```
In[1]:= Off[General::"spell"]; Off[General::"spell1"];
```

■ The Hamiltonian

```
In[2]:= h2mns = 1 / 2 / M + n / 4 (t1 (1 + x1 / 2) + t2 (1 + x2 / 2)) + nn / 4 (t2 (1 / 2 + x2) - t1 (1 / 2 + x1))
```

$$\text{Out[2]}= \frac{1}{2\,M}+\frac{1}{4}\,n\left(t1\left(1+\frac{x1}{2}\right)+t2\left(1+\frac{x2}{2}\right)\right)+\frac{1}{4}\,nn\left(-t1\left(\frac{1}{2}+x1\right)+t2\left(\frac{1}{2}+x2\right)\right)$$

```
In[3]:= h2mps = 1 / 2 / M + n / 4 (t1 (1 + x1 / 2) + t2 (1 + x2 / 2)) + np / 4 (t2 (1 / 2 + x2) - t1 (1 / 2 + x1))
```

$$\text{Out[3]}= \frac{1}{2\,M}+\frac{1}{4}\,n\left(t1\left(1+\frac{x1}{2}\right)+t2\left(1+\frac{x2}{2}\right)\right)+\frac{1}{4}\,np\left(-t1\left(\frac{1}{2}+x1\right)+t2\left(\frac{1}{2}+x2\right)\right)$$

```
In[4]:= kfn = (3 π^2 nn)^(1/3)
```

$$\text{Out[4]}= 3^{1/3}\,nn^{1/3}\,\pi^{2/3}$$

```
In[5]:= kfp = (3 π^2 np)^(1/3)
```

$$\text{Out[5]}= 3^{1/3}\,np^{1/3}\,\pi^{2/3}$$

```
In[6]:= τn = kfn^5 / 5 / π^2
```

$$\text{Out[6]}= \frac{3}{5}\,3^{2/3}\,nn^{5/3}\,\pi^{4/3}$$

```
In[7]:= τp = kfp^5 / 5 / π^2
```

$$\text{Out[7]}= \frac{3}{5}\,3^{2/3}\,np^{5/3}\,\pi^{4/3}$$

```
In[8]:= Hbulk = Simplify[τn h2mns + τp h2mps + t0 / 2 ((1 + x0 / 2) n^2 - (1 / 2 + x0) (nn^2 + np^2)) +
          a t3 / 6 ((1 + x3 / 2) n^α nn np + 2^(α-2) (1 - x3) (nn^(α+2) + np^(α+2))) +
          b t3 / 12 ((1 + x3 / 2) n^2 - (1 / 2 + x3) (nn^2 + np^2)) n^α /. n → nn + np]
```

$$\begin{aligned}\text{Out[8]}= \frac{1}{120}\Bigg(&60\,t0\left(-(nn^2+np^2)\left(\frac{1}{2}+x0\right)+\frac{1}{2}\,(nn+np)^2\,(2+x0)\right)-\\&\frac{9\,3^{2/3}\,np^{5/3}\,\pi^{4/3}\,(-4-M\,(np\,(t1-t1\,x1+3\,t2\,(1+x2))+nn\,(t1\,(2+x1)+t2\,(2+x2))))}{M}-\\&\frac{9\,3^{2/3}\,nn^{5/3}\,\pi^{4/3}\,(-4+M\,(nn\,(t1\,(-1+x1)-3\,t2\,(1+x2))-np\,(t1\,(2+x1)+t2\,(2+x2))))}{M}-\\&5\,b\,(nn+np)^{\alpha}\,t3\,(nn^2\,(-1+x3)+np^2\,(-1+x3)-2\,nn\,np\,(2+x3))+\\&5\,a\,t3\,(-2^{\alpha}\,(nn^{2+\alpha}+np^{2+\alpha})\,(-1+x3)+2\,nn\,np\,(nn+np)^{\alpha}\,(2+x3))\Bigg)\end{aligned}$$

■ The energy of symmetric nuclear matter:

```
In[9]:= Hnuc = Simplify[Hbulk /. nn → n / 2 /. np → n / 2]
```

$$\text{Out[9]}= \frac{n^{5/3}\left(10\,M\left(6\,n^{1/3}\,t0+(a+b)\,n^{\frac{1}{3}+\alpha}\,t3\right)+3\,2^{1/3}\,3^{2/3}\,\pi^{4/3}\,(8+M\,n\,(3\,t1+5\,t2+4\,t2\,x2))\right)}{160\,M}$$

```
In[10]:= kr23 = 3 / 10 / M (3 / 2 π^2 n)^(2/3)
         β = M / 2 (1 / 4 (3 t1 + 5 t2) + t2 x2)
```

$$\text{Out[10]}= \frac{3 \left(\frac{3}{2}\right)^{2/3} n^{2/3} \pi^{4/3}}{10 M}$$

$$\text{Out[11]}= \frac{1}{2} M \left(\frac{1}{4} (3 t1 + 5 t2) + t2 x2\right)$$

```
In[12]:= Hnuc2 = n (kr23 (1 + β n) + 3 t0 n / 8 + (a + b) t3 n^(1+α) / 16)
```

$$\text{Out[12]}= n \left(\frac{3 n t0}{8} + \frac{1}{16} (a + b) n^{1+\alpha} t3 + \frac{3 \left(\frac{3}{2}\right)^{2/3} n^{2/3} \pi^{4/3} \left(1 + \frac{1}{2} M n \left(\frac{1}{4} (3 t1 + 5 t2) + t2 x2\right)\right)}{10 M}\right)$$

```
In[13]:= Simplify[Hnuc2 - Hnuc]
```

$$\text{Out[13]}= 0$$

■ The effective masses in symmetric nuclear matter:

The inverse of the reduced effective mass:

```
In[14]:= MoMs = Simplify[2 M (h2mns /. nn → n / 2 /. np → n / 2)]
```

$$\text{Out[14]}= \frac{1}{8} (8 + M n (3 t1 + t2 (5 + 4 x2)))$$

```
In[15]:= MoMs2 = 1 + β n
```

$$\text{Out[15]}= 1 + \frac{1}{2} M n \left(\frac{1}{4} (3 t1 + 5 t2) + t2 x2\right)$$

```
In[16]:= Simplify[MoMs - MoMs2]
```

$$\text{Out[16]}= 0$$

■ The incompressiblity of nuclear matter:

```
In[17]:= K = Simplify[9 n^2 D[D[(Hbulk /. nn → n / 2 /. np → n / 2) / n, n], n]]
```

$$\text{Out[17]}= \frac{3 n^{2/3} \left(2^{1/3} 3^{2/3} \pi^{4/3} (-8 + 5 M n (3 t1 + t2 (5 + 4 x2))) + 15 (a + b) M n^{\frac{1}{3}+\alpha} t3 \alpha (1 + \alpha)\right)}{80 M}$$

```
In[18]:= K2 = -2 kr23 + 10 kr23 β n + 9 / 16 α (α + 1) (a + b) t3 n^(1+α)
```

$$\text{Out[18]}= -\frac{3 \left(\frac{3}{2}\right)^{2/3} n^{2/3} \pi^{4/3}}{5 M} + \frac{3}{2} \left(\frac{3}{2}\right)^{2/3} n^{5/3} \pi^{4/3} \left(\frac{1}{4} (3 t1 + 5 t2) + t2 x2\right) + \frac{9}{16} (a + b) n^{1+\alpha} t3 \alpha (1 + \alpha)$$

```
In[19]:= Simplify[ K2 - K]
```

$$\text{Out[19]}= 0$$

■ The symmetry energy:

Neutron matter:

In[20]:=
```
Solve[{(nn - np) == n δ, n == nn + np}, {nn, np}]
```

Out[20]=
$$\left\{\left\{\text{nn} \to -\frac{1}{2}\ (-\text{n}-\text{n}\,\delta),\ \text{np} \to -\frac{1}{2}\ (-\text{n}+\text{n}\,\delta)\right\}\right\}$$

In[21]:=
```
Esym =
 Simplify[(D[D[(Hbulk /. nn → 1 / 2 (n + n δ) /. np → 1 / 2 (n - n δ)), δ], δ] / 2 / n) /. δ → 0]
```

Out[21]=
$$\frac{1}{96\,\text{M}}\left(8\,2^{1/3}\,3^{2/3}\,\text{n}^{2/3}\,\pi^{4/3} - 12\,\text{M}\,\text{n}\,\text{t0}\,(1+2\,\text{x0}) + 2\,2^{1/3}\,3^{2/3}\,\text{M}\,\text{n}^{5/3}\,\pi^{4/3}\,(-3\,\text{t1}\,\text{x1} + \text{t2}\,(4+5\,\text{x2})) - \text{M}\,\text{n}^{1+\alpha}\,\text{t3}\,(2\,\text{b}\,(1+2\,\text{x3}) + \text{a}\,(2-3\,\alpha-\alpha^2+\text{x3}\,(4+3\,\alpha+\alpha^2)))\right)$$

In[22]:=
```
Esym2 = 5 / 9 kr23 + 10 / 3 M kr23 n (1 / 6 t2 (1 + 5 / 4 x2) - 1 / 8 t1 x1) - 1 / 24 b t3 (1 / 2 + x3) n^(1+α) -
   1 / 4 t0 (1 / 2 + x0) n - 1 / 96 a n^(1+α) t3 (2 - α (3 + α) + x3 (4 + α (3 + α)))
```

Out[22]=
$$\frac{\text{n}^{2/3}\,\pi^{4/3}}{2\,2^{2/3}\,3^{1/3}\,\text{M}} - \frac{1}{4}\,\text{n}\,\text{t0}\left(\frac{1}{2}+\text{x0}\right) + \left(\frac{3}{2}\right)^{2/3}\text{n}^{5/3}\,\pi^{4/3}\left(-\frac{\text{t1}\,\text{x1}}{8}+\frac{1}{6}\,\text{t2}\left(1+\frac{5\,\text{x2}}{4}\right)\right) - \frac{1}{24}\,\text{b}\,\text{n}^{1+\alpha}\,\text{t3}\left(\frac{1}{2}+\text{x3}\right) - \frac{1}{96}\,\text{a}\,\text{n}^{1+\alpha}\,\text{t3}\,(2-\alpha\,(3+\alpha)+\text{x3}\,(4+\alpha\,(3+\alpha)))$$

In[23]:=
```
Simplify[Esym - Esym2]
```

Out[23]=
```
0
```

In[24]:=
```
EPaul = 5 / 9 kr23 (1 + 6 M n (1 / 6 t2 (1 + 5 / 4 x2) - t1 x1 / 8)) - t0 / 4 (1 / 2 + x0) n +
   a t3 / 24 n^(1+α) (-1 - x3 / 2 + 1 / 4 (1 - x3) (α + 2) (α + 1)) - b t3 / 24 (1 / 2 + x3) n^(1+α)
```

Out[24]=
$$-\frac{1}{4}\,\text{n}\,\text{t0}\left(\frac{1}{2}+\text{x0}\right) + \frac{\text{n}^{2/3}\,\pi^{4/3}\,\left(1+6\,\text{M}\,\text{n}\,\left(-\frac{\text{t1}\,\text{x1}}{8}+\frac{1}{6}\,\text{t2}\,\left(1+\frac{5\,\text{x2}}{4}\right)\right)\right)}{2\,2^{2/3}\,3^{1/3}\,\text{M}} - \frac{1}{24}\,\text{b}\,\text{n}^{1+\alpha}\,\text{t3}\left(\frac{1}{2}+\text{x3}\right) + \frac{1}{24}\,\text{a}\,\text{n}^{1+\alpha}\,\text{t3}\left(-1-\frac{\text{x3}}{2}+\frac{1}{4}\,(1-\text{x3})\,(1+\alpha)\,(2+\alpha)\right)$$

In[25]:=
```
Simplify[Esym - EPaul]
```

Out[25]=
```
0
```

■ Re−express Hamiltonian as in code:

In[26]:=
```
vars = {ham1 -> t0 / 2 (1 + x0 / 2),
   ham2 -> -t0 / 2 (1 / 2 + x0),
   ham3 -> a t3 / 6 (1 + x3 / 2),
   ham4 -> a t3 2^(α-2) / 6 (1 - x3),
   ham5 -> b t3 / 12 (1 + x3 / 2),
   ham6 -> -b t3 / 12 (1 / 2 + x3)}
```

Out[26]=
$$\left\{\text{ham1} \to \frac{1}{2}\,\text{t0}\left(1+\frac{\text{x0}}{2}\right),\ \text{ham2} \to -\frac{1}{2}\,\text{t0}\left(\frac{1}{2}+\text{x0}\right),\ \text{ham3} \to \frac{1}{6}\,\text{a}\,\text{t3}\left(1+\frac{\text{x3}}{2}\right),\ \text{ham4} \to \frac{1}{3}\,2^{-3+\alpha}\,\text{a}\,\text{t3}\,(1-\text{x3}),\ \text{ham5} \to \frac{1}{12}\,\text{b}\,\text{t3}\left(1+\frac{\text{x3}}{2}\right),\ \text{ham6} \to -\frac{1}{12}\,\text{b}\,\text{t3}\left(\frac{1}{2}+\text{x3}\right)\right\}$$

In[27]:=
```
Hcode = τn h2mns + τp h2mps + ham1 n^2 + ham2 (nn^2 + np^2) +
   ham3 n^α nn np + ham4 (nn^(α+2) + np^(α+2)) + ham5 n^(2+α) + ham6 (nn^2 + np^2) n^α
```

Out[27]=
$$\text{ham1}\,\text{n}^2 + \text{ham5}\,\text{n}^{2+\alpha} + \text{ham3}\,\text{n}^{\alpha}\,\text{nn}\,\text{np} + \text{ham2}\,(\text{nn}^2+\text{np}^2) + \text{ham6}\,\text{n}^{\alpha}\,(\text{nn}^2+\text{np}^2) + \text{ham4}\,(\text{nn}^{2+\alpha}+\text{np}^{2+\alpha}) + \frac{3}{5}\,3^{2/3}\,\text{nn}^{5/3}\,\pi^{4/3}\left(\frac{1}{2\,\text{M}}+\frac{1}{4}\,\text{n}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\,\text{nn}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right) + \frac{3}{5}\,3^{2/3}\,\text{np}^{5/3}\,\pi^{4/3}\left(\frac{1}{2\,\text{M}}+\frac{1}{4}\,\text{n}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\,\text{np}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right)$$

In[28]:=
```
Simplify[(Hcode /. vars /. n → nn + np) - Hbulk]
```

Out[28]=
$$0$$

In[29]:=
```
D[(Hcode /. n → nn + np), nn]
```

Out[29]=
$$2\,\text{ham2}\,\text{nn} + 2\,\text{ham1}\,(\text{nn}+\text{np}) + 2\,\text{ham6}\,\text{nn}\,(\text{nn}+\text{np})^{\alpha} + \text{ham3}\,\text{np}\,(\text{nn}+\text{np})^{\alpha} + \frac{3}{20}\,3^{2/3}\,\text{np}^{5/3}\,\pi^{4/3}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right) + \frac{3}{5}\,3^{2/3}\,\text{nn}^{5/3}\,\pi^{4/3}\left(\frac{1}{4}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right) + 3^{2/3}\,\text{nn}^{2/3}\,\pi^{4/3}\left(\frac{1}{2\,\text{M}}+\frac{1}{4}\,(\text{nn}+\text{np})\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\,\text{nn}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right) + \text{ham3}\,\text{nn}\,\text{np}\,(\text{nn}+\text{np})^{-1+\alpha}\,\alpha + \text{ham6}\,(\text{nn}+\text{np})^{-1+\alpha}\,(\text{nn}^2+\text{np}^2)\,\alpha + \text{ham4}\,\text{nn}^{1+\alpha}\,(2+\alpha) + \text{ham5}\,(\text{nn}+\text{np})^{1+\alpha}\,(2+\alpha)$$

In[30]:=
```
D[(Hcode /. n → nn + np), np]
```

Out[30]=
$$2\,\text{ham2}\,\text{np} + 2\,\text{ham1}\,(\text{nn}+\text{np}) + \text{ham3}\,\text{nn}\,(\text{nn}+\text{np})^{\alpha} + 2\,\text{ham6}\,\text{np}\,(\text{nn}+\text{np})^{\alpha} + \frac{3}{20}\,3^{2/3}\,\text{nn}^{5/3}\,\pi^{4/3}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right) + \frac{3}{5}\,3^{2/3}\,\text{np}^{5/3}\,\pi^{4/3}\left(\frac{1}{4}\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right) + 3^{2/3}\,\text{np}^{2/3}\,\pi^{4/3}\left(\frac{1}{2\,\text{M}}+\frac{1}{4}\,(\text{nn}+\text{np})\left(\text{t1}\left(1+\frac{\text{x1}}{2}\right)+\text{t2}\left(1+\frac{\text{x2}}{2}\right)\right)+\frac{1}{4}\,\text{np}\left(-\text{t1}\left(\frac{1}{2}+\text{x1}\right)+\text{t2}\left(\frac{1}{2}+\text{x2}\right)\right)\right) + \text{ham3}\,\text{nn}\,\text{np}\,(\text{nn}+\text{np})^{-1+\alpha}\,\alpha + \text{ham6}\,(\text{nn}+\text{np})^{-1+\alpha}\,(\text{nn}^2+\text{np}^2)\,\alpha + \text{ham4}\,\text{np}^{1+\alpha}\,(2+\alpha) + \text{ham5}\,(\text{nn}+\text{np})^{1+\alpha}\,(2+\alpha)$$

In[31]:=