UNIVERSIDADE DE SÃO PAULO

INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01452-990 SÃO PAULO - SP
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THREE-BODY FADDEEV CALCULATION FOR ^{11}Li WITH A SEPARABLE p-WAVE NEUTRON-^{9}Li POTENTIAL

H. Miyake, K. Ueta
Instituto de Física, Universidade de São Paulo

G.W. Bund
Instituto de Física Teórica, Universidade Estadual Paulista
Rua Pamplona, 145, 01405-900 São Paulo, SP, Brazil

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Instituto de Física, Universidade de São Paulo,

C.P. 20516, 01452-990 São Paulo, S.P., Brasil

G.W. Bund

Instituto de Física Teórica, Universidade Estadual Paulista,

Rua Pamplona 145, 01405 São Paulo, Brasil

ABSTRACT

The two neutron separation energy and mean square radius of ^{11}Li are calculated using the Faddeev formalism in a model in which the ^{11}Li consists of a structureless ^{9}Li core and two neutrons. The n-^{9}Li interaction is described by a separable potential which acts only on the $p_{1/2}$ wave and is adjusted to reproduce the resonance observed in the n-^{9}Li system. For the n-n interaction a separable s-wave potential that describes low energy scattering is used.

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21.60.−n

11.80.Jy

27.20.+n

I - INTRODUCTION

Recently many calculations have been made treating the nucleus ^{11}Li as a three-body system composed of a ^{9}Li core plus two valence neutrons [1–6]. Although neither two-body subsystem of ^{11}Li is able separately to form a bound state, nevertheless the three-body system is known to have a bound state of about 0.3 MeV [7–8]. This particular situation in which one has two nucleons interacting in a low density medium suggests the possibility of applying the minimal coupling three-body model developed earlier and which proved to be quite effective in the description of the structure of ^{6}Li, ^{6}He, ^{18}O and ^{18}F [9,15].

We shall assume that the n-^{9}Li interaction is dominated by a $p_{1/2}$ single particle resonance. According to the experimental data of Wilcox et al. [10] a resonance corresponding to ^{10}Li occurs at 0.80 ± 0.25 MeV and has a width of 1.20 ± 0.30 MeV. According to more recent work [11] it is split into a $J^\pi = 2^+$ state situated at 0.42 MeV and a 1^+ state at 0.80 MeV. One can consider these resonances as the splitting, due to a spin-spin n-^{9}Li interaction, of a single particle resonance at 0.66 MeV [4], the centroid of the 2^+ and 1^+ resonances.

II - THE TWO BODY INTERACTION

As in Ref. [15], we shall use separable potentials. Thus the n-^{9}Li interaction in momentum representation will be written as

$$\langle \mathbf{p}_i|V_i|\mathbf{p}'_i\rangle = -\frac{\Lambda}{2m}\, v\,(p_i)\; v\,(p'_i) \sum_\mu \langle \hat{\mathbf{p}}_i|y_{1\frac{1}{2}\mu}\rangle\, \langle y_{1\frac{1}{2}\mu}|\hat{\mathbf{p}}'_i\rangle \quad , \qquad (i=1,2) \quad , \tag{1}$$

where m is the mass of neutron and, $\mathbf{p}_i$ is the momentum of neutron i and

$$\langle \hat{\mathbf{p}}_i|y_{lj\mu}\rangle = \sum_{m_l m_s} \left(l\; m_l\; \frac{1}{2}\; m_s|j\; \mu\right)\; Y_l^{m_l}\,(\hat{\mathbf{p}}_i)\, |\frac{1}{2}\; m_s\rangle \quad . \tag{2}$$

For simplicity in the three-body kinematics we consider the mass of the core to be infinite.

The form factor $v(Q)$ was chosen to be

$$v(Q) = Q \exp(-\beta^2 Q^2/2) \quad . \tag{3}$$

The parameter β was fixed as follows. Since the spin-orbit splitting of the single particle $1p_{1/2}$ and $1p_{3/2}$ levels in ^{10}Li is about 5 MeV [12], we assume that the $1p_{3/2}$ level has a binding energy of 4 MeV. This single particle state can be reproduced by a separable potential of the form

$$-\frac{\Lambda_{p\frac{3}{2}}}{2m} v_{p\frac{3}{2}}(Q)\, v_{p\frac{3}{2}}(Q') \sum_\mu \langle \hat{\mathbf{Q}} | y_{1\,\frac{3}{2}\mu}\rangle \langle y_{1\,\frac{3}{2}\mu} | \hat{\mathbf{Q}}'\rangle \quad . \tag{4}$$

Choosing the form factor $v_{p\frac{3}{2}}(Q)$ equal to the form factor given by Eq. (3) (with the same value of β) and requiring the mean square radius of the bound state generated by the above potential to be equal to the mean square radius of the $1p$ state of a harmonic oscillator whose frequency is given by the prescription [13]

$$\hbar\omega = 45\, A^{-1/3} - 25\, A^{-2/3}\mathrm{MeV} \quad , \tag{5}$$

appropriate to light nuclei, we obtain the value $\beta = 0.931$fm. For this value of β we show in Fig. 1 the total $p_{1/2}$ cross section for neutron-^{9}Li scattering calculated for different values of the parameter Λ adjusted to produce resonance energies 0.66 MeV, 0.80 MeV and 0.93 MeV.

For the n-n interaction which is assumed to act only in the s-wave we use the separable potential.

$$\langle \mathbf{p} | V_{12} | \mathbf{p}'\rangle = -\frac{\Lambda_0}{m} v_0(p)\, v_0(p')\, |00\rangle\langle 00| \tag{6}$$

where $\mathbf{p}$ is the relative momentum $(\mathbf{p}_1 - \mathbf{p}_2)/2$ of the neutrons and $|00\rangle$ is the spin wave function of the singlet state . For $v_0(p)$ the Yamaguchi form $[p^2 + \alpha_0^2]^{-1}$ was chosen. The value of the parameters of the potential are $\alpha_0 = 1.13\mathrm{fm}^{-1}$ and $\Lambda_0 = 0.323\mathrm{fm}^{-3}$

which were determined assuming the values -17fm and 2.84fm for the scattering length and effective range of the singlet s-wave n-n scattering [14].

III - THREE BODY FORMALISM

The formal treatment of ^{11}Li as a three-body system is essentially the same as that applied to ^{18}O and ^{18}F [15]. The Hamiltonian of the system is $H = H_0 + V_1 + V_2 + V_{12}$, where H_0 is the kinetic energy, V_1 and V_2 the neutron-core interaction and V_{12} the interaction between the two neutrons. The bound state wave function Ψ may be decomposed into a sum of three terms $\Psi = \Psi^{(1)} + \Psi^{(2)} + \Psi^{(3)}$ which are determined through the coupled homogeneous Faddeev equations

$$\begin{aligned} \Psi^{(1)} &= G_0\, T_1 \left(\Psi^{(2)} + \Psi^{(3)}\right) \quad , \\ \Psi^{(2)} &= G_0\, T_2 \left(\Psi^{(3)} + \Psi^{(1)}\right) \quad , \\ \Psi^{(3)} &= G_0\, T_{12} \left(\Psi^{(1)} + \Psi^{(2)}\right) \quad . \end{aligned} \tag{7}$$

Here $G_0 = (E + i0 - H_0)^{-1}$ is the Green's function and T_1, T_2 and T_{12} are the two body T-matrices corresponding to the potentials V_1, V_2 and V_{12} respectively. By factoring out the angular momentum part the functions, $\Psi^{(i)}$ may be expressed as

$$\Psi^{(1)}(\mathbf{p}_1, \mathbf{p}_2) = \frac{2m}{2mE - p_1^2 - p_2^2}\, v(p_1)\, \frac{H^{(1)}(p_2)}{p_2}\, y_{1\frac{1}{2},1\frac{1}{2};00}(\hat{\mathbf{p}}_1, \hat{\mathbf{p}}_2) \quad , \tag{8}$$

$$\Psi^{(2)}(\mathbf{p}_1, \mathbf{p}_2) = \frac{2m}{2mE - p_1^2 - p_2^2}\, v(p_2)\, \frac{H^{(2)}(p_1)}{p_1}\, y_{1\frac{1}{2},1\frac{1}{2};00}(\hat{\mathbf{p}}_1, \hat{\mathbf{p}}_2) \quad , \tag{9}$$

$$\Psi^{(3)}(\mathbf{P}, \mathbf{p}) = \frac{2m}{2mE - P^2/2 - 2p^2}\, \sqrt{4\pi}\, v_0(p)\, \frac{H^{(3)}(P)}{P}\, y_{00(0)0;00}(\hat{\mathbf{P}}, \hat{\mathbf{p}}) \quad , \tag{10}$$

where $H^{(1)}, H^{(2)}$ and $H^{(3)}$ are the spectator functions and the angular momentum functions are

$$y_{lj,l'j';JM_J}(\hat{\mathbf{p}}_1,\hat{\mathbf{p}}_2) = \sum_{mm'}(jmj'm'|JM_J)\, y_{ljm}(\hat{\mathbf{p}}_1)\, y_{l'j'm'}(\hat{\mathbf{p}}_2) \quad , \tag{11}$$

$$y_{\Lambda\lambda(L)S;JM_J}(\hat{\mathbf{P}},\hat{\mathbf{p}}) = \sum_{M_LM_S}(LM_L\,SM_S|JM_J) \left[\sum_{M_\Lambda m_\lambda}(\Lambda M_\Lambda\,\lambda m_\lambda|LM_L)\, Y_\Lambda^{M_\Lambda}(\mathbf{P})\, Y_\lambda^{m_\lambda}(\mathbf{p})\right] |SM_S\rangle \quad . \tag{12}$$

Here $\mathbf{p}_i(i=1,2)$ are the momenta of the neutrons relative to the ^{9}Li core, $\mathbf{P}$ is the total momentum $\mathbf{p}_1+\mathbf{p}_2$ of the two neutrons and $\mathbf{p}$ is the relative momentum $(\mathbf{p}_1-\mathbf{p}_2)/2$. In addition, symmetry requirements impose the equality $H^{(1)}(Q)=H^2(Q)$.

Substitution of Eqs. (8)-(10) for the functions $\Psi^{(i)}$ into Eq. (7) leads to a system of coupled integral equations connecting the spectator functions $H^{(1)}$ and $H^{(3)}$, which are solved numerically.

IV - RADIAL PROBABILITY DENSITY

In order to obtain the radial probability density of a single neutron we expressed the functions $\Psi^{(1)},\Psi^{(2)}$ and $\Psi^{(3)}$ in the coordinate representation by making the Fourier transformations [16]

$$\Omega^{(i)}(\mathbf{r}_1,\mathbf{r}_2) = \frac{1}{(2\pi)^3}\iint d\mathbf{p}_1\, d\mathbf{p}_2\, \Psi^{(i)}(\mathbf{p}_1,\mathbf{p}_2)\, e^{i(\mathbf{p}_1\cdot\mathbf{r}_1+\mathbf{p}_2\cdot\mathbf{r}_2)} \quad , \quad i=1,2 \quad , \tag{13}$$

$$\Omega^{(3)}(\mathbf{R},\mathbf{r}) = \frac{1}{(2\pi)^3}\iint d\mathbf{P}\, d\mathbf{p}\, \Psi^{(3)}(\mathbf{P},\mathbf{p})\, e^{i(\mathbf{P}\cdot\mathbf{R}+\mathbf{p}\cdot\mathbf{r})} \quad , \tag{14}$$

where $\mathbf{r}=\mathbf{r}_1-\mathbf{r}_2$ and $\mathbf{R}=(\mathbf{r}_1+\mathbf{r}_2)/2$. Making these transformations one gets

$$\Omega^{(i)}(\mathbf{r}_1,\mathbf{r}_2) = F^{(i)}(r_1,r_2)\, y_{1\frac{1}{2},1\frac{1}{2};00}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2) \quad , \quad i=1,2 \quad , \tag{15}$$

$$\Omega^{(3)}(\mathbf{R},\mathbf{r}) = F^{(3)}(R,r)\,\frac{1}{4\pi}|00\rangle \quad . \tag{16}$$

The function $F^{(i)}$ are given by

$$F^{(1)}(r_1,r_2) = -\frac{2}{\pi}\int_0^\infty dp_2 p_2 H^{(1)}(p_2)\, j_1(p_2r_2)\, R^E(r_1,p_2) \quad , \tag{17}$$

$$F^{(2)}(r_1,r_2) = -\frac{2}{\pi}\int_0^\infty dp_1 p_1 H^{(2)}(p_1)\, j_1(p_1r_1)\, R^E(r_2,p_1) \quad , \tag{18}$$

$$F^{(3)}(R,r) = \frac{2}{\pi}\int_0^\infty dPPH^{(3)}(P) j_0(PR)\sqrt{4\pi}R_0^E(P,r) \quad , \tag{19}$$

where

$$R^E(r_1,p_2) = 2m\int_0^\infty dp_1\, \frac{p_1^2\, v(p_1)\, j_1(p_1r_1)}{2mE-p_1^2-p_2^2} \quad , \tag{20}$$

$$R_0^E(P,r) = 2m\int_0^\infty dp\, \frac{p^2\, v_0(p)\, j_0(pr)}{2mE-P^2/2-2p^2} \quad . \tag{21}$$

The function $\Omega^{(3)}$ is expanded in partial waves as

$$\Omega^3(\mathbf{R},\mathbf{r}) = \Omega^{(3)}\left(\frac{\mathbf{r}_1+\mathbf{r}_2}{2},\mathbf{r}_1-\mathbf{r}_2\right) = \sum_l f_l(r_1,r_2)\, P_l(\cos\theta_{12})\, |00\rangle \quad , \tag{22}$$

which may be written as

$$\Omega^{(3)}(\mathbf{R},\mathbf{r}) = \sum_{l=0}^{\infty}\sum_{j=|l-1/2|}^{|l+1/2|}\sqrt{j+\frac{1}{2}}\,(-1)^l\,\frac{4\pi}{2l+1}\, f_l(r_1,r_2)\, y_{lj,lj;00}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2) \quad . \tag{23}$$

Thus the term $\Omega^{(3)}$ of the total three-body wave function $\Omega(\mathbf{r}_1,\mathbf{r}_2)$ is cast into the same form as $\Omega^{(1)}$ and $\Omega^{(2)}$ in equation (15) and we may write

$$\Omega(\mathbf{r}_1,\mathbf{r}_2) = \sum_a \Gamma_{aa;0}(r_1,r_2)\, y_{a,a;oo}(\hat{\mathbf{r}}_1,\hat{\mathbf{r}}_2) \quad , \quad a=(l,j) \quad , \tag{24}$$

where

$$\Gamma_{1\frac{1}{2},1\frac{1}{2};0}(r_1,r_2) = -\frac{4\pi}{3}\, f_1(r_1,r_2) + F^{(1)}(r_1,r_2) + F^{(2)}(r_1,r_2) \tag{25}$$

and

$$\Gamma_{lj,lj;0}(r_1,r_2) = (-1)^l\sqrt{j+\frac{1}{2}}\,\frac{4\pi}{2l+1}\, f_l(r_1,r_2)\, , (l,j)\neq\left(1,\frac{1}{2}\right) \quad . \tag{26}$$

The radial probability density $W(r_1)$ for finding a valence neutron between r_1 and $r_1 + dr_1$ is given by

$$W(r_1) = \frac{r_1^2}{\mathcal{N}^2} \int_0^\infty dr_2\, r_2^2 \int d\hat{r}_1\, d\hat{r}_2 \Omega(\mathbf{r}_1, \mathbf{r}_2)^+ \Omega(\mathbf{r}_1, \mathbf{r}_2) \qquad (27)$$

and the mean square radius of the valence neutron is written

$$\langle r_1^2 \rangle = \int_0^\infty r_1^2 W(r_1)\, dr_1 \quad . \qquad (28)$$

Using expansion (24) we write the mean square radius as a sum of contributions from different partial wave

$$\langle r_1^2 \rangle = \sum_a \langle r_1^2 \rangle_a \qquad (29)$$

where

$$\langle r_1^2 \rangle_a = \mathcal{N}^{-2} \int_0^\infty dr_1 r_1^4 \int_0^\infty dr_2 r_2^2 \left|\Gamma_{a,a;0}(r_1, r_2)\right|^2 \quad . \qquad (30)$$

The square of the normalization factor $\mathcal{N}$ may be written as

$$\mathcal{N}^2 = \sum_a \mathcal{N}_a^2 \quad , \qquad (31)$$

where

$$\mathcal{N}_a^2 = \int_0^\infty dr_1, r_1^2 \int_0^\infty dr_2 r_2^2 \left|\Gamma_{a,a;0}(r_1, r_2)\right|^2 \quad . \qquad (32)$$

V - RESULTS

In Table 1 we are presenting the values of the coupling constant Λ of the n-^{9}Li interaction (eq. (1)), which correspond to chosen values of the resonance energy of the n-^{9}Li system in the neighborhood of 0.80 MeV . The value of β was taken as 0.931fm. The corresponding resonance widths, the ^{11}Li $2n$ separation energies, the mean square

radii of the valence neutron and the ^{11}Li matter radii are given. The ^{11}Li radius was calculated following the expression

$$\langle r^2 \rangle_{^{11}\mathrm{Li}} = \frac{2}{11} \left\langle r_1^2 \right\rangle + \frac{9}{11} \langle r^2 \rangle_{^9\mathrm{Li}} \quad , \qquad (33)$$

where $\left[\langle r^2 \rangle_{^9\mathrm{Li}}\right]^{1/2} = 2.32$fm according Ref. [7].

In the following we shall give additional results corresponding to the two neutron separation energy of 0.25 MeV, which is close to the experimental value [8]. In Figs. 2 and 3 the spectator functions $H^{(1)}$ and $H^{(3)}$ (Eqs. (8–10)) are plotted. The neutron probability density function $W(r_1)$ is presented in Fig. 4. Notice that this function has an exponential tail

$$W(r_1) \sim A \exp(-br_1) \quad , \qquad b = 0.347\mathrm{fm}^{-1} \quad . \qquad (34)$$

In Table 2 we give the contributions of the partial waves of the expansion of Ω (Eq. (24)) to the mean square radius of the external neutrons and also the contribution which comes from $\Omega^{(1)} + \Omega^{(2)}$ alone. The results of this table show that a substantial contribution to the mean square radius comes from the term $\Omega^{(3)}$ of the wave function. We remark here that this term has the structure of dineutron coupled to the ^{9}Li core.

A question which arises is whether the contributions from the $s_{1/2}$ and $p_{3/2}$ partial waves violate the Pauli Principle with respect to the orbits occupied in the ^{9}Li core. We estimated this effect by calculating the overlap of the $s_{1/2}$ and $p_{3/2}$ partial waves in Eq. (23) with the single particle wave functions of the $1s_{1/2}$ and $1p_{3/2}$ orbits, for which we took harmonic oscillator wave functions. The results shows that the $1s_{1/2}$ forbidden state contributes about 0.7% to the $s_{1/2}$ partial wave and that forbidden $1p_{3/2}$ state contributes only 0.2% to the $p_{3/2}$ partial wave .Therefore the main part of the contribution of the $s_{1/2}$ and $p_{3/2}$ partial waves to the mean square radius of the valence neutrons arises from Pauli allowed components.

As explained in section 2, the above results were obtained by fixing the parameter β (somewhat arbitrarily) by utilizing the $p_{1/2} - p_{3/2}$ spin orbit splitting and the radius of the $1p_{3/2}$ single particle orbit. Another possibility is to fix instead, the resonance energy E_R of the n-^{9}Li system and the ^{11}Li $2n$ separation energy S_{2n}. In table 3 we give the results for $E_R = 0.66$ MeV and $E_R = 0.80$ MeV using $S_{2n} = 0.25$ MeV. One finds that the parameter β does change at most by 20% from that of Table 1. Recent experimental values of the ^{11}Li radius are (3.10 $\pm$ 0.17)fm [7] and (3.02 $\pm$ 0.2)fm [17]. We can see that by making the adjustment corresponding to Table 3 we were able to get a better radius than the value 2.77fm for $S_{2n} = 0.25$ MeV of Table 1.

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TABLE CAPTIONS

1) Calculated mean square radius of the external neutrons and of the ^{11}Li nucleus for $\beta = 0.931$fm and several values of Λ. E_R and Γ are the resonance energy and width of the n-^{9}Li system and S_{2n} is the $2n$ separation energy of ^{11}Li. $E_R = 0.80$ MeV corresponds to the data of Wilcox et al. [10] and $E_R = 0.66$ MeV is the centroid of the 1^+ and 2^+ resonances according to Ref. [11].

2) $\mathcal{N}_{lj}^2$ and $\langle r_{lj}^2 \rangle$ are the contributions of the (l, j) partial wave to the square of the normalization factor and to the mean square radius. (a) Only the contributions from $\Omega^{(1)}(\mathbf{r}_1, \mathbf{r}_2) + \Omega^{(2)}(\mathbf{r}_1, \mathbf{r}_2)$ with the same norm $\mathcal{N}$.

3) Calculated mean square radius of the external neutrons and of the ^{11}Li nucleus by fixing the resonance energy E_R of the n-^{9}Li system and the ^{11}Li $2n$ separation energy S_{2n}.

FIGURE CAPTIONS

1) Total $p_{1/2}$ cross sections for neutron ^{9}Li scattering for $\beta = 0.931$fm and the resonance energies at 0.66 MeV, 0.80 MeV an 0.93 MeV.

2) Spectator function $H^{(1)}$ in momentum representation corresponding to a $2n$ separation energy $S_{2n} = 0.25$ MeV. The values of β and Λ are respectively 0.931fm, and 1694fm^3 (see Table 1).

3) Same as figure 1, for spectator function $H^{(3)}$.

4) Neutron probability density function W corresponding to $S_{2n} = 0.25$ MeV, β = 0.931fm and $\Lambda = 1.694$fm .

Table 1

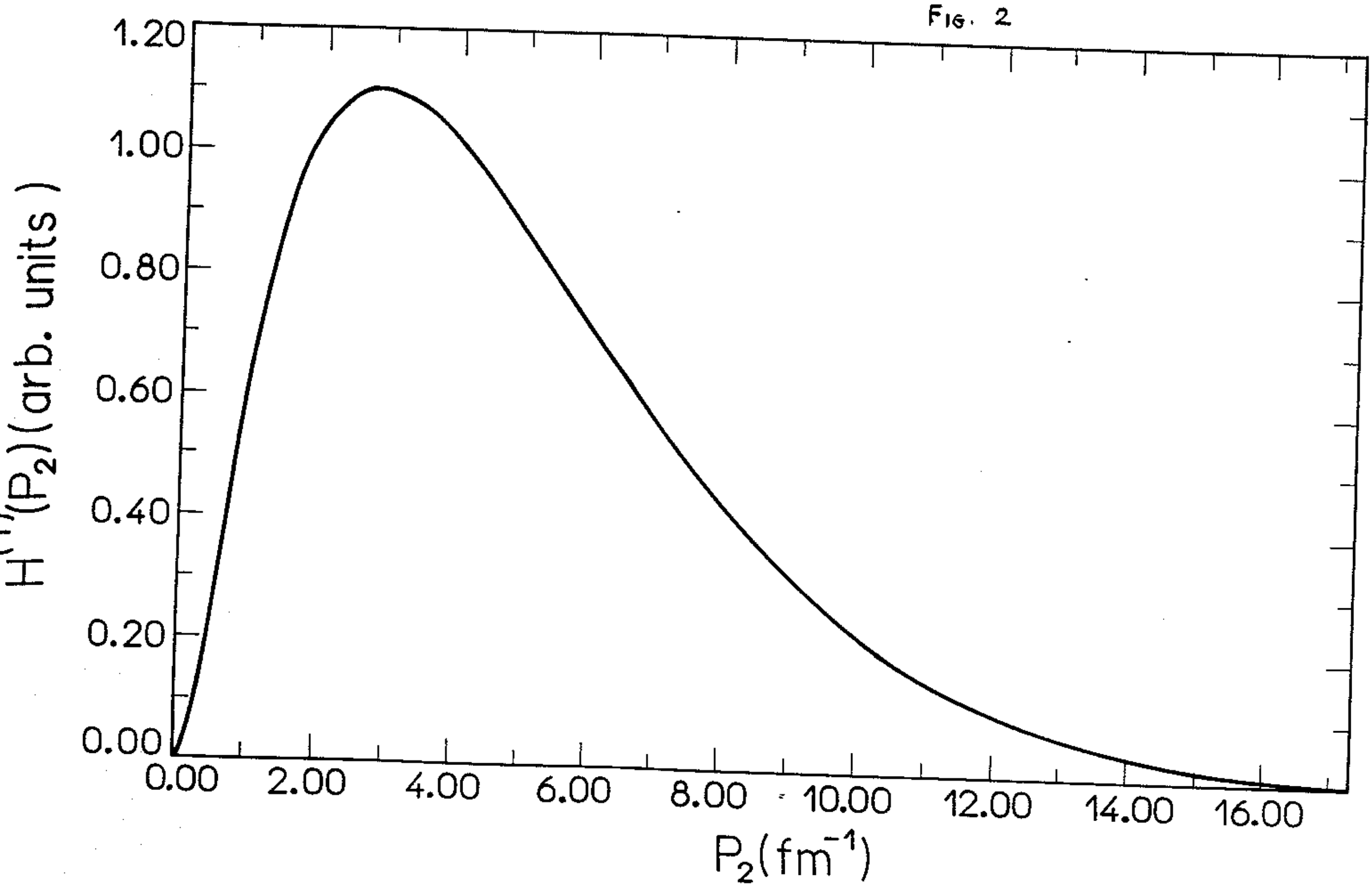
E_R (MeV)	Λ (fm^3)	Γ (MeV)	S_{2n} (MeV)	$\langle r^2\rangle_n^{1/2}$ (fm)	$\langle r^2\rangle_{^{11}\mathrm{Li}}^{1/2}$ (fm)
0.55	1.744	0.32	0.97	3.48	2.57
0.66	1.729	0.42	0.75	3.61	2.60
0.80	1.710	0.58	0.47	3.86	2.67
0.93	1.694	0.74	0.25	4.24	2.77
1.05	1.678	0.90	0.07	5.02	3.00

Table 2

l	j	$\mathcal{N}_{lj}^2/\mathcal{N}^2$	$\langle r^2\rangle_{lj}$ (fm^2)
0	1/2	0.1983	6.1282
1	1/2	0.7585	10.6049
1	3/2	0.0267	0.7186
2	(3/2 + 5/2)	0.0103	0.3117
3	(5/2 + 7/2)	0.0035	0.1231
4	(7/2 + 9/2)	0.0015	0.0576
5	(9/2 + 11/2)	0.0007	0.0316
6	(11/2 + 13/2)	0.0003	0.0170
7	(13/2 + 15/2)	0.0002	0.0102
$1^{(a)}$	1/2	0.5956	7.7728

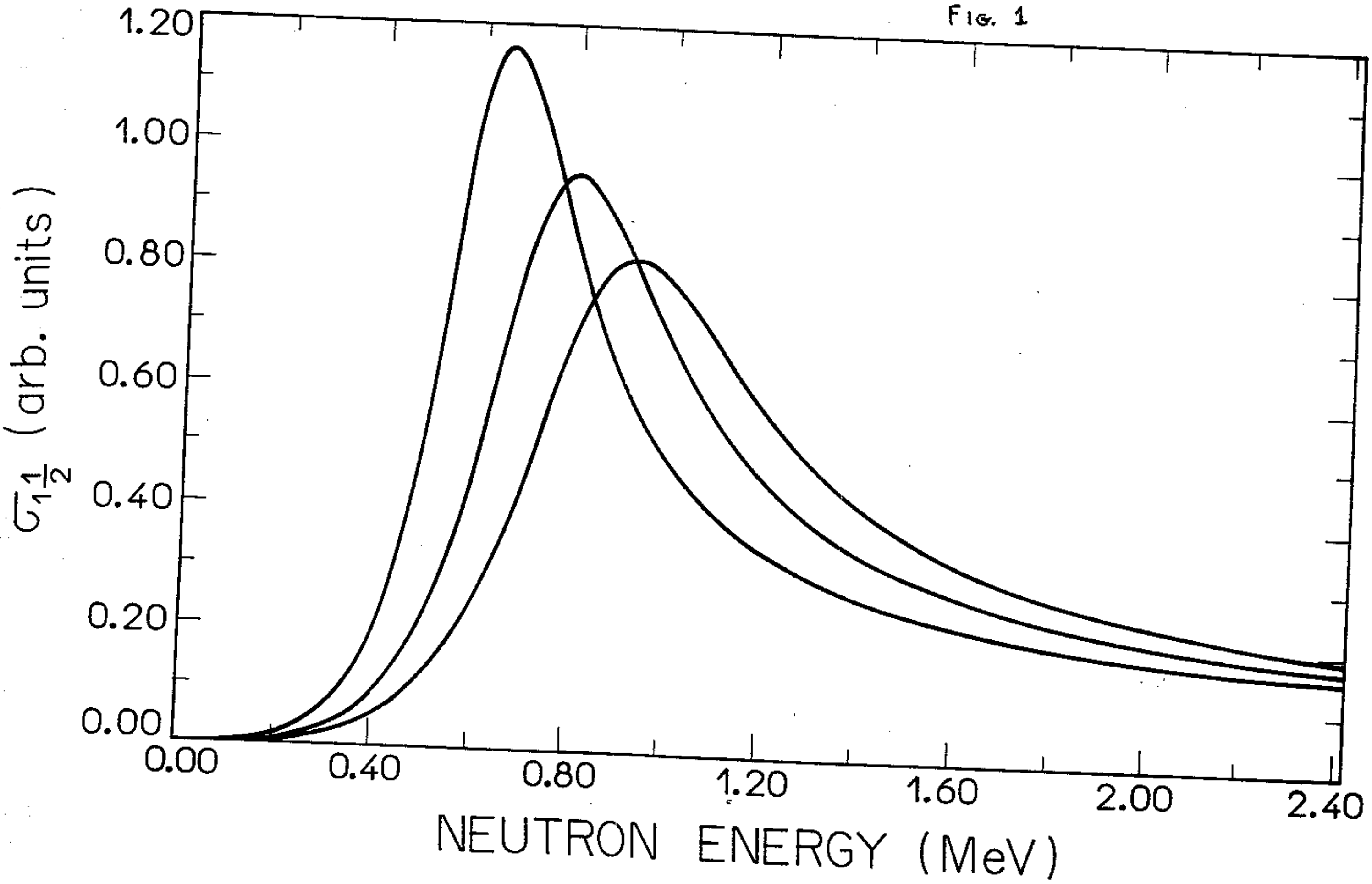
Table 3

β (fm)	E_R (MeV)	Λ (fm^3)	Γ (MeV)	S_{2n} (MeV)	$\langle r^2\rangle_n^{1/2}$ (fm)	$\langle r^2\rangle_{^{11}\mathrm{Li}}^{1/2}$ (fm)
1.040	0.80	2.345	0.66	0.25	4.45	2.83
1.185	0.66	3.452	0.56	0.25	4.84	2.94



1.20
1.00
0.80
0.60
0.40
0.20
0.00
$H^{(1)}(P_2)$(arb. units)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
$P_2(fm^{-1})$

FIG. 2



1.20
1.00
0.80
0.60
0.40
0.20
0.00
$\sigma_{1\frac{1}{2}}$ (arb. units)
0.00
0.40
0.80
1.20
1.60
2.00
2.40
NEUTRON ENERGY (MeV)

FIG. 1

Fig. 4

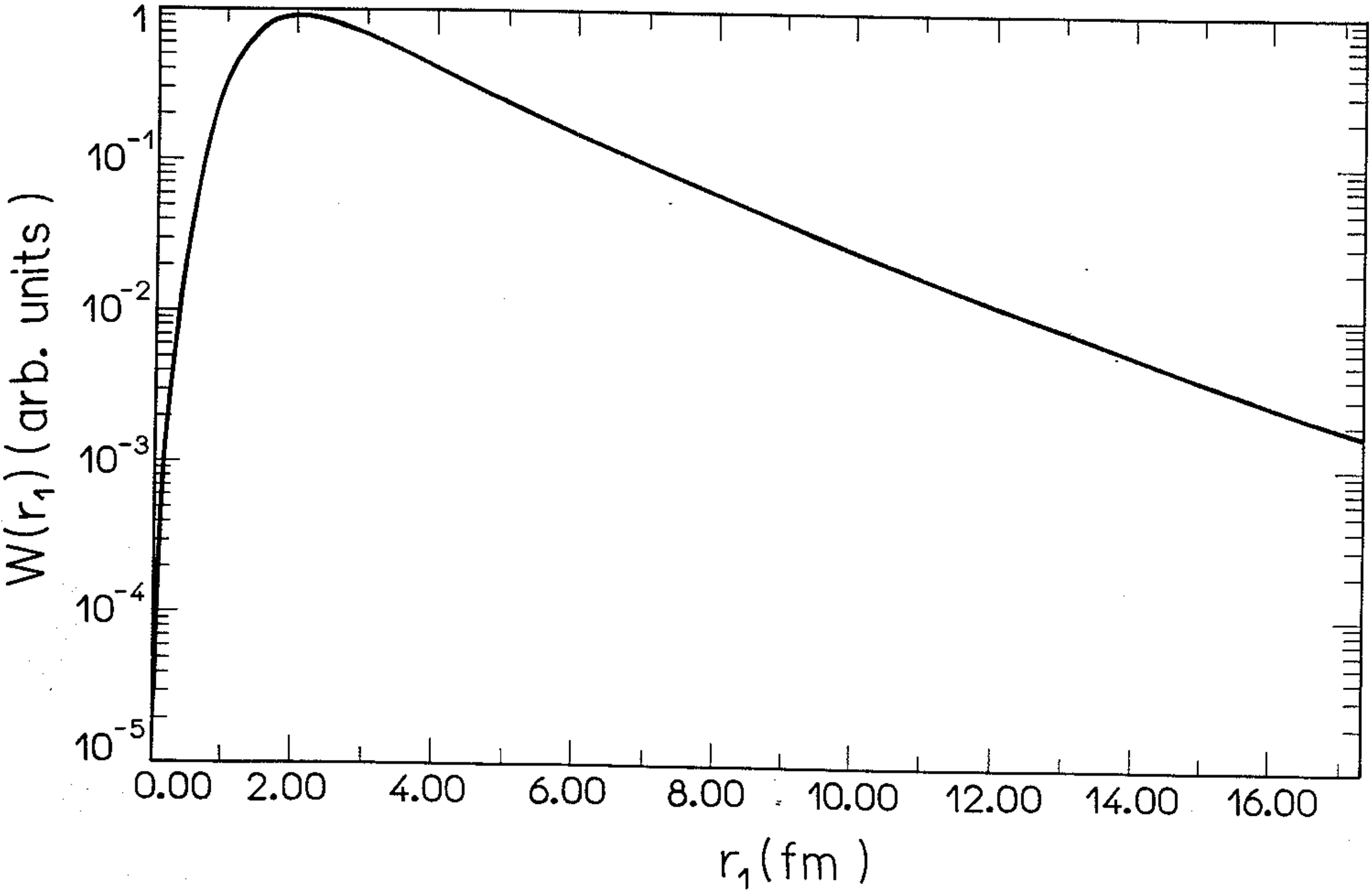
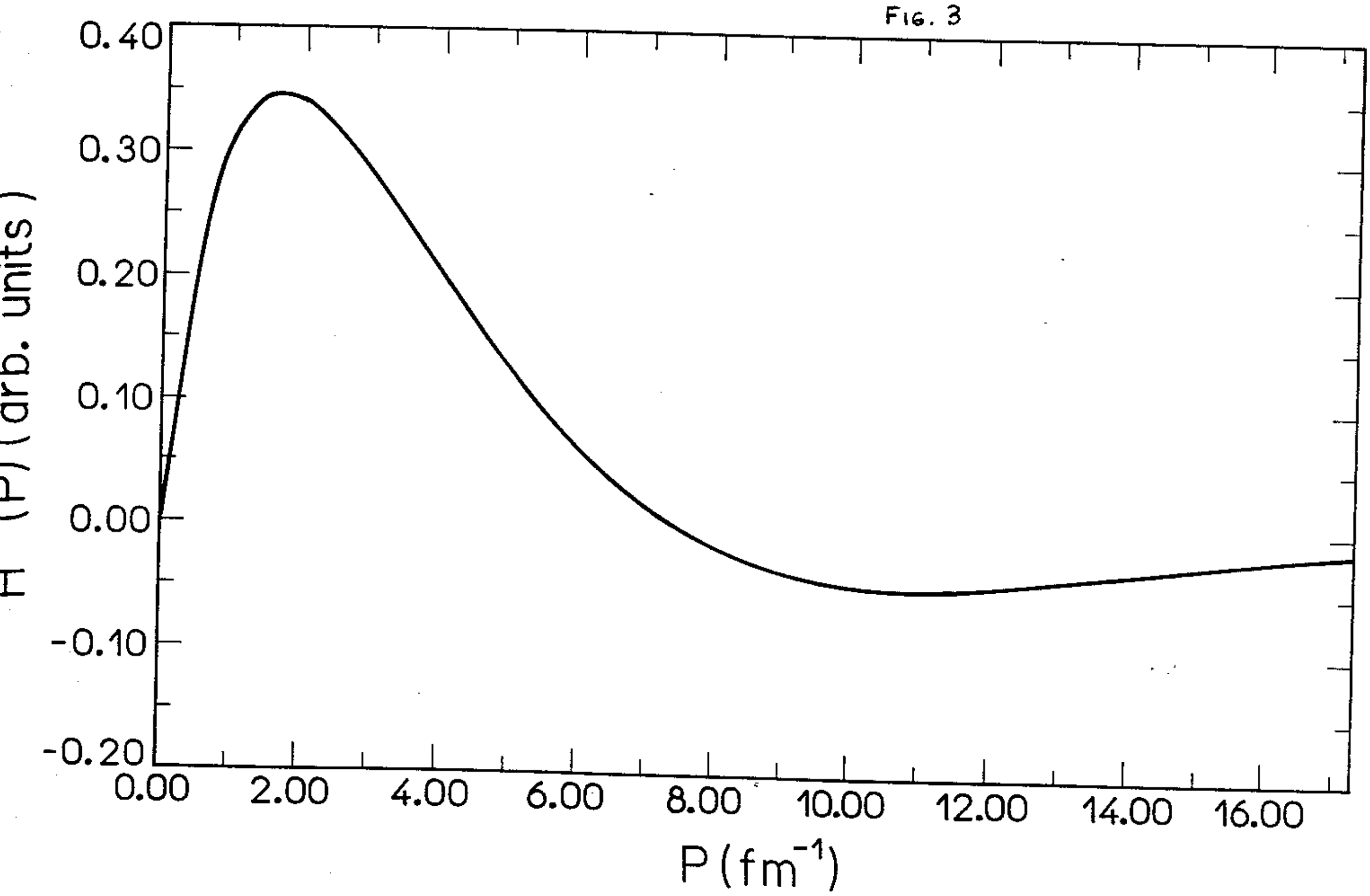

1
10^-1
10^-2
10^-3
10^-4
10^-5
W(r1) (arb. units)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
r1 (fm)

Fig. 3


0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
H(3)(P) (arb. units)
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
P (fm-1)