also remains to be conclusively demonstrated that the mesonic atom hypothesis is ruled out. The nuclear fragments of this type which have been detected so far are known to live at least as long as $10^{-12}$ sec. Since a $\pi$ meson in the lowest Bohr orbit has a mean life for nuclear absorption much shorter than $10^{-12}$ sec, the only way a $\pi$-mesonic atom may be expected to live as long as $10^{-12}$ sec is for the $\pi$ meson to be originally trapped in a Bohr orbit whose principal quantum number is greater than, say, 10. On the other hand, since the fragment is formed in a high energy event, it may be assumed that it is initially completely stripped of its electrons. Then this fragment will live a considerable fraction of its slowing-down time in an almost completely stripped state, preventing many Auger transitions of the $\pi$ meson from the higher Bohr orbits to the lowest; consequently the mesonic atom mean life will be determined in first approximation by radiative transition rates.[11] Such radiative transition rates between Bohr orbits of principal quantum numbers $\approx 10$ are $\approx 10^{11}$ sec$^{-1}$ for light nuclei and vary as $Z^4 \sim A^4$; the apparent mean life of mesonic atom-type nuclear fragments would therefore vary as $A^{-4}$. On the other hand, the mean life of the nuclear fragments on the imbedded-$V$-particle hypothesis would vary roughly as $A^{-1}$ [Eqs. (18) and (19)].

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[10] The one-to-one branching ratio follows from Eqs. (16b), (18), (20) with $\alpha\approx$"deuteron radius"$\approx 3.5\times10^{-13}$ cm; $n(s_{\frac{1}{2}})=1$, $n(p)=0$; $P\approx 1$. We have also checked it by an explicit properly antisymmetrized calculation, *ab initio*, for the deuteron. This calculation gives $1/\tau_{\text{bound; nonmesonic}}$ for the deuteron as in Eq. (16b) but with $(2^{\frac{1}{2}}\pi^{\frac{1}{2}}\kappa_\pi\alpha)^{-3}$ replaced by $2(2^{\frac{1}{2}}\kappa_\pi)^{-3}|U(0)|^2$, where $|U(0)|^2$ is the space part of the $V$-deuteron internal wave function evaluated at zero distance (more strictly at distances $\lessapprox(3\kappa_\pi)^{-1}$) between the $V$ and the nucleon. Thus, taking $|U(0)|^2\approx[(\pi^{\frac{1}{2}}3.5\times10^{-13})^{-3}/2]$ the same result is obtained; this last value of $|U(0)|^2$ is about ten times smaller than the corresponding quantity in an ordinary deuteron governed by an attractive square-well $n$-$p$ potential of range $\kappa_\pi^{-1}$—we remark that any actually present repulsive core in the n-p and ($V$-p) potential could easily account for such a factor of 10.

[11] We estimate only a small probability for such a mesonic atom to lose its orbital meson (in a path length equal to its range) as a consequence of Coulomb interactions with the nuclei of the emulsion.